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EDUCATION

Stanford University; Stanford, California

Ph.D., Aeronautics and Astronautics

Graduation Date: June 1996

GPA: 3.9/4.0

Thesis title: *Probabilistic Engineering Design Optimization: Applications to Spacecraft and Navigation Systems*

M.S., Aeronautics and Astronautics (emphasis on guidance and control systems)

Graduation Date: June 1990

GPA: 3.8/4.0

Massachusetts Institute of Technology; Cambridge, Massachusetts

S.B., Aeronautics and Astronautics

S.B., History (emphasis on modern Europe, technology strategy and development)

Graduation Date: June 1989

GPA: 4.8/5.0

EXPERIENCE

Senior Research Engineer, May 1999 – present (part-time since August 2011)

(Research Associate from July 1996 – April 1999)

Hansen Laboratories and Dept. of Aeronautics and Astronautics; Stanford University;
Stanford, California

- Head of the Ground Based Augmentation System (GBAS)/Local Area Augmentation System (LAAS) research project, overseeing 5 – 15 engineers and graduate students working on algorithm research, safety assurance, prototype development, and test and validation.
- Developed, installed, and validated the first LAAS ground system prototype (the “Integrity Monitor Testbed”) that included all elements and algorithms needed to protect user safety.
- Supported the FAA in developing specifications, algorithms, and test procedures for vendor systems that evolved into the SLS-4000 and -5000 LAAS Ground Facilities. Several key algorithms were first developed and tested in Stanford’s Integrity Monitor Testbed.
- Developed original methods for spacecraft reliability and risk assessment for the Gravity Probe-B Relativity Mission developed at Stanford under NASA/MSFC management.
- Provided research support to other projects, including WAAS, JPALS, and PPP integrity verification. Developed the first comprehensive predictions of WAAS performance and availability and extended these tools to support WAAS architecture design optimization.
- Taught graduate-level course, “Space Mechanics,” in 1999-2000. Guest lecturer for “Global Positioning Systems” and other courses in Aero/Astro department.

Consultant, January 1996 – present (self-employed and via NavAstro; Los Gatos, California)

- Technical review and support of concepts for integrity verification and certification of train control systems using GNSS and augmented GNSS.
- Technical support of integrity algorithm design, test, and validation for multiple companies developing LAAS/GBAS ground and airborne equipment.

- Expert witness analysis, report generation, and testimony concerning navigation technology, patent rights, and defects, including litigation in U.S. and Canadian courts. Applications include GPS receivers, aircraft, automobiles, and train control systems (see separate list).
- Analysis and development of Advanced RAIM (ARAIM) for military and civilian aircraft.
- Conceptual development of GNSS systems for automated land vehicle guidance, including real-time verification of GNSS integrity at the levels needed for automated driving.
- Technical support of system architecture, algorithm design, and requirements assessment for the U.S. Navy Sea-Based JPALS Program.
- Technical support of the GPS III Modernization effort under contract to the DOD GPS Joint Program Office, including requirements definition and performance simulation.
- Design and development of onboard GPS satellite self-integrity monitoring.
- Technical support of the Johns Hopkins University Applied Physics Laboratory GPS Risk Assessment, including problem formulation, performance simulation, and risk analysis.
- Tutorial presentations on LAAS fundamentals, algorithms, and aviation applications.
- Space satellite and constellation reliability analysis, including pre-launch reliability estimates (using thesis research methodology) and revisions after observing initial behavior in orbit.

Researcher, *on-site*: June - December 1990; *consultant*: January 1991 – September 1997

The RAND Corporation; Santa Monica, California

Examined the current and proposed future basing structures of the U.S. Air Force in Europe.

Developed a software tool to model and assess future aircraft basing options. The results of this study were validated by subsequent experience as aircraft were withdrawn from Europe.

ACADEMIC AND PROFESSIONAL SERVICES

- **Editor of “GNSS Solutions” column**, *Inside GNSS magazine*, January 2020 – present
- **Associate Editor for Navigation**, *IEEE Transactions on Aerospace and Electronic Systems*, October 2007 – January 2015
- **Tutorial Instructor** on GNSS augmentations and integrity, ION GNSS 2011 – 2013
- **Reviewer** for IEEE, AIAA, ION, and other journals, 1998 – present
- **Institute of Navigation (ION) Council Member**, 2003 – 2005
- **Session Chair** at multiple ION, IEEE, and other conferences

AWARDS AND HONORS

- Fellow of the Institute of Navigation (ION) (2017)
- ION Early Achievement Award (1999)
- ION GPS/GNSS Conference “Best Paper” Awards (1999, 2000, 2001, 2009)
- National Science Foundation Graduate Fellowship (1989 – 1992)
- Tau Beta Pi and Sigma Gamma Tau engineering honor societies at MIT (1987, 1988)

OTHER SKILLS

- Japanese language ability and extensive familiarity with Japanese business and personal culture, including NSF-supported and consulting engagements in Japan.
- Extensive knowledge of finance, investing, and economics through consulting and private study.

Proficient in programming (C, C++, Python), engineering/statistics applications (Matlab, R), and spreadsheet (Excel) applications.

PATENTS

- [P03] R.W. Rose, M.T. Nehrenz, **S. Pullen**, “Radar augmented receiver autonomous integrity monitoring in aircraft,” US Patent Filing US20220365224A1, Filed Nov. 30, 2021.
<https://patents.google.com/patent/US20220365224A1/>
- [P02] R.W. Rose, M.T. Nehrenz, **S. Pullen**, “Filter augmented receiver autonomous integrity monitoring in aircraft,” US Patent Filing US20220365222A1, Filed Nov. 30, 2021.
<https://patents.google.com/patent/US20220365222A1/>
- [P01] G. Green, **S. Pullen**, “Self-monitoring satellite system,” U.S. Patent No. 6,667,713, Issued Dec. 23, 2003. <http://www.google.com/patents/about?id=HoMOAAAAEBAJ&dq=6,667,713>

BOOK CHAPTERS AND REPORTS

- [B6] S. Datta-Barua, E. Altshuler, T. Walter, **S. Pullen**, “Ionospheric Scintillation Effects on Satellite Navigation,” Ch. 20 in *Ionosphere Dynamics and Applications*, C. Huang, G. Lu, et al., Eds., Hoboken, NJ, Wiley-American Geophysical Union (AGU), 2021.
<https://doi.org/10.1002/9781119815617>
- [B5] **S. Pullen**, M. Joerger, “GNSS Integrity and Receiver Autonomous Integrity Monitoring (RAIM),” Ch. 23 in *Position, Navigation, and Timing Technologies in the 21st Century*, J. Morton, F. van Diggelen, et al., Eds., Hoboken, NJ: Wiley-IEEE, 2021. <https://ieeexplore.ieee.org/book/9304973>
- [B4] **S. Pullen**, “Ground Based Augmentation Systems,” Ch. 31 in *Springer Handbook of Global Navigation Satellite Systems*. P. Teunissen, O. Montenbruck, Eds., Switzerland: Springer AG, 2017. <https://www.springer.com/us/book/9783319429267>
- [B3] J. Rife, **S. Pullen**, “Aviation Applications,” Ch. 10 in *GNSS Applications and Methods*. S. Gleason, D. Gebre-Egziabher, Eds., Norwood, MA: Artech House, 2009.
<http://www.artechhouse.com/Detail.aspx?strIsbn=978-1-59693-329-3>
- [B2] **S. Pullen**, J. Rife, “Differential GNSS: Accuracy and Integrity,” Ch. 4 in *GNSS Applications and Methods*. S. Gleason, D. Gebre-Egziabher, Eds., Norwood, MA: Artech House, 2009.
<http://www.artechhouse.com/Detail.aspx?strIsbn=978-1-59693-329-3>
- [B1] T. Corrigan, J. Hartranft, L. Levy, K. Parker, J. Pritchett, A. Pue, **S. Pullen**, T. Thompson, *GPS Risk Assessment Study: Final Report*. Laurel, MD., The Johns Hopkins University Applied Physics Laboratory, VS-99-007. January 1999. <http://www.rvs.uni-bielefeld.de/publications/Incidents/DOCS/Research/Other/Article/gps-risk-ass.pdf>

JOURNAL PAPERS

- [J43] L. Marini-Pereira, A.O. Moraes, **S. Pullen**, “Advanced Warning of Threatening Equatorial Plasma Bubbles to Support GBAS in Low Latitudes,” *IEEE Trans. Aerospace and Electronic Systems*, Feb. 2023, pp. 1-14. <https://doi.org/10.1109/TAES.2023.3243581>
- [J42] H. Lee, **S. Pullen**, J. Lee, B. Park, M. Yoon, J. Seo, “Optimal Parameter Inflation to Enhance the Availability of Single-Frequency GBAS for Intelligent Air Transportation,” *IEEE Trans. Intelligent Transportation Systems*, Vol. 23, No. 10, Oct. 2022, pp. 17801-17808.
<https://doi.org/10.1109/TITS.2022.3157138>
- [J41] B.J. Affonso, A.O. Moraes, J. Sousasantos, L. Marini-Pereira, **S. Pullen**, “Strong Ionospheric Spatial Gradient Events Induced by Signal Propagation Paths Aligned with Equatorial Plasma Bubbles,” *IEEE Trans. Aerospace and Electronic Systems*, Vol. 58, No. 4, Aug. 2022, pp. 2868-2879. <https://doi.org/10.1109/TAES.2022.3144622>
- [J40] L. Marini-Pereira, **S. Pullen**, A.O. Moraes, “Ground-Based Augmentation Systems Operation in Low Latitudes - Part 2: Space Weather, Ionospheric Behavior and Challenges,” *J. Aerospace*

Technology and Management, Vol. 13, 2021.

<https://www.scielo.br/j/jatm/a/hmWtVQL4XFrSWmQVXtpNTWg/>

- [J39] L. Marini-Pereira, **S. Pullen**, A.O. Moraes, “Ground-Based Augmentation Systems Operation in Low Latitudes - Part 1: Challenges, Mitigations, and Future Prospects,” *J. Aerospace Technology and Management*, Vol. 13, 2021. <https://www.scielo.br/j/jatm/a/4y64KqSDVGsNVHqhCxyRtfv/>
- [J38] K.A. Sun, H. Chang, **S. Pullen**, H. Kil, J. Seo, Y.J. Morton, J. Lee, “Markov Chain-Based Stochastic Modeling of Deep Signal Fading: Availability Assessment of Dual-Frequency GNSS-Based Aviation Under Ionospheric Scintillation,” *Space Weather*, Vol. 19, No. 9, Sept. 2021. <https://doi.org/10.1029/2020SW002655>
- [J37] D. Kim, M. Yoon, **S. Pullen**, J. Lee, “Closed-form Analysis of Undetected Range Errors due to Ionospheric Impacts for GBAS Category I Operations,” *Navigation*, Vol. 68, No. 3, Fall 2021, pp. 507-519. <https://doi.org/10.1002/navi.442>
- [J36] L. Marini-Pereira, A.O. Moraes, **S. Pullen**, “Reexamining Low-Latitude Ionospheric Error Bounds: An SBAS Approach for Brazil,” *IEEE Trans. Aerospace and Electronic Systems*, Vol. 57, No. 1, Feb. 2021, pp. 674-689. <https://doi.org/10.1109/TAES.2020.3029623>
- [J35] L. Marini-Pereira, L.F.D. Lourenco, J. Sousasantos, A.O. Moraes, **S. Pullen**, “Regional Ionospheric Delay Mapping for Low-Latitude Environments,” *Radio Science*, Vol. 55, No. 12, Dec. 2020, pp. 1-16. <https://doi.org/10.1029/2020RS007158>
- [J34] H. Chang, M. Yoon, **S. Pullen**, L. Marini-Pereira, J. Lee, “Ionospheric Spatial Decorrelation Assessment for GBAS Daytime Operations in Brazil,” *Navigation*, Vol. 68, No. 2, Summer 2021, pp. 391-404. <https://doi.org/10.1002/navi.418>
- [J33] M. Yoon, J. Lee, **S. Pullen**, “Integrity Risk Evaluation of Impact of Ionospheric Anomalies on GAST D GBAS,” *Navigation*, Vol. 67, No. 2, Summer 2020, pp. 223-234. <https://doi.org/10.1002/navi.339>
- [J32] M. Yoon, D. Kim, **S. Pullen**, J. Lee, “Assessment and mitigation of equatorial plasma bubble impacts on category I GBAS operations in the Brazilian region,” *Navigation*, Vol. 66, No. 3, Fall 2019, pp. 643-659. <https://doi.org/10.1002/navi.328>
- [J31] T. Sasaki, T. Shimomura, **S. Pullen**, H. Schaub, “Attitude and Vibration control with Double-Gimbal Variable-Speed Control Moment Gyros,” *Acta Astronautica*, Vol. 152, November 2018, Pages 740-751. <https://doi.org/10.1016/j.actaastro.2018.08.047>
- [J30] N. Kubo, H. Tokura, **S. Pullen**, “Mixed GPS–BeiDou RTK with inter-systems bias estimation aided by CSAC,” *GPS Solutions*, Vol. 22, No. 1, Jan. 2018. <https://link.springer.com/article/10.1007/s10291-017-0670-1>
- [J29] M. Yoon, J. Lee, **S. Pullen**, J. Gillespie, N. Mathur, R. Cole, J. Rodrigues de Souza, P. Doherty, R. Pradipta, “Equatorial Plasma Bubble Threat Parameterization to Support GBAS Operations in the Brazilian Region,” *Navigation*, Vol. 64, No. 3, Fall 2017, pp. 309-321. <https://www.ion.org/publications/abstract.cfm?articleID=102720>
- [J28] S. Saito, S. Sunda, J. Lee, **S. Pullen**, S. Supriadi, T. Yoshihara, M. Terkildsen, F. Lecat, “Ionospheric delay gradient model for GBAS in the Asia-Pacific region,” *GPS Solutions*, Vol. 21, No. 4, Oct. 2017, pp. 1937-1947. <https://link.springer.com/article/10.1007/s10291-017-0662-1>
- [J27] J. Lee, **S. Pullen**, S. Datta-Barua, J. Lee, “Real-Time Ionospheric Threat Adaptation Using a Space Weather Prediction for GNSS-Based Aircraft Landing Systems,” *IEEE Trans. Intelligent Transportation Systems*, Vol. 18, No. 7, July 2017, pp. 1752-1761. <https://ieeexplore.ieee.org/abstract/document/7774997/>

- [J26] M. Kim, E. Bang, **S. Pullen**, Y.J. Lee, J. Lee, "Feasibility Studies for Applications of Long-Term Ionospheric Anomaly Monitor," *IEEE Trans. Aerospace and Electronic Systems*, Vol. 53, No. 3, June 2017, pp. 1581-1588. <https://ieeexplore.ieee.org/abstract/document/7859336/>
- [J25] M-S. Circiu, M. Meurer, M. Felux, D. Gerbeth, S. Thöler, M. Vergara, C. Enneking, M. Sgammini, **S. Pullen**, F. Antreich, "Evaluation of GPS L5 and Galileo E1 and E5a Performance for Future Multifrequency and Multiconstellation GBAS," *Navigation*, Vol. 64, No. 1, Spring 2017, pp. 149-163. <https://www.ion.org/publications/abstract.cfm?articleID=102710>
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- [J23] **S. Pullen**, P. Enge, "Using Outage History to Exclude High-Risk Satellites from GBAS Corrections," *Navigation*, Vol. 60, No. 1, Spring 2013, pp. 41-51. <https://www.ion.org/publications/abstract.cfm?articleID=102590>
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- [J21] J. Seo, J. Lee, **S. Pullen**, P. Enge, S. Close, "Targeted Parameter Inflation within Ground-Based Augmentation Systems to Minimize Anomalous Ionospheric Impact," *AIAA J. Aircraft*, Vol. 49, No. 2, March-April 2012, pp. 587-599. <http://preview.tinyurl.com/JA-N2-12>
- [J20] J. Lee, S. Datta-Barua, G. Zhang, **S. Pullen**, P. Enge, "Observations of Low-Elevation Ionospheric Anomalies for Ground-Based Augmentation of GNSS," *Radio Science*, Vol. 46, Nov. 22, 2011. <http://www.agu.org/journals/rs/rs1106/2011RS004776/2011RS004776.pdf>
- [J19] J. Lee, J. Seo, Y.S. Park, **S. Pullen**, P. Enge, "Ionospheric Gradient Threat Mitigation by Geometry Screening in GNSS Ground Based Augmentation Systems," *AIAA J. Aircraft*, Vol. 48, No. 4, July-Aug. 2011, pp. 1422-1433. <http://preview.tinyurl.com/JA-N4-11>
- [J18] S. Datta-Barua, J. Lee, **S. Pullen**, M. Luo, A. Ene, D. Qiu, G. Zhang, P. Enge, "Ionospheric Threat Parameterization for Local Area Global-Positioning-System-Based Aircraft Landing Systems," *AIAA J. Aircraft*, Vol. 47, No. 4, July-Aug. 2010, pp. 1141-1151. <http://preview.tinyurl.com/JA-N4-10>
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- [J15] J. Rife, S. Khanafseh, **S. Pullen**, D. De Lorenzo, U.S. Kim, M. Koenig, T.Y. Chiou, B. Kempny, B. Pervan, "Navigation, Interference Suppression, and Fault Monitoring in the Sea-Based Joint Precision Approach and Landing System," *Proc. IEEE*, Vol. 96, No. 12, Dec. 2008, pp. 1958-1975. <http://preview.tinyurl.com/PrIE-N12-08>
- [J14] J. Lee, **S. Pullen**, S. Datta-Barua, P. Enge, "Assessment of Ionosphere Spatial Decorrelation for Global Positioning System-Based Aircraft Landing Systems," *AIAA J. Aircraft*, Vol. 44, No. 5, Sept.-Oct. 2007, pp. 1662-1669. <http://preview.tinyurl.com/JA-N5-07>
- [J13] **S. Pullen**, P. Enge, "An Overview of GBAS Integrity Monitoring with a Focus on Ionospheric Spatial Anomalies," *Indian J. Radio & Space Physics*, Vol. 36, Aug. 2007, pp. 249-260. <http://preview.tinyurl.com/IRSP-07>

- [J12] J. Rife, **S. Pullen**, P. Enge, B. Pervan. "Paired Overbounding for Nonideal LAAS and WAAS Error Distributions," *IEEE Trans. Aerospace and Electronic Systems*, Vol. 42, No. 4, Oct. 2006, pp. 1386-1395. <http://preview.tinyurl.com/TAES-N4-06>
- [J11] J. Lee, **S. Pullen**, P. Enge, B. Pervan, L. Gratton, "Monitoring Global Positioning System Satellite Orbit Errors for Aircraft Landing Systems," *AIAA J. Aircraft*, Vol. 43, No. 3, May-June 2006, pp. 799-808. <http://preview.tinyurl.com/JA-N3-06>
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- [J08] D. Gebre-Egziabher, A. Razavi, P. Enge, J. Gautier, **S. Pullen**, B. Pervan, D. Akos, "Sensitivity and Performance Analysis of Doppler-Aided GPS Carrier-Tracking Loops," *Navigation*, Vol. 52, No. 2, Summer 2005, pp. 49-60. http://www.ion.org/search/view_abstract.cfm?jp=j&idno=2392
- [J07] M.B. Heo, B. Pervan, **S. Pullen**, J. Gautier, P. Enge, D. Gebre-Egziabher, "Autonomous Fault Detection with Carrier-Phase DGPS for Shipboard Landing Navigation," *Navigation*, Vol. 51, No. 3, Fall 2004, pp. 185-198. http://www.ion.org/search/view_abstract.cfm?jp=j&idno=2376
- [J06] B. Pervan, F.C. Chan, D. Gebre-Egziabher, **S. Pullen**, P. Enge, G. Colby, "Performance Analysis of Carrier-Phase DGPS Navigation for Shipboard Landing of Aircraft," *Navigation*, Vol. 50, No. 3, Fall 2003, pp. 181-192. http://www.ion.org/search/view_abstract.cfm?jp=j&idno=2354
- [J05] T. Shimomura, **S. Pullen**, "Strictly Positive Real H_2 Controller Synthesis via Iterative Algorithms for Convex Optimization," *AIAA J. Guidance, Control, and Dynamics*, Vol. 25, No. 6, Nov.-Dec. 2002, pp. 1003-1011. <http://preview.tinyurl.com/JGCD-N6-02>
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- [J03] B. Pervan, **S. Pullen**, J. Christie, "A Multiple Hypothesis Approach to Satellite Navigation Integrity," *Navigation*, Vol. 45, No. 1, Spring 1998, pp. 61-84. http://www.ion.org/search/view_abstract.cfm?jp=j&idno=6
- [J02] B. Pervan, D. Lawrence, K. Gromov, G. Opshaug, J. Christie, P.Y. Ko, A. Mitelman, **S. Pullen**, P. Enge, B. Parkinson, "Flight Test Evaluation of an Alternative Local Area Augmentation System Architecture," *Navigation*, Vol. 45, No. 1, Spring 1998, pp. 31-38. http://www.ion.org/search/view_abstract.cfm?jp=j&idno=3
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MAGAZINE ARTICLES

- [A20] **S. Pullen**, F. Rispoli, A. Neri, A. Vennarini, A. Persia, R. Capua, "How can GNSS augmentation services be combined to simultaneously support multiple user classes with demanding but different requirements?", GNSS Solutions column, *Inside GNSS*, Vol. 18, No. 4, July/Aug. 2023 (forthcoming).
- [A19] R. Wang, T. Walter, **S. Pullen**, "What are typical features of GNSS satellite faults in recent years? Are there any differences between satellite constellations?", GNSS Solutions column, *Inside GNSS*, Vol. 18, No. 2, Mar./Apr. 2023, pp. 28-35. <http://tiny.cc/March23-SP>
- [A18] **S. Pullen**, J. Lee, G. Nam, K.A. Sun, "How can two-way communications between reference stations and users enhance the performance and integrity of differential GNSS navigation?",

- GNSS Solutions column, *Inside GNSS*, Vol. 17, No. 6, Nov./Dec. 2022, pp. 22-29.
<http://tiny.cc/Nov22-SP>
- [A17] **S. Pullen**, S. Lo, A. Katz, “How can ground monitoring of GNSS constellations improve on the performance and integrity commitments made by GNSS constellation providers regarding the integrity of their signals and services? What performance benefits might result?”, GNSS Solutions column, *Inside GNSS*, Vol. 17, No. 4, July/Aug. 2022, pp. 22-27. <http://tiny.cc/July22-SP>
- [A16] **S. Pullen**, T. Walter, J. Blanch, R. Wang, “What commitments have the various constellation providers made to GNSS users regarding the integrity of their signals and services? How are these commitments transmitted to users, and how can they be updated if circumstances require?”, GNSS Solutions column, *Inside GNSS*, Vol. 17, No. 3, May/June 2022, pp. 26-33.
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- [A15] J. Anderson, T. Walter, S. Lo, **S. Pullen**, “How could GNSS users determine in real time that their received navigation signals are authentic? What methods are recommended, and when might they go into operation?”, GNSS Solutions column, *Inside GNSS*, Vol. 17, No. 1, Jan./Feb. 2022, pp. 22-27. <https://tiny.cc/Jan22-SP>
- [A14] **S. Pullen**, “To what degree does the greater ionospheric activity in equatorial regions degrade GNSS positioning? How does this degradation occur? What mitigations are available?”, GNSS Solutions column, *Inside GNSS*, Vol. 16, No. 5, Sept./Oct. 2021, pp. 20-26.
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- [A12] **S. Pullen**, “How can the parameters given in the most recent GPS Standard Positioning Service (SPS) Performance Standard (SPS PS) be used to quantify the performance of GPS applications?”, GNSS Solutions column, *Inside GNSS*, Vol. 16, No. 1, Jan./Feb. 2021, pp. 18-23.
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- [A11] **S. Pullen**, “Can analytical techniques guarantee that GNSS errors are bounded under rare conditions? What techniques are available?”, GNSS Solutions column, *Inside GNSS*, Vol. 15, No. 5, Sept./Oct. 2020, pp. 18-26. <https://tiny.cc/Sept20-SP>
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- [A09] **S. Pullen**, “What freeware or open-source software packages are available to support GNSS performance evaluations?”, GNSS Solutions column, *Inside GNSS*, Vol. 15, No. 1, Jan./Feb. 2020, pp. 46-51. <http://tiny.cc/Jan20-SP>
- [A08] **S. Pullen**, “Lessons Learned from the Development of GNSS Integrity Augmentations,” *Coordinates*. Vol. 12, No. 8, Aug. 2016, pp. 8-13. <http://mycoordinates.org/lessons-learned-from-the-development-of-gnss-integrity-augmentations/>
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- [A06] **S. Pullen**, G. Gao, “GNSS Jamming in the Name of Privacy: Potential Threat to GPS Aviation,” *Inside GNSS*, Vol. 7, No. 2, March/April 2012, pp. 34-43.
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INVITED TALKS (Since 2003)

- [T40] "Lessons Learned from the Mitigation of Ionospheric Anomalies on Ground-and Satellite-based GNSS Augmentation," *VIII SBGEA & SimFAST Symposium*, São José dos Campos, Brazil, March 26, 2021.
- [T39] "SBAS and GBAS Overview: Fundamentals, Similarities, and Differences," *Seoul National University (SNU) Tutorial*, Seoul, Korea, July 11, 2017.
- [T38] "Reliability of GNSS Positioning: Integrity and Continuity for Standalone and Augmented GNSS Users," *Seoul National University (SNU) Tutorial*, Seoul, Korea, July 10, 2017.
- [T37] "GNSS Vulnerabilities: Threats and Failure Modes that May Affect GNSS Positioning," *Seoul National University (SNU) Tutorial*, Seoul, Korea, July 10, 2017.
- [T36] "Safe Separation of UAVs based on Local-Area DGNSS Networks," *Korea Navigation Institute (KONI) Advanced Navigation System Workshop*, Seoul, Korea, July 7, 2017.
- [T35] "Reliability of GNSS Positioning: Integrity and Continuity for Standalone and Augmented GNSS Users," *International Seminars on Positioning and Navigation 2017*, ENAC Toulouse, France, May 12, 2017.
- [T34] "Lessons Learned from the Study of Anomalous Ionospheric Gradients and their Impact on GBAS and SBAS," *International Seminars on Positioning and Navigation 2017*, ENAC Toulouse, France, May 11, 2017.
- [T33] "GNSS Vulnerabilities: An Overview of Challenges to Safe and Predictable GNSS Positioning," *International Seminars on Positioning and Navigation 2017*, ENAC Toulouse, France, May 10, 2017.
- [T32] "Lessons Learned During the Development of GNSS Integrity Monitoring and Verification Techniques for Aviation Users," *International Technical Symposium on Navigation and Timing 2016*, ENAC, Toulouse, France, Nov. 16, 2016.
- [T31] "Lessons Learned from Two Decades of Research on GNSS Integrity Verification," *Tokyo University of Marine Science and Technology (TUMST)*, Tokyo, Japan, Nov. 20, 2015.
- [T30] "Lessons Learned from Two Decades of Research on GNSS Integrity Verification," *International Symposium on GNSS 2015 (IS-GNSS 2015)*, Plenary Presentation, Kyoto, Japan, Nov. 16, 2015.

- [T29] “Development of Ground Based Augmentation of Global Positioning Systems: Addressing the Key Challenges,” *Osaka Prefecture University Symposium*, Sakai (Osaka), Japan, Nov. 13, 2015.
- [T28] “Safety Analysis and Verification for Users of Global Navigation Satellite Systems (GNSS),” *Osaka Prefecture University Symposium*, Sakai (Osaka), Japan, Nov. 12, 2015.
- [T27] “The Use of Threat Models in Aviation Safety Assurance and an Update on Technical Challenges for Ground-Based Augmentation Systems (GBAS),” *Technical University of Munich (TUM) Satellite Navigation Colloquium*, Munich, Germany, July 11, 2014.
- [T26] “A Review of GBAS Integrity Risk Mitigation: Focused on Ionospheric Threats to Equatorial Locations and CAT II/III Operations,” *German Aerospace Center (DLR) GBAS Workshop*, Oberpfaffenhofen (Munich), Germany, July 10, 2014.
- [T25] “Augmented GNSS: Fundamentals and Keys to Integrity and Continuity,” *ION GNSS 2013 Tutorial*, Nashville, TN, Sept. 16, 2013.
- [T24] “Augmented GNSS: Fundamentals and Keys to Integrity and Continuity,” *ION GNSS 2012 Tutorial*, Nashville, TN, Sept. 18, 2012.
- [T23] “Unintentional RF Interference to GNSS: A Growing Problem,” *18th Korean GNSS Workshop*, Jeju, Korea, Nov. 3, 2011.
- [T22] “The Impact of Personal Privacy Devices on GBAS and Potential Mitigations,” *3rd Asia-Oceania Regional Workshop on GNSS*, Jeju, Korea, Nov. 2, 2011.
- [T21] “Augmented GNSS: Fundamentals and Keys to Integrity and Continuity,” *ION GNSS 2011 Tutorial*, Portland, OR, Sept. 20, 2011.
- [T20] “Improvements to GBAS Ionospheric Mitigation,” *International GBAS Working Group (I-GWG) 11 Meeting*, Osaka, Japan, Feb. 23, 2011.
- [T19] “GNSS Research at Stanford University: Recent Activities and Results,” *Tokyo University of Mercantile Marine*, Tokyo, Japan, Nov. 15, 2010.
- [T18] “Recent Progress on GNSS and Ground-Based Augmentation Systems (GBAS),” *JAXA Chofu Aerospace Center (CAC)*, Chofu, Tokyo, Japan, Nov. 9, 2010.
- [T17] “Highlights of Recent Stanford Work on GBAS,” *German Aerospace Center (DLR)*, Oberpfaffenhofen (Munich), Germany, Sept. 30, 2010.
- [T16] “Ionospheric Anomaly Mitigation: Present and Future,” *International GBAS Working Group (I-GWG) 10 Meeting*, Brussels, Belgium, June 3, 2010.
- [T15] “Recent Stanford GBAS Research: CAT III and DCPS,” *German Aerospace Center (DLR)*, Oberpfaffenhofen (Munich), Germany, March 3, 2010.
- [T14] “An Overview of Ground-Based Augmentation of GNSS,” *Technical University of Braunschweig*, Braunschweig, Germany, Feb. 24, 2010.
- [T13] “Stanford GNSS Research: Recent Activities and Results,” *German Aerospace Center (DLR)*, Oberpfaffenhofen (Munich), Germany, Feb. 22, 2010.
- [T12] “Local Area Augmentation of the Global Positioning System: An Overview of the Technology and its Development,” *Stanford University, AA 297 Seminar*, May 13, 2009.
- [T11] “Completion of CAT I LAAS Integrity Analysis and Future Work,” *German Aerospace Center (DLR)*, Oberpfaffenhofen (Munich), Germany, Oct. 1, 2008.
- [T10] “Fundamentals of Ground Based Augmentation Systems (GBAS) and Key Drivers of GBAS User Performance,” *Japan GPS/GNSS Symposium 2007*, Invited Tutorial, Tokyo, Japan, Nov. 20, 2007.

- [T09] “LAAS Overview and Highlights of Stanford LAAS Research,” *Peking University*, “Digital China” Symposium, Beijing, China, Nov. 16, 2007.
- [T08] “LAAS Technical Overview and Key Details from Stanford Research,” *Beihang University (BUAA)*, Beijing, China, Nov. 14, 2007.
- [T07] “The Fundamentals of Satellite Navigation: Present and Future,” *Beihang University (BUAA)*, Beijing, China, Nov. 13, 2007.
- [T06] “An Update on LAAS Ionosphere Anomaly Mitigation Strategy for CONUS,” *International GBAS Working Group (I-GWG) 6 Meeting*, Mukilteo (Seattle), Washington, July 18, 2007.
- [T05] “Ionosphere Anomaly Mitigation for CAT I GBAS Users Outside CONUS,” *International GBAS Working Group (I-GWG) 5 Meeting*, Toulouse, France, Nov. 29, 2006.
- [T04] “Mitigation of Ionosphere Spatial Anomaly Threat to GBAS,” *International GBAS Working Group (I-GWG) 4 Meeting*, Sydney, Australia, Feb. 8, 2006.
- [T03] “Update on LAAS Ionosphere Spatial Anomaly Threat Studies,” *RTCA Special Committee 159*, Washington, DC, March 8, 2005.
- [T02] “Status of CAT I LAAS Ionosphere Anomaly Resolution,” *RTCA Special Committee 159*, Washington, DC, Oct. 5, 2004.
- [T01] “System Overview, Recent Developments, and Future Outlook for SBAS and GBAS,” *Osaka Prefectural University*, Sakai, Osaka, Japan, Nov. 21, 2003.

CONFERENCE PAPERS (Note: within numbering, “[Mxy]” = “[C1xy]”)

- [M58] J. Lee, G. Nam, D. Min, A.K. Sun, **S. Pullen**, “Network-Based Augmentation System (NBAS) Architectures Optimized to Support Urban Air Mobility (UAM),” *Proc. ION ITM 2023*, Long Beach, CA, Jan. 24-26, 2023, pp. 441-453. <https://doi.org/10.33012/2023.18603>
- [M57] **S. Pullen**, S. Lo, I. Colobong, S. Oak, J. Blanch, T. Walter, M. Crews, R. Jackson, S. Young, K. Huttenhoff, “GNSS Constellation Performance Using ARAIM with Inclined Geosynchronous Satellite and Low-Earth-Orbit Satellite Augmentation,” *Proc. ION ITM 2023*, Long Beach, CA, Jan. 24-26, 2023, pp. 664-678. <https://doi.org/10.33012/2023.18661>
- [M56] Y. Zhang, N. Kubo, **S. Pullen**, “Evaluation of QZSS Centimeter Level Augmentation System (CLAS): Open-Sky to Urban Environments and Geodetic to Low-Cost Receivers,” *Proc. ION GNSS+ 2022*, Denver, CO, Sept. 19-23, 2022, pp. 2729-2750. <https://doi.org/10.33012/2022.18517>
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- [M54] G. Nam, K.A. Sun, **S. Pullen**, “Networked UAV Detection and Alerting of Ionospheric Anomalies within LADGNSS Navigation Framework,” *Proc. ION GNSS+ 2022*, Denver, CO, Sept. 19-23, 2022, pp. 1529-1536. <https://doi.org/10.33012/2022.18424>
- [M53] F. Rispoli, A. Vennarini, A. Vizzarri, R. Capua, A. Neri, **S. Pullen**, “On the GNSS Augmentation Services for the ERTMS Train Control and Connected Car Applications: Technical Synergies and Opportunities,” *Proc. ION GNSS+ 2022*, Denver, CO, Sept. 19-23, 2022, pp. 1514-1528. <https://doi.org/10.33012/2022.18423>
- [M52] G. Nam, D. Min, N.M. Kim, J. Lee, **S. Pullen**, “Optimal Smoothing and Monitor Strategies for Dual-Frequency Dual-Constellation (DFDC) LADGNSS under Anomalous Ionospheric Conditions,” *Proc. ION ITM 2022*, Long Beach, CA, Jan. 25-27, 2022, pp. 1156-1174. <https://doi.org/10.33012/2022.18166>

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- [M50] G. Nam, D. Kim, N.M. Kim, J. Lee, **S. Pullen**, "Enhanced Local-Area DGNS for Autonomous Vehicle Navigation: Optimal Smoothing Strategy," *Proc. ION GNSS+ 2021*, St. Louis, MO, Sept. 20-24, 2021, pp. 4080-4096. <https://doi.org/10.33012/2021.18066>
- [M49] A. Katz, **S. Pullen**, S. Lo, J. Blanch, T. Walter, A. Katronick, M. Crews, R. Jackson, "ARAIM for Military Users: ISM Parameters, Constellation-Check Procedure and Performance Estimates," *Proc. ION ITM 2021*, Virtual Meeting, Jan. 25-28, 2021, pp. 173-188. <https://doi.org/10.33012/2021.17812>
- [M48] R. Capua, A. Filip, A. Neri, **S. Pullen**, F. Rispoli, P. Salvatori, C. Stallo, "A Multi-sensor Platform for High Integrity Multi-modal Positioning System," *Proc. ION GNSS+ 2020*, Virtual Meeting, Sept. 21-25, 2020, pp. 362-386. <https://doi.org/10.33012/2020.17608>
- [M47] K.A. Sun, H. Chang, J. Lee, J. Seo, Y.J. Morton, **S. Pullen**, "Performance Benefit from Dual-Frequency GNSS-based Aviation Applications under Ionospheric Scintillation: A New Approach to Fading Process Modeling," *Proc. ION ITM 2020*, San Diego, CA, Jan. 21-24, 2020, pp. 889-899. <https://doi.org/10.33012/2020.17184>
- [M46] P. Salvatori, C. Stallo, A. Coluccia, **S. Pullen**, S. Lo, A. Neri, "An Augmentation and Integrity Monitoring Network for Railway and Automotive Transportation," *Proc. ION ITM 2019*, Reston, VA, Jan. 28-31, 2019, pp. 790-801. <https://doi.org/10.33012/2019.16724>
- [M45] H. Chang, M. Yoon, J. Lee, **S. Pullen**, L.M. Pereira, "Assessment of Ionospheric Spatial Decorrelation for Daytime Operations of GBAS in the Brazilian Region," *Proc. ION ITM 2019*, Reston, VA, Jan. 28-31, 2019, pp. 618-631. <https://doi.org/10.33012/2019.16673>
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- [M43] **S. Pullen**, "A Review of GNSS Anomalies, Existing Mitigations, and Extensions to Autonomous Users," *Proc. 16th IAIN World Congress 2018*, Makuhari, Chiba, Japan, Nov. 28 – Dec. 1, 2018. <https://iain2018.org/>
- [M42] **S. Pullen**, J. Kilfeather, J. Goddard, T. Nowitzky, B. Shah, W. Doong, A. Welton, D. Kagan, K. Greer, "Enhanced Navigation, Robustness, and Safety Assurance for Autonomous Vehicles as part of the Globalstar Connected Car Program," *Proc. ION GNSS+ 2018*, Miami, FL, Sept. 24-28, 2018, pp. 1538-1565. <https://doi.org/10.33012/2018.16106>
- [M41] J. Lee, M. Kim, J. Lee, **S. Pullen**, "Integrity Assurance of Kalman-filter Based GNSS/IMU Integrated Systems against IMU faults for UAV Applications," *Proc. ION GNSS+ 2018*, Miami, FL, Sept. 24-28, 2018, pp. 2484-2500. <https://doi.org/10.33012/2018.15977>
- [M40] S. Khanafseh, M. Joerger, T. Walter, **S. Pullen**, J. Blanch, K. Doherty, L. Norman, L. de Groot, B. Pervan, "GNSS Multipath Error Modeling for Automotive Applications," *Proc. ION GNSS+ 2018*, Miami, FL, Sept. 24-28, 2018, pp. 1573-1589. <https://doi.org/10.33012/2018.16107>
- [M39] P. Salvatori, C. Stallo, **S. Pullen**, S. Lo, P. Enge, "Use of SBAS Corrections with Local-Area Monitoring for Railway Guidance and Control Applications," *Proc. IEEE/ION PLANS 2018*, Monterey, CA, April 23-26, 2018, pp. 1379-1387. <https://www.ion.org/publications/abstract.cfm?articleID=15815>
- [M38] C. Hegarty, K. Bean, O. Julien, S. Kalyanaraman, A.J. Van Dierendonck, **S. Pullen**, K. Shallberg, S. Ericson, "Updated Assessment of GNSS Intrasytem and Intersystem Interference for Airborne

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- [M37] **S. Pullen**, J. Lee, M. Kim, D. Kim, J. Lee “Coordinated UAV Operations Based on Local-Area Differential GNSS Navigation and Guidance,” *Proc. 5th ENRI Int’l. Workshop on ATM/CNS 2017 (EIWAC 2017)*, Tokyo, Japan, Nov. 14-16, 2017.
https://www.enri.go.jp/eiwac/eiwac_2017_eng.html
- [M36] **S. Pullen**, R. Cassell, B. Johnson, M. Brenner, D. Weed, L. Cypriano, M. Topland, M. Stakkeland, B. Pervan, M. Harris, S. Saito, J. Lee, B. Clark, S. Beauchamp, J. Dennis, “Impact of Ionospheric Anomalies on GBAS GAST D Service and Validation of Relevant ICAO SARPs Requirements,” *Proc. ION GNSS+ 2017*, Portland, OR, Sept. 25-29, 2017, pp. 2085-2105.
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- [M35] T. Cashin, B. El-Arini, V. Massimini, R. Niles, A. Odeh, G. Zheng, **S. Pullen**, C.-G. Wei, G. Shu, “Development and Implications of the Singapore GBAS Ionospheric Threat Model (GITM),” *Proc. ION GNSS+ 2017*, Portland, OR, Sept. 25-29, 2017, pp. 1429-1449.
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- [M34] S. Lo, **S. Pullen**, J. Blanch, P. Enge, A. Neri, V. Palma, M. Salvitti, C. Stallo, “Projected Performance of a Baseline High Integrity GNSS Railway Architecture under Nominal and Faulted Conditions,” *Proc. ION GNSS+ 2017*, Portland, OR, Sept. 25-29, 2017, pp. 2148-2171.
http://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Lo_IONGNSS_2017_Railway.pdf
- [M33] T. Sasaki, T. Shimomura, **S. Pullen**, H. Schaub, “Attitude and Vibration Control for a Flexible Spacecraft with Double-Gimbal Variable-Speed Control Moment Gyros,” *Proc. 3rd IAA Conference on Dynamics and Control of Space Systems (DYCOSS 2017)*, Moscow, Russia, May 30 – June 1, 2017. <http://hanspeterschaub.info/Papers/Sasaki2017.pdf>
- [M32] D. Kim, M. Yoon, J. Lee, **S. Pullen**, D. Weed, “Monte Carlo Simulation for Impact of Anomalous Ionospheric Gradient on GAST-D GBAS,” *Proc. ION Pacific PNT 2017*, Honolulu, HI, May 1-4, 2017, pp. 47-55. <https://www.ion.org/publications/abstract.cfm?articleID=15049>
- [M31] A. Neri, V. Palma, F. Rispoli, **S. Pullen**, S. Zhang, S. Lo, P. Enge, “A Method for Multipath Detection and Mitigation in Railway Control Applications,” *Proc. ION GNSS+ 2016*, Portland, OR, Sept. 12-16, 2016, pp. 1843-1855.
<https://www.ion.org/publications/abstract.cfm?articleID=14650>
- [M30] M. Yoon, D. Kim, J. Lee, S. Rungruengwajiake, **S. Pullen**, “Assessment of Equatorial Plasma Bubble Impacts on Ground-Based Augmentation Systems in the Brazilian Region,” *Proc. ION ITM 2016*, Monterey, CA, Jan. 25-28, 2016, pp. 368-379.
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- [M29] **S. Pullen**, J. Lee, M. Yoon, “Optimal Scheduling of Arrivals at Low-Latitude Airports under Severe Ionospheric Spatial Gradients,” *Proc. 4th ENRI Int’l. Workshop on ATM/CNS 2015 (EIWAC 2015)*, Tokyo, Japan, Nov. 17-19, 2015. <http://comm.stage.ac/eiwac2015/en/index.html>
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<http://ion.org/publications/abstract.cfm?articleID=12824>
- [M27] J. Lee, M. Yoon, **S. Pullen**, J. Gillespie, N. Mathur, R. Cole, J.R. de Souza, P. Doherty, R. Pradipta, “Preliminary Results from Ionospheric Threat Model Development to Support GBAS Operations in the Brazilian Region,” *Proc. ION GNSS+ 2015*, Tampa, FL, Sept. 14-18, 2015, pp. 1500-1506. <http://ion.org/publications/abstract.cfm?articleID=13040>
- [M26] M-S. Ciciu, M. Felux, B. Belabbas, M. Meurer, J. Lee, M. Kim, **S. Pullen**, “Evaluation of GPS L5, Galileo E1 and Galileo E5a Performance in Flight Trials for Multi Frequency Multi

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- [M24] M-S. Ciciu, M. Felux, S. Thöler, F. Antreich, M. Vergara, M. Sgammini, C. Enneking, **S. Pullen**, “Evaluation of GPS L5 and Galileo E1 and E5a Performance for Future Multi Frequency and Multi Constellation GBAS,” *Proc. ION ITM 2015*, Dana Point, CA, Jan. 26-28, 2015, pp. 374-382.
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- [M23] **S. Pullen**, P. Enge, “GPS III Accuracy and Integrity Improvements Using ARAIM with Shorter Age of Data,” *Proc. ION GNSS+ 2014*, Tampa, FL, Sept. 8-12, 2014, pp. 3352-3362.
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- [M22] M. Kim, K. Kim, J. Lee, **S. Pullen**, “High Integrity GNSS Navigation and Safe Separation Distance to Support Local-Area UAV Networks,” *Proc. ION GNSS+ 2014*, Tampa, FL, Sept. 8-12, 2014, pp. 869-878. <http://ion.org/publications/abstract.cfm?articleID=12424>
- [M21] **S. Pullen**, “The Use of Threat Models in Aviation Safety Assurance: Advantages and Pitfalls,” *Proc. 2014 Intl. Symp. on Certification of GNSS Systems & Services (CERGA 2014)*, Dresden, Germany, July 7-8, 2014.
- [M20] J. Lee, S. Datta-Barua, **S. Pullen**, “Conceptual Study of Real-time Ionospheric Threat Adaptation Using Space Weather Forecasting for GNSS Augmentation Systems,” *Proc. ION ITM 2014*, San Diego, CA, Jan. 27-29, 2014, pp. 645-656.
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- [M19] M-S. Ciciu, M. Felux, P. Remi, L. Yi, B. Belabbas, **S. Pullen**, “Evaluation of Dual Frequency GBAS Performance Using Flight Data,” *Proc. ION ITM 2014*, San Diego, CA, Jan. 27-29, 2014, pp. 645-656. <http://ion.org/publications/abstract.cfm?articleID=11535>
- [M18] H. Tokura, H. Yamada, N. Kubo, **S. Pullen**, “The Use of Multiple GNSS Constellations with Strict Quality Constraints for Achieving High Accuracy in Urban Environments,” *Proc. ION ITM 2014*, San Diego, CA, Jan. 27-29, 2014, pp. 488-498.
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APPENDIX A

31. Ground Based Augmentation Systems

Sam Pullen

This chapter explains the fundamentals of ground-based augmentation systems (GBASs). GBASs are fielded at airports to support civil aviation operations down to and including precision approach and landing. This chapter describes how GBAS generates differential corrections for Global Positioning System (GPS) pseudorange (L1 C/A-code) signals based on measurements taken at known (reference) locations, how reference measurements are monitored to protect against GPS and GBAS faults or anomalies, and what information is broadcast to users to support enhanced accuracy and integrity (or safety). The application of GBAS to civil aviation precision approach and landing is explained along with the key considerations in fielding GBAS reference equipment at airports. Augmentation systems that transmit additional global navigation satellite system (GNSS)-like ranging signals to users are also briefly introduced.

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Terrestrial augmentation of GNSSs can take the form of differential correction broadcasts and/or the broadcast of GNSS-like ranging signals from ground locations by so-called *pseudolites*. The original motivation for adding pseudolites to GNSSs was to compensate for the limited number of GPS satellites in the sky. For example, over-the-air tests of GPS transmitters at the Yuma test ground in the late 1970s were used to verify the performance of the GPS signal concept before sufficient satellites were in orbit to obtain position fixes solely from space [31.1]. While GPS today almost always provides four or more visible satellites above 10° of elevation, users with restricted sky visibility may still benefit from local ground-based transmitters [31.2].

Pseudolites have also been used to improve ranging geometry in such a way that carrier-phase integer ambiguities can be resolved once a user passes nearby [31.3].

The original motivation for broadcasting differential corrections to GNSS ranging signals came from the deliberate degradation of the timing accuracy of the GPS L1 C/A-code signals, which was known as selective availability, or S/A [31.4]. Error on the order of 10–20 m was artificially induced on the clock component of each GPS satellite (when receiving C/A-code) in order to prevent civil users from obtaining greater accuracy than was originally intended by the system designers. The error induced by S/A on a given satellite was the same for all C/A-code users tracking that

satellite. It was soon realized that receivers located at fixed and known (precisely surveyed) sites could estimate the error in each satellite ranging measurement and, by broadcasting this information, allow nearby users to remove the impact of S/A from their measurements [31.5]. This relatively simple means of defeating S/A was one reason that the US decided to deactivate S/A in May of 2000 [31.6].

Well before S/A was deactivated, the other advantages of what became known as *differential GPS* had become apparent. Once S/A was removed, other natural error sources such as satellite clock and ephemeris errors and ionospheric and tropospheric delays became significant contributors to GPS navigation accuracy. These are all highly correlated over short to medium distances; thus the application of differential corrections removes most of their effects. In addition, differential GPS was a key component of the task of verifying the integrity, or safety of use, of GPS signals using individual ground stations or networks of stations. Ground

systems that combine differential corrections with real-time integrity information became known as *GNSS augmentation systems*.

This chapter will focus on augmentation systems that are based on a single ground station site and dissemination of corrections and integrity information via radio link. This approach is generally denoted as local area differential GNSS, or LADGNSS. The adaptation of this technology for civil aircraft precision approaches and landings, known internationally as ground-based augmentation systems (GBAS) and as local area augmentation systems (LAAS) in the US, will be discussed in detail, as it covers almost all of the key considerations that apply to single-reference-site (SRS) augmentation systems. In particular, LAAS and GBAS have been approved to support precision approaches (with assured lateral and vertical guidance) down to Category I criteria – 200 ft above the surface – and extensions of this technology are expected to support approaches all the way to the ground (Category IIIB).

31.1 Components

Figure 31.1 shows the primary components of a GBAS reference station sited at an airport [31.7]. GBAS includes multiple (four or more) ground reference receivers and antennas for redundancy and integrity monitoring. Each receiver antenna is located in a carefully presurveyed site and is tested in advance to confirm that the multipath characteristics of the site selected are bounded by predetermined models that are used in determining the standard deviations (or *sigmas*) of the errors in the pseudorange corrections that are broadcast to aircraft. These antenna sites are separated by enough distance for their multipath errors (from ground reflections and distant obstacles) to be approximately statistically independent, allowing averaging of these errors under nominal conditions and making it easier to distinguish faulty measurements in a single reference receiver. For GBAS, it is important to minimize multipath errors at these receiver antennas because these errors will not be correlated with user ranging errors and thus will not be mitigated by differential corrections. Therefore, specialized ground antenna designs are used, and these will be described further in Sect. 31.3.

In GBAS, a master control processor typically located near or next to the reference receivers collects the receiver measurements and determines the pseudorange corrections and correction rates to broadcast for each satellite approved for use. This includes determining, using a series of monitor algorithms and

exclusion logic, which satellite and ground measurements are safe for the intended purpose, as will be discussed further in Sect. 31.3. This information is updated twice per second and includes (at lower update rates) information on station characteristics as well as the ideal approach geometries to be followed for all allowed precision approaches at this airport. It is packaged into several different message types, transferred by wire or optical fiber to a very high frequency (VHF) data broadcast (VDB) transmitter and antenna somewhere on airport property, and broadcast to users using the instrument landing system (ILS) localizer band from 108–118 MHz [31.8]. Siting of the VDB antenna at each airport is key to maximizing the airport surface area where the signal can be received while also ensuring acceptable signal levels throughout the precision approach coverage region in the air.

Because of the very high demands on GBAS for integrity and continuity (safety) and availability (the percentage of time operations are possible), multiple degrees of redundant equipment are essential. The same is not true of many less-demanding uses of LADGNSS. Many short-duration applications (such as day-long survey activities) can be adequately supported by a single reference receiver and antenna. In these cases, the equipment can be checked out before and after each application, and the penalty for a failed application is limited to repeating it after the equipment is

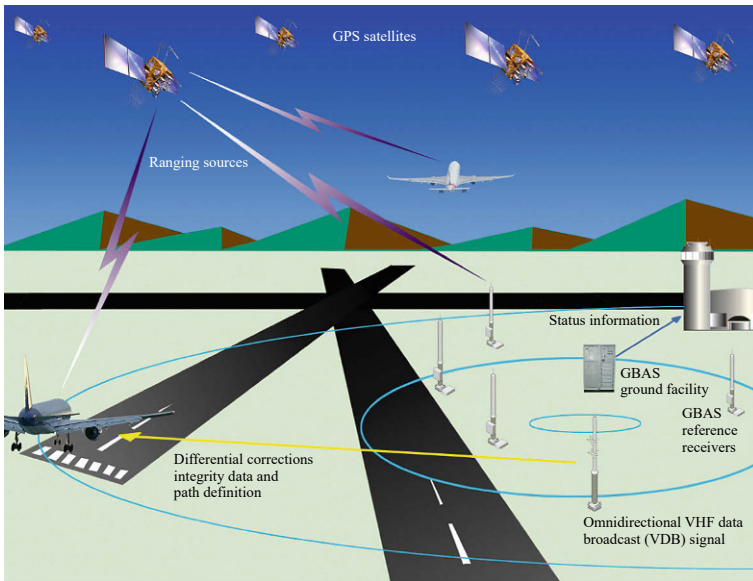


Fig. 31.1 GBAS ground station components—advanced example of terrestrial local area differential GNSS (DGNSS) systems (courtesy of the FAA satellite navigation team)

fixed. Permanent, fixed local area differential GNSS (LADGNSS) reference stations or networks will likely possess at least some redundancy to minimize mainte-

nance demands, but practically all LADGNSS applications other than GBAS are likely to need a subset of the equipment needed for GBAS.

31.2 An Overview of Local Area Approaches

While the hardware components for most LADGNSS systems are similar, significant differences exist between the algorithms used to generate differential corrections and the specific measurements that are corrected. This section will describe a few of these variations and refer to other chapters of this volume for more details.

31.2.1 Pseudorange Corrections

Almost all LADGNSS systems broadcast either corrections to pseudorange measurements or pseudorange measurements themselves so that users can remove common-mode errors by applying the broadcast information to their own measurements. In the most common case, where pseudorange corrections are sent, these corrections express the ground's best estimate of the pseudorange error on each visible satellite as measured by nearby users based on knowledge of the true positions of the reference receiver antenna(s) and the satellite locations included in the navigation data. Users then simply subtract this correction from their own pseudorange measurements to arrive at improved ones that are used in positioning calculations (Chap. 26). Note that a common procedure is required between ref-

erence and user systems to ensure that common terms are applied or not applied at both ends. GBAS, for example, applies satellite clock corrections (based on navigation data) to its reference measurements. These corrections will be the same for reference and user receivers. To maintain proper error cancellation, GBAS users must also apply satellite clock corrections but not relativistic corrections [31.9].

When a *corrections* approach similar to GBAS is used, the broadcast corrections should be close to zero and should approximate the actual error on the pseudoranges measured by users due to satellite (clock and ephemeris) and atmospheric (ionosphere and troposphere) causes. The small magnitude of this number makes it easy to broadcast with a small dynamic range; i.e., a small number of bits in a digital message format (one value for each usable satellite). Because standalone user errors are often dominated by ionospheric delay, pseudorange corrections under nominal conditions are typically their largest for low-elevation satellites when the ionosphere is particularly active (Chap. 39). The maximum magnitude of GBAS pseudorange corrections is ± 327.67 m [31.8], but anything larger than ± 125 to 150 m suggests a potential satellite anomaly, as this exceeds the range

of ionospheric delays even under extreme conditions.

Due to the time delay that exists between the measurements used to generate differential corrections on the ground and the application of the resulting corrections to user measurements, pseudorange rate corrections or other means to interpolate over the resulting latency are needed. GBAS provides a time tag for each pseudorange correction and broadcasts pseudorange rate corrections based upon the difference between the last two pseudorange corrections divided by the time interval. Users apply this pseudorange correction rate to linearly extrapolate forward from the correction time tag to the time of their measurements as long as this latency is within a time to alert that is protected by the ground station. Satellites suffering from *clock* failures can have range measurements that vary wildly and nonlinearly over a few seconds to minutes; thus these faults need to be detected quickly to protect the linear extrapolation performed by GBAS users.

31.2.2 Carrier-Phase Corrections

In addition to broadcasting pseudorange corrections, some LADGNSS systems also transmit raw carrier-phase measurements or corrections to them in support of users applying what is known as carrier-phase differential GNSS (CDGNSS) or real time kinematic (RTK) GNSS processing. CDGNSS users include those with centimeter- or even millimeter-level positioning accuracy requirements, such as surveyors and scientific users.

Carrier-phase measurements contain unknown integer ambiguities (i.e., integer numbers of sine-wave cycles) and thus do not provide unambiguous range estimates. Solving for these ambiguities is a key component of most algorithms applied by CDGNSS and RTK users, and it is this step that provides centimeter-level or better range and position accuracy (Chap. 23 and [31.3]). Some CDGPS techniques do not depend upon always resolving integer ambiguities (*fixed* solutions) but instead upon refining *floating* estimates of these ambiguities over time; thereby improving upon the performance that can be obtained from pseudorange-based LADGNSS alone. For examples of these techniques used for aviation, see [31.10, 11]. Existing GBAS systems do not broadcast carrier-phase corrections, but because of these potential benefits, Message type 6 has been reserved to support future carrier-phase corrections in the GBAS interface control document (ICD) [31.8].

31.2.3 Reference Station Distribution

Most LADGNSS systems derive and broadcast corrections from essentially a single location. This includes GBAS and other systems with reference receiver and antenna siting redundancy on a local scale (i.e., within several kilometers), because antennas this close together are observing almost identical GNSS satellite and atmospheric behavior under normal conditions. The alternative technique of distributing reference stations widely (hundreds of kilometers) apart and developing corrections that can be used over entire countries or continents is normally supported by corrections broadcast from space (so-called *space-based augmentation systems*, or SBAS) and is described in Chap. 12. In between these extremes are terrestrial LADGNSS systems, which also use networks of reference stations instead of single sites. These networks are defined as *terrestrial* instead of *space-based* because they broadcast corrections using ground-based means (Sect. 31.2.4). Station separations in terrestrial networks tend to be shorter than those in space-based networks, but this is not always the case.

The primary motivation for LADGNSS reference station networks is to provide service to a relatively large area without the need to place a large number of individual reference stations, as demonstrated for CDGNSS users in [31.12]. One system of this type conceived for aviation use in Australia was the ground-based regional augmentation system, or GRAS, described in [31.13]. It married the network concept of multiple widely-spread reference stations transmitting corrections to a central processor (as in SBAS) with the GBAS method of broadcasting corrections via terrestrial VHF radio on the ILS localizer band. The GBAS message format from [31.8] was extended with an additional message type (*type 101*) to accommodate GRAS, while the single-transmitter approach of GBAS was replaced with a network of VHF transmitter stations that already existed in Australia [31.14]. This *hybrid* approach, while not actually put into operation, illustrates the many possible variations of LADGNSS and wide-area GNSS technology that can be applied to support particular service providers and classes of users.

31.2.4 Broadcast Techniques

The most common means of communicating LADGNSS corrections to users is by radio frequency (RF) transmissions using separate transmitters and receivers. The use of the VHF ILS localizer band from 108–118 MHz for this purpose in GBAS allows the reuse of ILS localizer antennas that already

exist on almost all aircraft that will be equipped with GBAS [31.7, 8]. An RF technique commonly used in marine LADGNSS systems is digitally encoding messages on existing direction-finding radiobeacons transmitting at around 300 kHz, as is done by the US Coast Guard NDGPS [31.5, 15]. Ultra high frequency (UHF) radiomodems are commonly used in relatively low-cost commercial and experimental systems. An example of a radiomodem transmitter used in unmanned aerial vehicle (UAV) LADGNSS flight tests conducted by KAIST in Daejeon, Korea is the IP-921 made by Microhard Systems, Inc [31.16]. It transmits at a frequency range of 902–928 MHz with a maximum data rate of 1.1 Mbps out to a line-of-sight range of 100 km or more at a lower data rate of 345 kbps, which

should be completely adequate for single-reference-site LADGNSS [31.17].

Now that Internet connectivity is widespread, disseminating corrections via the Internet is also possible for some applications that do not require the highest levels of timeliness or reliability. The corrections of some existing GBAS and SBAS systems are available on the Internet after some delay. For example, the Federal Aviation Administration (FAA) William J. Hughes Technical Center, which oversees the fielding and operations of GBAS (LAAS) sites in the Conterminous United States (CONUS), includes near-real-time and archived corrections and other broadcast information for several CONUS GBAS sites on a website for analysis [31.18].

31.3 Ground-Based Augmentation Systems

31.3.1 Overview and Requirements

As described previously, GBAS is a subset of LADGNSS that supports civil aviation precision approach and landing operations at airports where a GBAS ground station is sited. The key components of a GBAS ground station are shown in Fig. 31.1 and are described briefly in Sect. 31.1. This section will describe in more detail the requirements that GBAS must meet and how GBAS satisfies these requirements through a combination of high-accuracy differential corrections, monitoring of possible faults and anomalies to protect integrity, and optimization to maximize availability and continuity in the presence of these anomalies.

Figure 31.2 expands upon Fig. 31.1 to show how the GBAS ground system components are typically sited relative to the territory of a given airport and how they support precision approaches to all runway ends at that airport. In existing sites, the GBAS reference receivers

and antennas are placed relatively close together but just far enough apart to keep multipath errors at each antenna uncorrelated, as discussed in Sect. 31.1. The central processing unit that determines the information to be broadcast is also nearby, but the VHF transmitter antenna may be some distance away to cover as much of the airport and its surrounding approaches as possible. Note that most airports have multiple runways and can at least theoretically support precision approaches in two directions (two runway ends) for each runway. Approaching aircraft are supported by GBAS to at least the Category I approach minima at all runway ends for which GBAS precision guidance is allowed (and path-guidance information is broadcast). Aircraft using GBAS derive Cartesian (e.g., east-north-up) positions from their corrected GNSS measurements and convert these to angular *ILS-lookalike* measurements to be compatible with existing avionics built for the angular measurements (offsets from desired vertical glidepath and lateral localizer) provided by the instrument landing system (ILS) [31.7, 9].

The development of GBAS from LADGNSS over the last 25 years has been spearheaded by aviation service providers such as the FAA in the US, companies that provide equipment for civil aviation such as Honeywell, Raytheon, Rockwell Collins, and Thales Group, and universities and other research groups. The requirements for GBAS have been developed from earlier systems such as ILS by Radio Technical Commission for Aeronautics (RTCA) in the US, European Organisation for Civil Aviation Equipment (EUROCAE) in Europe, and the International Civil Aviation Organization (ICAO), which devises *Standards and Recommended Practices* (SARPS) for various aircraft systems [31.7–9].

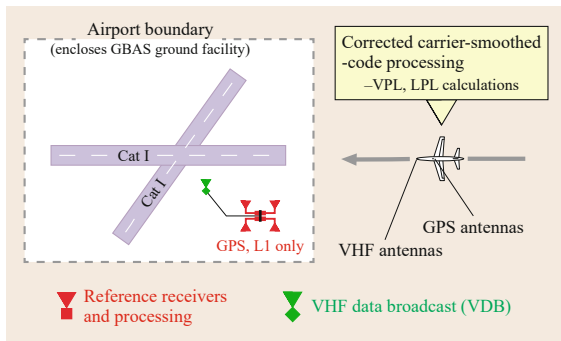


Fig. 31.2 GBAS ground station and airborne operations at a typical airport (Category I precision approach operations)

In practice, RTCA and EUROCAE standards are *harmonized* at ICAO so that GBAS ground and airborne designers work to a single, unified set of requirements to the greatest extent possible.

Table 31.1 summarizes the requirements for different modes of aviation precision approach under limited visibility as defined for GBAS [31.19]. The term *GSL* in the left-hand column stands for *GBAS Service Level* and refers to different *categories* of precision approach, which correspond to different levels of pilot visibility in horizontal (*RVR*, runway visual range) and vertical (*ceiling*). Current GBAS systems primarily support *GSL C*, which corresponds to *Category I* precision approaches down to a 200 ft minimum decision height above the runway threshold. *GSL A* and *B* support less-demanding variations of *Category I* precision approach that can be supported, with slightly different values, by SBAS (Chap. 12 and [31.20]). *GSL D*, *E*, and *F* refer to versions of *Category II* and *III* precision approaches that support lower decision heights. GBAS ground systems and airborne equipment that support *GSL D* and allow for *Category III* operations (including zero-visibility landings) are now under development [31.21, 22].

The columns in Table 31.1 express requirements in terms of *accuracy*, *integrity*, and *continuity*. The *accuracy* requirement is expressed as a 95th-percentile bound on navigation system error (NSE), or the difference between true (unknown) position and that output by a GBAS-qualified airborne receiver. *Continuity* is expressed as an upper bound on the probability (per 15 or 30 s exposure interval) that an operation in progress is unexpectedly aborted due to a GBAS system interruption, which can take one of several forms. *Integrity* generally refers to the trust that can be placed in the outputs of a system and the ability of a system to alert when its outputs cannot be trusted (i.e., are unsafe to use). For GBAS, this is expressed by three related requirements. The first is an upper bound on the probability (per exposure interval – typically the length of a precision approach, or about 150 to 200 s) that integrity is lost, meaning that unsafe or *misleading* information is output. The second is a *time to alert* within which a warning from the system needs to be output to avoid an unsafe condition. In other words, if the output of misleading information lasts for less than the time to alert before the system alerts that the information should not be used. This condition is not unsafe and does not count against the integrity loss probability. The third requirement, the *alert limit*, expresses the maximum error in both vertical and lateral dimensions that is regarded as *safe* for a given operation [31.23].

Availability requirements are not shown in Table 31.1 because they vary widely by airport. The

most common definition of availability is the percentage of time that the accuracy, integrity, and continuity requirements are met simultaneously, allowing GBAS-supported operations to take place. When one or more of these requirements are violated, this will be known to users and operators so that operations can be avoided. If operations begin and then must stop suddenly due to an unexpected change of system state (e.g., the failure of a GNSS satellite needed for acceptable performance, which is known as a *critical satellite*), *continuity* is lost. This means that implementing the integrity monitoring needed to meet the integrity requirements unavoidably increases the probability of continuity loss. Since integrity and continuity requirements thus compete directly with each other, the design of integrity monitoring algorithms and measurement-exclusion logic is a much greater challenge than it appears at first glance.

31.3.2 Generation of Differential Corrections

As described in Sect. 31.3.1, GBAS generates pseudorange differential corrections and correction rates for each satellite from redundant reference receiver measurements. This section provides the specified equations used to compute these values to clarify the procedure [31.24].

The first step in processing pseudorange and carrier-phase measurements from each reference receiver is to perform what is known as carrier smoothing, which takes advantage of the greater precision of carrier-phase measurements to attenuate noise and multipath errors in the pseudorange measurements (Sects. 22.3.1 and 20.4). To maximize commonality in smoothing between ground and airborne equipment, a specific algorithm is mandated for the ground system, and the airborne is given a very small tolerance for variation given nominal input conditions [31.9]. This typically requires that the same smoothing time of 100 s is used in both ground and airborne systems. The ground smoothing algorithm (at least for FAA LAAS systems) is given by [31.24]

$$\begin{aligned} \text{PR}_s(k) = & \left(\frac{1}{N} \right) \text{PR}_r(k) \\ & + \left(\frac{N-1}{N} \right) [\text{PR}_s(k-1) + \phi(k) - \phi(k-1)], \end{aligned} \quad (31.1)$$

where PR_r is the raw (measured) pseudorange for a given GNSS satellite at a given reference receiver, PR_s is the output smoothed pseudorange, f is the carrier-phase (accumulated Doppler) measurement, k represents the current time epoch, and $N = S/T$ (nom-

Table 31.1 GBAS precision approach requirements summary

GSL	Accuracy		Integrity			Continuity	
	95% Lat. (NSE) (m)	95% Vert. NSE (m)	Pr (loss of integrity) (s)	Time to alert (s)	LAL (m)	VAL (m)	Pr (loss of continuity) (s)
A	16	20	$2 \cdot 10^{-7}/150$	6	40	50	$8 \cdot 10^{-6}/15$
B	16	8	$2 \cdot 10^{-7}/150$	6	40	20	$8 \cdot 10^{-6}/15$
C	16	4	$2 \cdot 10^{-7}/150$	6	40	10	$8 \cdot 10^{-6}/15$
D	5	2.9	$10^{-9}/15$ (vert.); 30 (lat.)	2	17	10	$8 \cdot 10^{-6}/15$
E	5	2.9	$10^{-9}/15$ (vert.); 30 (lat.)	2	17	10	$4 \cdot 10^{-6}/15$
F	5	2.9	$10^{-9}/15$ (vert.); 30 (lat.)	2	17	10	$2 \cdot 10^{-6}/15$ (vert.); 30 (lat.)

NSE – navigation system error

inally 200 at filter steady-state) represents the number of samples used in the smoothing filter, where T is the measurement sampling interval (nominally 0.5 s), and $S = 100$ s.

The smoothed pseudoranges from (31.1) are the basis of the pseudorange corrections (PR_{sc}) computed for each reference receiver m and each satellite n [31.24]

$$PR_{sc}(n, m) = R(n, m) - PR_s(n, m) - t_{sv_gps}(n), \quad (31.2)$$

where R is the predicted range based on the surveyed antenna position and the satellite position provided by the broadcast ephemeris data, and t_{sv_gps} is the clock correction for satellite n (for L1 C/A-code) as computed from the GPS navigation data, including relativistic terms. Note that neither ionospheric nor tropospheric corrections are applied. As mentioned in Sect. 31.2.1, corrections that would be the same (or very nearly the same) at both ground and aircraft must either be applied in both places or neither place to avoid introducing uncommon errors.

The next step for GBAS is to perform a *clock adjustment* to the corrections generated by each reference receiver. This is done to remove the large common bias created by reference receiver clock errors from the broadcast corrections and to allow straightforward comparison or corrections across reference receivers (all variables apply for a specific epoch k) [31.24]

$$PR_{sca}(n, m) = PR_{sc}(n, m) - \frac{1}{N_c} \sum_{n \in S_c} PR_{sc}(n, m), \quad (31.3)$$

where PR_{sca} is the resulting smoothed and clock-adjusted correction for receiver m and satellite n , S_c is the *common set* of satellites, meaning the set of satellites tracked by all healthy reference receivers, and N_c

is the number of satellites in set S_c . For each receiver m , (31.3) removes the average bias in the nonadjusted pseudorange correction across the N_c satellites in the common set. This works well because the receiver clock bias on each receiver is the same for all satellites tracked by that receiver.

Under nominal conditions when no receivers are removed due to detected anomalies, the broadcast pseudorange correction (PR_{corr} or PRC) for each satellite n is simply the average over the $M(n)$ smoothed and clock-adjusted corrections from each receiver tracking that satellite [31.24]

$$PR_{corr} = \frac{1}{M(n)} \sum_{m \in S_n} PR_{sca}(n, m). \quad (31.4)$$

The broadcast range rate correction (RR_{corr} or RRC) for satellite n is derived by differencing the current and immediately previous pseudorange correction values for that satellite divided by the time gap T between them (nominally 0.5 s).

Figure 31.3 shows a block-diagram representation of the functions carried out by the GBAS ground system. It corresponds specifically to the integrity monitor testbed (IMT) developed at Stanford University as a ground system prototype and algorithm development tool [31.25], but the same (or very similar) functions are carried out by all GBAS ground systems. The functions shown in Fig. 31.3 that have been described in this section include **SISRAD** (signal-in-space receive and decode), smooth (31.1), correction ((31.2) and (31.3)), and average (31.4). The other functions shown in this figure are needed for integrity verification and are described (at least briefly) in the following section.

31.3.3 Fault Monitoring

While the processing needed to generate pseudorange corrections from raw measurements is not demanding,

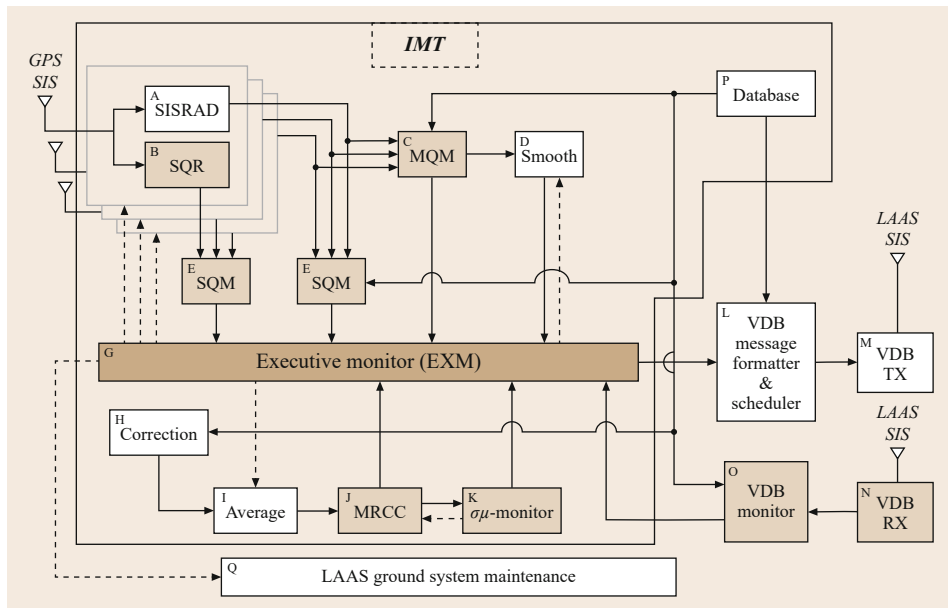


Fig. 31.3 Block diagram of GBAS ground station processing, integrity monitoring, and measurement exclusion logic

it is dwarfed by the many different algorithms used to verify the integrity of these measurements (and thus the broadcast corrections) in real time. Detailed descriptions of these algorithms are beyond the scope of this chapter. Summaries of the key algorithms and the anomalies that they address are provided along with references that contain further details.

The failures and/or anomaly conditions that could create hazardous errors for GBAS users if not detected or mitigated can be broken down into three categories:

- *Faults within GNSS:* This includes failures within GNSS satellites and failures or errors in the control segment that manages a given GNSS constellation, such as the GPS operational control segment (OCS).
- *Faults within augmentation system equipment:* This includes failures within individual GNSS reference receivers as well as anomalous multipath at reference receiver antennas.
- *Signal propagation anomalies:* This includes anomalous spatial gradients when GNSS signals pass through the ionosphere or the troposphere on their way to reference and user antennas. This can result in measured pseudoranges at the reference receiver that are significantly different than those measured by users. Other impacts, such as ionosphere *scintillation* (Chap. 39), are much more likely to cause loss of lock (or monitor detection) and thus lead to continuity breaches as opposed to loss of integrity.

The terminology of Fig. 31.3 is useful in further classifying the threats that the GBAS ground system must guard against. The following functions in that figure protect against the following subclasses of failures or anomalies.

Signal Deformation Monitoring (SDM)

This examines both the received power of the incoming satellite signals and the quality of the L1 C/A-code waveforms, meaning the degree to which the transmitted waveforms match the ideal ones. Significant waveform anomalies have occurred at least once, on GPS space vehicle number/pseudo-random noise (SVN/PRN) 19 as discovered in 1993, and nominal waveforms have small imperfections that must be accounted for in the design of GBAS [31.26, 27]. While most waveform abnormalities are highly correlated between reference and user receivers, these receivers are not required to be identical; thus large anomalies can cause significant user errors [31.28]. A threat model describing and bounding anomalous signal deformation for existing GPS satellites on L1 was developed based on a detailed analysis of the SVN/PRN 19 event [31.26, 28] and is used to quantify the integrity threat to GBAS from signal deformation after the implementation of the monitoring described below.

Detection of waveform abnormalities requires receivers that output GNSS measurements at multiple points along the code correlation peak so that asymmetries and unusual features can be observed and identified [31.28, 29]. This is performed by the *SQR* or *signal quality reception* function in Fig. 31.3. In prac-

tice, to avoid hardware duplication, this *SQR* capability is built into the reference receivers that also provide the measurements from which pseudorange corrections are generated [31.30].

Figure 31.4 shows an (exaggerated) example of a deformed code correlation peak and illustrates the monitor test statistics that are defined to detect significant deformations. The *ideal* code correlation peak differs slightly with pseudorange noise (PRN) code but is basically a perfectly symmetric triangle with *rounding* at the top due to the limited RF bandwidth in the GPS receiver. Multipath deforms the trailing (right-hand) side of the correlation peak, while satellite-generated signal deformation can alter both sides. The *delta* and *ratio* metrics shown in Fig. 31.4 quantify the difference between the observed correlation peak for each satellite (provided by the *SQR* function) and the ideal peak for the PRN broadcast by that satellite [31.28]. Thresholds on these metrics (to identify actual SDM faults within the continuity budget) must consider nominal deformations due to multipath and the nominal signal deformations mentioned above.

SDM is the major component of *signal quality monitoring*, or *SQM*, which is shown within Fig. 31.1. Additional monitoring that falls within this category includes testing the measured signal power from each satellite at each reference receiver to confirm that it falls within expected norms [31.31, 32]. This is not only a test of satellite performance but also a potential indicator of external RF interference (*RFI*), which will be discussed later.

Another satellite performance monitor with multiple purposes is that for code-carrier divergence, or *CCD*. CCD is caused by ionospheric delay that affects pseudorange and carrier measurements with equal magnitude but opposite sign. This degrades the accuracy of

carrier smoothing to an acceptable degree as long as the CCD rate (twice the rate of ionospheric delay change) is small, as it typically is. The CCD monitor in GBAS estimates the CCD rate in real time based on feeding the difference between raw L1 code and carrier-phase measurements into two successive smoothing filters, both with time constants of around 30 s. The resulting estimate of CCD rate is compared to a threshold, and a flag is issued if this rate exceeds an acceptable level [31.33]. In theory, it is possible for satellites to lose coherence between code and carrier elements of the broadcast signal and thus generate an unacceptable level of CCD. This is thought to be exceedingly unlikely, which means that, in practice, the CCD monitor serves as a means to detect unusual ionospheric behavior. The importance of this feature in mitigating threats due to large ionospheric spatial gradients will be explained later.

Data Quality Monitoring (DQM)

While this considers all of the navigation data broadcast by each satellite, its focus is the correctness of the ephemeris data that provides knowledge of the satellite position in space at any given time. Because GBAS reference receivers and aircraft are separated by no more than 10–20 km during the most critical flight phases, only very large ephemeris errors, such as a difference of over 1000 m between reported and actual satellite position, are potentially threatening. Errors so much larger than what is typical (differences of several meters) are considered to be possible from two causes [31.34].

Type A failure. OCS generation and upload of erroneous navigation data along with a maneuver of the affected satellite (i. e., the satellite changes orbits).

Type B failure. OCS generation and upload of erroneous navigation data without a maneuver of the affected satellite (i. e., the satellite remains in the same orbit).

Type B failures represent the simpler scenario where an observation, mathematical, or transcription error occurs in the process of generating updated ephemeris parameters for satellites that do not experience any external thrust that would cause an orbit change. GPS users would see a series of valid (correct) ephemeris messages (typically updated at 2 h intervals) followed by the sudden appearance of invalid (grossly erroneous) data after a particular message update. Therefore, consistency checking between old and new ephemerides is one means of detecting changes large enough to represent errors hazardous to GBAS. Because individual ephemeris messages are tightly fit to 2–4 h periods to maximize accuracy, and GPS satellite orbits change significantly (relative to the errors of con-

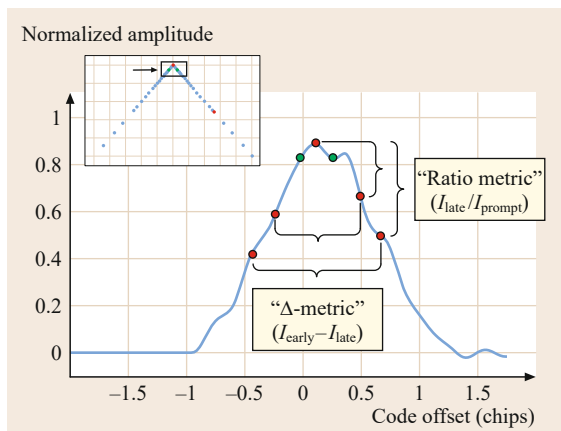


Fig. 31.4 Code correlation peak monitor test statistics for SDM

cern) over periods of 6–12 h, some degree of correcting for nominal satellite motion is desirable. The so-called *FOH-YETE* test described in [31.34] is a good compromise between simplicity and ability to detect significant type B failures. More involved orbit fitting of GPS satellites can greatly reduce the size of detectable errors, but the practical benefits of this additional complexity are small.

Type A events may also involve generation or upload mistakes but are complicated by the existence of a satellite maneuver. Deliberate satellite maneuvers are conducted occasionally to maintain the constellation and correct for normal orbit variation. Maneuvers change satellite orbits significantly; thus ephemeris parameters broadcast prior to a maneuver would be hazardous to use. To prevent this, satellites are flagged as *unhealthy* preceding maneuvers (meaning that their broadcast health bits indicate *do not use*) and are not flagged as *healthy* again until the maneuver is completed and new ephemeris messages reflecting the revised orbit are generated, uploaded, and double-checked for accuracy. Faults during this process that lead to hazardingly incorrect ephemeris messages being broadcast by satellites flagged as healthy are denoted as type A failures.

Figure 31.5 shows an example of a relatively simple type A failure that occurred on GPS SVN 54 (PRN 18) on 10 April 2007 [31.35]. The plot shows the effects of this failure on uncorrected C/A-code range error of the affected satellite as measured at Honolulu, Hawaii along with the resulting 3-D position error at Honolulu, Los Angeles, California, and Billings, Montana (all in the western part of the US). The measured range error at Honolulu grew to about 350 m, and position error at Honolulu grew to over 500 m before the fault was noticed and the satellite uploaded to broadcast an *unhealthy* flag, which occurred about an hour after the fault began.

Subsequent investigation of this event showed that this was the result of a normal, planned orbit maneuver of SVN 54. The only problem was that the satellite was not updated to broadcast a status of *unhealthy* prior to beginning the maneuver. As a result, SVN 54 began moving away from its old broadcast ephemeris while still indicating its status as *healthy*. The fact that SVN 54 would be maneuvered was alerted ahead of time by a forecast Notice Advisory to Navstar Users (NANU) message, but NANU messages are not included in the broadcast navigation data and are not meant to substitute for the broadcast health status.

Type A faults of this sort are not directly observable to GBAS ground stations, but they can be readily detected by observing the computed pseudorange and carrier-phase corrections and changes over short inter-

vals (carrier-phase corrections are not normally broadcast but can be computed and used for monitoring – see [31.8]) [31.34]. In Fig. 31.5, the increasing range error experienced at Honolulu would have appeared as an increasing pseudorange correction to a GBAS ground station sited there and would have exceeded any reasonable value of this correction well before the satellite was flagged as *unhealthy* (and before any significant error was experienced by GBAS users). Demonstrating that all possible type A faults are protected by these checks requires extensive Monte Carlo simulations of possible orbit maneuvers in which conditions most difficult for these checks to detect are emphasized in the sampling of possible maneuvers [31.36].

Measurement Quality Monitoring (MQM)

This refers to monitoring of the time consistency of pseudorange and carrier measurements received at each ground reference receiver (or the average of all reference receivers). Sudden, sizeable inconsistencies in the received pseudorange, carrier-phase, or the difference between the raw pseudorange measured on a particular epoch and the pseudorange projected by the carrier-smoothing filter from the two most recent carrier-phase measurements (*carrier-smoothed-code innovations* – see (31.5) below) indicate the presence of a fault either in the received satellite signals or in one or more receivers tracking the affected satellites. To protect users, these must be detected quickly after they occur and either removed or corrected depending on their source and nature. Note that *cycle slips* in receiver carrier-phase tracking loops are an example of a receiver fault and are mitigated by MQM. Cycle slips must be sufficiently rare to meet the prior probability assumed by MQM, which places a lower bound on the signal power at which reliable carrier-phase measurements can be obtained in GBAS.

MQM algorithms for checking the time consistency of adjacent carrier-phase measurements and carrier-smoothed-code innovations are given in [31.25, 37]. The former is complicated by the need to duplicate the clock-adjustment steps shown (for computing pseudorange corrections) in (31.3) and (31.4). For each receiver at each epoch, clock-adjusted carrier-phase measurements for the last ten epochs (5 s) are used to fit a second-order polynomial that is then applied to predict the current (just acquired) phase measurement. The difference between actual and predicted phase measurement is compared to a threshold based both on expected noise of nominal carrier-phase measurements fit over 10 s and the minimum differences that could lead to threatening user errors. The *acceleration* and *velocity* values resulting from the second-order polynomial fit are also compared to their own thresholds.

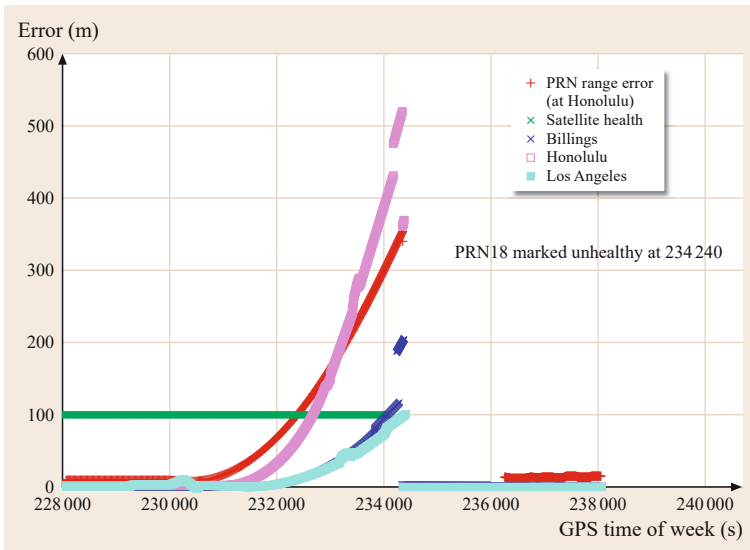


Fig. 31.5 Ephemeris type A failure example from April 2007. Standard positioning service (SPS) 3-D position error during PRN 18 anomaly

The monitor that detects anomalies in carrier-smoothed-code innovations is much simpler and can be expressed as follows using the notation of the smoothing filter definition in (31.1)

$$\text{Inno}(k) = \text{PR}_r(k) - [\text{PR}_s(k-1) + f(k) - f(k-1)] \quad (31.5)$$

As with the carrier-phase consistency test, the innovation (Inno) derived from (31.5) is compared to a threshold that separates acceptable from unacceptable discrepancies.

Distinguishing between satellite and receiver faults detected by MQM is important but is typically left to executive monitoring (EXM), which will be described next. Unlike satellite faults, which normally lead to the exclusion of the affected satellite(s), faults that can be confidently limited to failures or cycle slips of a single reference receiver can often be *patched* by a variation of the algorithm that detects (and thus measures) the inconsistency between measurements. For the innovations test shown in (31.5), patching is performed by replacing the raw pseudorange measurement for this epoch with the one projected from the carrier-phase measurement update (presuming that this condition is limited to one reference receiver and did not also occur on the previous epoch). Patching of carrier-phase discrepancies is more complex but uses the same concept of replacing the (faulty) current measurement with the projection of what the measurement should have been from past measurements. If the code and/or carrier phase offsets resulting from a cycle slip can be patched with acceptable integrity, continuity is improved by preventing the loss of measurements from the affected reference receiver.

Detection and exclusion of satellite-driven faults detected by MQM, which are normally due to clock failures and are the most common GPS satellite anomalies, is important for two reasons. First, satellite faults that affect the time consistency of GPS measurements make it potentially unsafe to linearly extrapolate old pseudorange corrections forward several seconds in time using the range-rate correction (RRC), which is allowed when VDB messages are missed by the aircraft. For this reason, monitoring of unsafe levels of range acceleration (i. e., time-changing terms not included in the estimated range rate) is known as *excess acceleration monitoring*. Second, satellite behavior that falls well outside specified levels (e.g., those given in the *GPS SPS Performance Standard* [31.38]) indicates that the satellite is in an unhealthy mode, which means that the prior probability of failure assigned to healthy satellites (typically 10^{-5} per satellite per hour for GPS) no longer applies to this satellite [31.39]. This logic also applies to observed low satellite signal power under SQM, which may not be hazardous by itself but which invalidates the assumptions under which the safety of use of the affected satellite is guaranteed.

Executive Monitoring (EXM)

As mentioned above, EXM represents a series of logical functions and software execution paths that manage the flow of results from the monitors listed above (and those to follow). It determines which measurements are safe to use in calculating the broadcast pseudorange corrections and other integrity-sensitive values based on the combined monitor outputs, usually expressed as binary flags (pass-fail) for each measurement tested by each monitor. Because integrity must be protected to very

low probabilities, measurements made *questionable* by the combined monitor outputs may be discarded even if they are not individually *flagged* (result in failed tests) by any monitor.

Figure 31.3 helps to illustrate how EXM interacts with monitoring and measurement processing in the Stanford Integrity Monitor Testbed developed to show the feasibility of GBAS ground system monitoring [31.31, 37]. Here, while EXM activities occur throughout the processing of each epoch of measurements, the key logical elements of EXM are divided into two phases. In each epoch, the first phase occurs once the calculations and monitors shown above the EXM box in Fig. 31.3 are completed, which includes the monitors discussed to this point. Each of these monitors produces one *pass-fail* flag for each receiver channel, meaning each visible satellite tracked on each operating reference receiver. For example, if four reference receivers are tracking ten satellites, a total of 40 channels are tracked, and each channel has multiple *pass-fail* flags from each of the monitors executed to this point. These monitor flags are *OR*-combined such that a given channel receives a *fail* flag if any of its tests produce a *fail* result. From this point, a series of logical *measurement isolation cases* are applied as described in [31.31].

In most cases, measurements excluded by EXM enter *self-recovery* mode, in which the smoothing filters for the affected channels are restarted, and the measurements are retested with much tighter thresholds to see if any evidence of a fault remains. Tighter thresholds are used for recovery because excluded measurements are presumed to still be faulted until proven otherwise, whereas unexcluded measurements assume a low prior probability of failure before exclusion. If self recovery is unsuccessful after two or three attempted restarts, the measurements enter *external maintenance* mode, meaning that external maintenance is needed to restore them to service. Under certain threatening circumstances, including the case where all ground system measurements enter *external maintenance* mode, an *alarm* is issued that terminates service from that GBAS facility until external maintenance arrives to check and restore the system to full working order.

A *second phase* of EXM applies to the monitors derived from *B-value* statistics that compare measurements across reference receivers, as described under *multiple receiver consistency check* below. The same logical concepts apply, but the process of exclusion is iterative and includes multiple steps because the inclusion of receiver clock adjustments from this point forward affect all corrections and B-values.

Note that there are many ways to integrate EXM within the processing structure of a GBAS ground system. The method outlined above focuses on several

steps of logic resolution to remove all threatening measurements. Another approach is to specifically arrange the order of monitor execution so that each monitor acts as a *gate* on the measurements. In other words, all measurements that pass the previous monitors are fed into the next monitor, and only those that pass that monitor get propagated onward. The general order of Fig. 31.3 is followed, in that monitors that are aimed at detecting satellite failures precede those that are aimed at detecting receiver faults. However, this successive-gating procedure is insufficient by itself. Logical steps and cross-checks among multiple monitors need to be added to this *order-based* approach to assure that all potentially hazardous measurements are removed.

Multiple Receiver Consistency Check (MRCC)

Once the first phase of monitor tests and EXM resolutions described above has been completed, the surviving measurements are used in equations (31.2), (31.3), and (31.4) to calculate receiver clock adjustments and pseudorange corrections for each satellite. Reference receiver redundancy is now exploited to cross-check the smoothed and clock-adjusted candidate corrections from each receiver. For each satellite n with a computed correction $PRC(n)$ from (31.4), *B-values* are calculated as follows for all receivers who contributed to that correction [31.24]

$$B_{PR}(n, m) = PR_{corr}(n) - \frac{1}{M(n) - 1} \sum_{\substack{i \in S_n \\ i \neq m}} PR_{sca}(n, i) . \quad (31.6)$$

Each $B_{PR}(n, m)$ (or $B_{n,m}$) value represents the error in the resulting pseudorange correction on satellite n that would occur if the measurement from receiver m were faulty. Here, faulty means that the measurement is not bounded by the zero-mean Gaussian distribution assumed for it under nominal conditions (more on this to follow). If receiver m were faulty, the *true* correction would be given by the average of the measurements from the other (nonfaulted) receivers tracking satellite n . Since the faulted measurement from receiver m is in fact included in the average used to generate the correction, the value $B_{i,j}$ indicates the error induced by this.

Given this logic, large values of $B_{n,m}$ suggest that the channel on receiver m tracking satellite n is faulted, and it is the role of MRCC and its associated EXM to exclude these channels before the final pseudorange correction is generated and broadcast. This starts by identifying (*flagging*) the B-values of any channels that exceed a preset threshold based on the bounding zero-mean distribution of B-values under nominal conditions. If any channels are flagged, at least one must

be removed, which means that the common satellite set and thus the clock-adjustment values for each reference receiver will change according to (31.3), leading to revised corrections and B-values.

Because it is possible (and indeed likely) for multiple B-value *failure* flags to be generated by a large-magnitude fault on a single measurement that propagates to other channels via the clock adjustment, EXM uses a special procedure of first excluding the *largest* fault (meaning the channel whose B-value exceeds its threshold by the highest percentage). This exclusion results in new corrections and B-values that are rechecked by MRCC. If flags remain on the (re-computed) B-values, logical isolation steps targeted at individual channel flags based on the EXM isolation cases shown above are applied in an iterative manner, meaning that the process of clock adjustment, correction, B-value recalculation, and threshold checking is repeated after each set of trial exclusions. This process should terminate in a viable, valid set of broadcast corrections and B-values within 1–3 iterations. If not, further exclusion iterations are abandoned, and the ground station is unable to broadcast any valid pseudorange corrections for this epoch (*self recovery* begins on all channels) [31.31].

Sigma-Mu Monitor

Receiver faults detected by MRCC as described above are rare for well-sited ground receivers. When they occur, the presence of large and unusual multipath from nearby reflecting sources is one likely cause (in addition to internal failures of the receiver, antenna, and connection hardware). MRCC and EXM remove faults that are potentially hazardous right away, but an additional concern is that unusual multipath is not immediately hazardous but is sufficient to violate the error bounds computed by GBAS users (to be discussed later). These more subtle receiver faults may be detected by MRCC given enough time, but additional monitors of the statistics of ground station receiver errors are added here to attempt to detect these conditions sooner: within hours for significant error increases or days for smaller ones.

Both the mean and the sigma of reference receiver errors are estimated using the just-computed (and passed by MRCC) B-values as inputs. Standard statistical estimation of the mean and sigma of a random process is used as one monitor, and this will normally detect significant error increases within hours to days. However, detection of larger errors (those just small enough not to be reliably detected by per-epoch MRCC) in minutes to several hours is desired, and this can be achieved by one or more additional approaches adapted from statistical quality control techniques. One is cumulative sum or *CUSUM* filtering, as described

in detail in [31.40]. Exponential (weighted toward the present) moving averages is another standard technique that achieves similar results. A simplification of the CUSUM technique is to accumulate the number of B-value threshold exceedances over time (using multiple thresholds below the MRCC threshold) and use these statistics to alert to significant error increases.

For well-sited ground systems with a significant performance margin built into them, flags from any of these monitors should be very rare. If they occur, the same iterative EXM procedure used to resolve MRCC flags can be used.

Message Field Range Check (MFRC)

The last step before the computed pseudorange corrections and correction rates can be approved for broadcast is to confirm that they fall within the message sizes that can be transmitted to users according to the ICD definition of GBAS message type one (this also applies to any broadcast parameters that change in real time based on reference receiver measurements). These limits are ± 327.67 m for the pseudorange correction (PRC) and ± 32.767 m for the correction rate (RRC) [31.8]. In practice, preliminary versions of these values are checked in advance (with tighter thresholds) as part of DQM monitoring to protect against type A ephemeris faults as described above. Therefore, this second check just before the values are sent to the VDB transmitter represents a *sanity check*.

31.3.4 User Processing and Integrity Verification

GBAS users who receive differential corrections and integrity information from it apply the broadcast information to improve their accuracy and guarantee their integrity in several steps [31.9]. First, the GPS satellite measurements of multiple redundant airborne receivers are individually checked for received signal power, properly decoded navigation data, CCD (for Category II/III users), and other basic quality tests. (Note that, unlike the ground system, the outputs of multiple airborne receivers are treated independently with regard to GBAS and are not compared together until later in the chain of airborne navigation processing, after GBAS position outputs are provided from each receiver). Measurements deemed acceptable for use then have the broadcast pseudorange corrections applied to them. The basic equation for the application of corrections is [31.9]

$$\begin{aligned} \text{PR}_{\text{corr_air}}(n) = & \text{PR}_{\text{air}}(n) + \text{PR}_{\text{corr}}(n) \\ & + \text{RR}_{\text{corr}}(n)(t - t_{\text{z_count}}) \\ & - \text{TC} + c(\Delta t(n))_{\text{L1}} \end{aligned} \quad (31.7)$$

with:

- $PR_{\text{corr_air}}(n)$ is the resulting corrected smoothed pseudorange airborne measurement for satellite n and the current time t
- $PR_{\text{air}}(n)$ is the smoothed pseudorange airborne measurement for satellite n and time t before applying the correction
- $PR_{\text{corr}}(n)$ is the pseudorange correction for satellite n broadcast by the ground system (31.4) that is valid at time t_{z_count} , which is also included in the broadcast message
- $RR_{\text{corr}}(n)$ is the range rate correction for satellite n broadcast by the ground system that is valid at time t_{z_count}
- TC is the tropospheric delay correction computed according to [31.9]
- c is the speed of light in vacuum
- $(\Delta t(n))_{L1}$ is the L1 clock correction from the navigation message for satellite n applied at time t .

Several protocols apply to the use of GBAS corrections [31.9]. The most important is that only satellites for which corrections are broadcast can be applied to compute GBAS user locations. It is not uncommon for an airborne receiver to track more satellites and obtain more valid measurements than the ground system provides corrections for. The primary reason for this is that the ground system reference receiver antennas cannot reliably track down to elevation angles as low as those that are visible from aircraft. Note that this protocol allows the ground system to protect users from threats detected on the ground – excluding the affected measurements means that no corrections will be generated for them, and users will also have to discard them. Users also confirm that, for each satellite corrected with ground measurements, the received clock and ephemeris navigation data at the user matches what was used by the ground system to compute the corrections. The ground supports this by broadcasting the 16 bit encoded cyclic redundancy check (CRC) of its received data for each approved satellite, allowing the airborne system to execute the same CRC algorithm on its received data and confirm that there is a match [31.8].

User position (in three dimensions: along-ground track, cross-track, and up) and time is computed first by defining a measurement weighting matrix $\mathbf{W}$, which is the inverse of an $N \times N$ diagonal matrix (N is the number of usable satellites) with entries given by the total (fault-free) error variances (σ_i^2) of each satellite i . This *total variance* is the root-sum-square (RSS) of ground and airborne noise components as follows [31.9]

$$\sigma_i^2 = \sigma_{\text{pr_gnd}}^2[i] + \sigma_{\text{tropo}}^2[i] + \sigma_{\text{pr_air}}^2[i] + \sigma_{\text{iono}}^2[i]. \quad (31.8)$$

Here $\sigma_{\text{pr_gnd}}$ bounds the ground pseudorange measurement error after carrier smoothing. It is a key parameter broadcast for each satellite in message type 1 and is based on the known azimuth and elevation angles of that satellite from the ground station, data collected at the ground station, and multipath error models [31.8]. Demonstrating that the broadcast values of $\sigma_{\text{pr_gnd}}$ are sufficient bounds on actual rare-event errors is a significant challenge for ground system design – see [31.41–43].

$\sigma_{\text{pr_air}}$ bounds the airborne pseudorange measurement error after carrier smoothing. It is determined by each user and is bounded by the airborne accuracy designator A or B models given in [31.9].

σ_{tropo} bounds the impact of tropospheric decorrelation due to altitude offset between user and ground station. It is determined by the user-estimated height offset and a sigma parameter broadcast by the ground in message type 2 [31.8, 9].

σ_{iono} , finally, bounds the impact of ionospheric decorrelation due to horizontal separation between user and ground station. It is determined by user-estimated horizontal separation and velocity estimates and a $\sigma_{\text{vert_iono_gradient}}$ (or σ_{vig}) parameter broadcast by the ground in message type 2 [31.8, 9]. The broadcast value of σ_{vig} may be inflated to help mitigate rare, very large spatial gradient events that cannot be bounded by the broadcast σ_{vig} . This is described further in Sect. 31.3.5 to follow.

The standard equation to solve for the four position states (vector $\mathbf{x}$) from the N smoothed and corrected measurements (vector $\mathbf{y}$) then applies (this ignores the successive steps of linearization needed to make this model valid [31.9])

$$\mathbf{x} = (\mathbf{G}^T \mathbf{W} \mathbf{G})^{-1} \mathbf{G}^T \mathbf{W} \mathbf{y}, \quad (31.9)$$

where $\mathbf{G}$ is the standard $N \times 4$ *geometry matrix* in which each row i ($i = 1, \dots, N$) is defined by the unit vectors from the user to satellite i

$$\mathbf{G}_i = \begin{bmatrix} -\cos \text{El}_i \cos \text{Az}_i \\ -\cos \text{El}_i \sin \text{Az}_i \\ -\sin \text{El}_i \\ 1 \end{bmatrix}^T. \quad (31.10)$$

User integrity is provided first by requiring users to exclude satellites for which corrections are not broadcast and is verified (or quantified) in real time by the user's calculation of *protection levels* in the position domain. These represent bounds on user position error at specific (very low) probabilities suballocated from the required loss-of-integrity probabilities for GBAS flight applications, including Category I/II/III precision approach. Protection levels are unique to each GBAS user

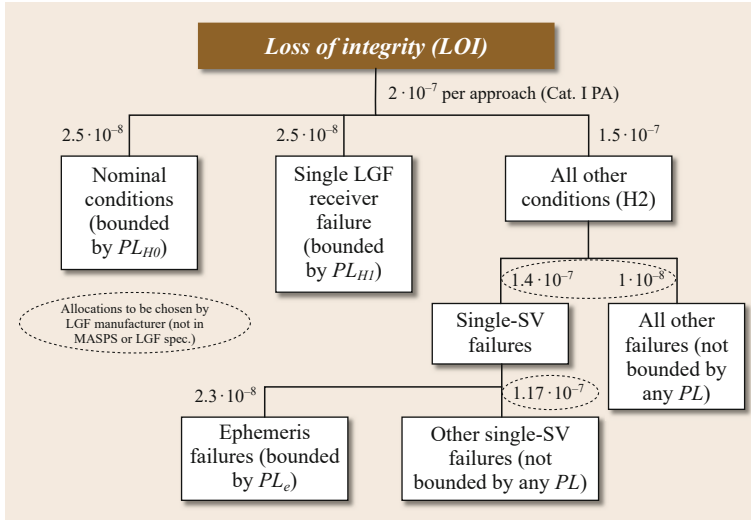


Fig. 31.6 GBAS top-level integrity risk allocation for Category I precision approach

because they include user-specific error terms, for example $\sigma_{pr_air}^2$ in (31.8), and include only the intersection of the set of satellites tracked by ground and airborne receivers. By comparing protection levels computed in real time to the safe error limits (*alert limits*) for a given type of operation, they allow each user to determine if continuing the operation is safe or if the operation should be aborted.

In simple terms, protection levels are constructed by extrapolating bounding probability distributions of expected user errors to the suballocated integrity probabilities mentioned above. Multiple protection levels are defined as needed to account for specific failure conditions, and the final protection level applied by users is the maximum of the protection levels defined to cover specific conditions. Figure 31.6 illustrates how the overall integrity requirement for Category I (GBAS Approach Service Type GAST-C) GBAS is suballocated to a set of scenarios, some of which are assigned protection levels. The top-level allowed integrity risk from Table 31.1 is $2 \cdot 10^{-7}$ per approach. This is first subdivided into three categories: *H0*, *H1*, and *H2*. The first two of these are defined below and are covered by protection levels. The third, *H2*, represents all other conditions (not *H0* or *H1*) and includes satellite faults and atmospheric anomalies, which is why it receives the bulk (75%) of the integrity allocation. Within the *H2* category, faults of single satellites are separated out, and among these, ephemeris faults are distinguished and given a unique suballocation because they are covered by a specific protection level. The other single-satellite faults, along with multiple-satellite faults and all other faults not yet described, do not have protection levels assigned to them. Each ground-system manufacturer can allocate probabilities among the faults not spec-

ified to have protection levels, which provides some flexibility.

The simplest protection level is that which applies to nominal conditions, called the *H0 case* to represent the *default hypothesis* in GBAS. Nominal conditions mean that a zero-mean Gaussian distribution with the total (ground plus airborne) variance computed in equation (31.1) bounds the actual distribution of range errors to the required integrity probability. If this is the case and range-domain error bounding persists in the position domain (e.g., errors among different satellites are uncorrelated), the *H0* protection level for the vertical direction is [31.9]

$$VPL_{Apr_H0} = K_{ffmd} \sqrt{\sum_{i=1}^N s_{Apr_vert,i}^2 \sigma_i^2 + D_V}, \quad (31.11)$$

where $s_{Apr_vert,i}$ is the vertical component for satellite *i* from the matrix **S**, which is the pseudo-inverse of the geometry matrix **G** and is computed from (31.9)

$$\mathbf{S} = (\mathbf{G}^T \mathbf{W} \mathbf{G})^{-1} \mathbf{G}^T \mathbf{W}.$$

K_{ffmd} is a scalar multiplier that represents the required integrity risk under the fault-free scenario (it is about 5.8 for Category I GBAS), and D_V is the difference in vertical position between 30 s-smoothed and 100 s-smoothed pseudorange solutions. Only 100 s smoothing is used in GAST-C for Category I, so $D_V = 0$. In GAST-D, 30 s smoothing is used in both ground and airborne positioning, but much of ground monitoring is still based on 100 s-smoothed pseudoranges. D_V represents the position-domain difference of the two different smoothing times, which is sensitive to anomalous ionospheric divergence. Thus, (31.11) propagates

the bounding range domain error distribution into the position domain, extrapolates it to the appropriate sub-allocated integrity probability (via K_{ffmd}), and adds an estimate of ionospheric divergence in the position domain (D_V) for Category II/III approaches.

Two additional protection levels are defined that cover two specific failure conditions. The first is a failure of a single reference receiver that was not detected and excluded by MRCC within the ground system. This is known the *H1 case* and has the following protection level [31.9]

$$\text{VPL}_{\text{Apr_H1}} = \max(\text{VPL}_{\text{Apr_H1}}[j]) + D_V, \quad (31.12)$$

where

$$\text{VPL}_{\text{Apr_H1}}[j] = |B_{j,\text{Apr_vert}}| + K_{\text{md}} \sigma_{\text{Apr_vert_H1}} \quad (31.13)$$

$$B_{j,\text{Apr_vert}} = \sum_{i=1}^N s_{\text{Apr_vert},i} B_{i,j}. \quad (31.14)$$

Here, the B-values come from the broadcast products of MRCC as described before for satellite i and reference receiver j , while K_{md} is the scalar multiplier that represents the missed-detection probability needed to cover the *H1* fault scenario. As in MRCC, the B-values express the actual correction errors that would occur under each *H1* fault subhypothesis, and *H1* protection levels include this as a bias (converted to the position domain) that is added to nominal errors extrapolated to a suballocated probability for *H1* events after correction for the relative rarity of these events. To be used in this way, B-values must be for each ground receiver (up to $M = 4$ receivers) and satellite must be included in the broadcast message type 2 [31.8]. The K_{md} values given in [31.9] assume a per-receiver failure value (for these purposes) of approximately 10^{-5} per approach; thus this value becomes a requirement on ground system design (in practice, continuity requirements on reference receiver failures are more constraining).

Note that $\sigma_{\text{Apr_vert_H1}}$ and $B_{j,\text{Apr_vert}}$ in (31.13) have already been converted into the position domain using the same approach as applied to (range-domain) σ_i in (31.11). The range domain version of σ_{H1} is slightly higher than σ_i because the *H1* scenario has one fewer nominal reference receiver that contributes to the nominal vertical error distribution. In fact, (31.13) can be interpreted as the sum of the nominal error distribution from the nonfaulted measurements plus the bias due to the faulted measurement. In the *H1* scenario, this bias results from a (hypothetical) single reference receiver fault as measured by the B-values computed on the ground, but the same approach applies to all protection levels computed for fault hypotheses.

Note that one value of VPL_{H1} is computed for each reference receiver j (from 1 to M) in (31.13), and the maximum combined B-value over all M reference receivers is applied in (31.13). This follows from the general approach of computing individual values for each scenario and taking the maximum (rather than a weighted average) to cover all of them.

The second failure condition with its own protection level models undetected satellite ephemeris faults [31.9]

$$\text{VBP}_{\text{Apr_e}} = \max(\text{VBP}_{\text{Apr_e}}[k]) + D_V, \quad (31.15)$$

where

$$\begin{aligned} \text{VBP}_{\text{Apr_e}}[k] = & |s_{\text{Apr_vert},k}| x_{\text{air}} P_{k,x} \\ & + K_{\text{md_e_x}} \sqrt{\sum_{i=1}^N s_{\text{Apr_vert},i}^2 \sigma_i^2}. \end{aligned} \quad (31.16)$$

Here, $K_{\text{md_e_x}}$ is the scalar multiplier that represents the missed-detection probability needed to cover the ephemeris fault scenario, and x_{air} is the horizontal distance between user and reference station (the geographic centroid of the reference receiver antennas is broadcast to users for this and other purposes). $P_{k,x}$ is a broadcast parameter that expresses the ground system's ephemeris detection capability in terms of the smallest spatial error gradient (for satellite k) that is assured to be detected with the required integrity probability. Therefore, the user remains potentially vulnerable to ephemeris faults that cause spatial error gradients at or below this level, and these must be accounted for by the ephemeris protection level. The inclusion of x_{air} allows each user to apply its own distance from the ground station, which is important for a fault whose user impact increases linearly with separation.

Analogous equations are used in real time to generate lateral protection levels (LPLs), meaning protection levels in the lateral (cross-track) direction. During precision approach, the requirements on vertical protection level (VPL) are almost always more constraining and are thus the focus of offline requirements analysis.

Protection levels resulting from failure modes other than the two for which specific protection levels exist (e.g., excess acceleration from satellite clock, signal deformation, etc.) must be covered by the three protection levels that are defined. In practice, since the equations for *H1* and ephemeris faults are specific to those cases, the *H0* protection level must bound all of these events. Demonstrating that this is the case requires analysis and (in most cases) simulation of each fault type to generate the worst-case range-domain user errors resulting

from them and comparing these to the range-domain protection level implied by the *H0* scenario. *Worst-case* in this context means the failure subscenario that potentially causes the largest differential range error either without detection or with monitor detection within the ground system time-to-alert. A detailed methodology for addressing the results of failure simulations is given in [31.44].

31.3.5 Additional Threats: RF Interference and Ionosphere

The consequences of two additional threats have become apparent over time as GBAS prototype systems have been fielded in various places. Both of these threats were recognized and treated by the original design of GBAS ground and airborne equipment but have proven to be more severe than first thought.

RF Interference (RFI)

RFI, as described in Chap. 16 refers to the imposition of external RF signals onto received GPS signals at the ground station or users in a manner that either makes the GPS signals unusable or subtly makes them less accurate. Strong interference to GPS from individual transmitters has been discovered several times in the past and can prevent the use of GPS signals over wide areas [31.45]. These events are rare, but more common interference results from what are known as *personal privacy devices* or *PPDs*, which are low-power jammers designed to *protect the privacy* of their users by preventing the use of GPS for tracking and surveillance. They are most commonly fielded in vehicles and typically achieve an effective jamming range of meters to tens of meters. *personal privacy devices (PPDs)* are illegal to operate in most places but are relatively easy and inexpensive to obtain over the Internet. The variety of devices available for purchase and their illicit nature means that their actual performance is variable; thus some devices may affect GPS over several hundred meters rather than the much shorter distances needed to *protect* a single vehicle [31.46]. For this reason, they can be troublesome to GBAS ground stations sited near major roadways [31.47].

The potential impact of PPDs on GBAS ground stations became evident in 2009, when the newly-fielded Honeywell SLS-4000 LAAS ground facility (LGF) began initial operation at Newark International Airport (EWR) in New Jersey, USA. The layout of this ground system is shown in Fig. 31.7. The site chosen within the property assigned to Newark Airport was not ideal and was selected due to the lack of suitability of several other locations considered. As a result, the four

reference receivers fielded at Newark are in almost a straight line with separations of about 100 m to make multipath errors among the antennas as statistically independent as possible. All four antennas are within 200 m of both lanes of the (very busy) New Jersey Turnpike (I-95). Several times a day, vehicles with strong PPDs passing by the airport would first make GPS unusable at one receiver, then the next, until service was lost (no valid corrections), and recovery from this condition took a significant period. The need to protect the integrity of the ground station measurements led to measurements being affected by PPDs to be excluded due to violations of one or more monitors, including the low-signal-power monitor, before the jamming became strong enough to prevent the receivers from making measurements [31.47].

Once this threat was evaluated and better understood, both physical and software changes were made to the Newark LGF (and other GBAS sites) to minimize the impact of PPD jamming. Software refinements to the monitors affected by PPDs and the EXM that handled monitor flags were key in preventing shutdown from PPD events while still protecting integrity. This was done by conservatively modeling the threat (from offline test data and RFI observations at Newark [31.46]) to determine the worst-case impact of several variations of refined monitor logic. The result was a validated means of tolerating the exclusion of two *jammed* reference receivers (out of four) for a brief period while still providing safe (albeit somewhat degraded) pseudorange corrections from the two *unjammed* ones. Since vehicles on the nearby roadway are almost always moving at speed, those with strong PPDs affect the revised LGF software but without bringing it to the *shutdown* point.

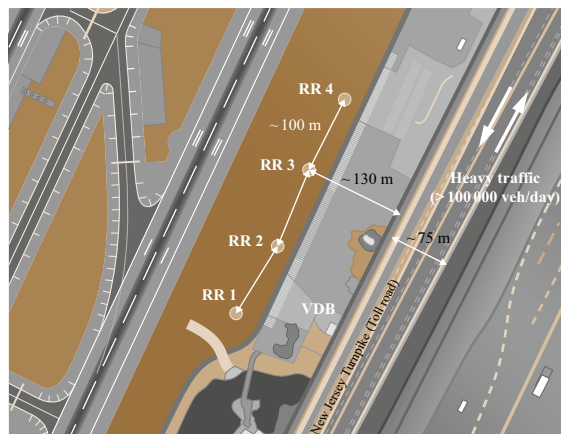


Fig. 31.7 GBAS ground system siting at Newark Airport, NJ, USA. Note four reference receiver antennas in a line close to a busy freeway

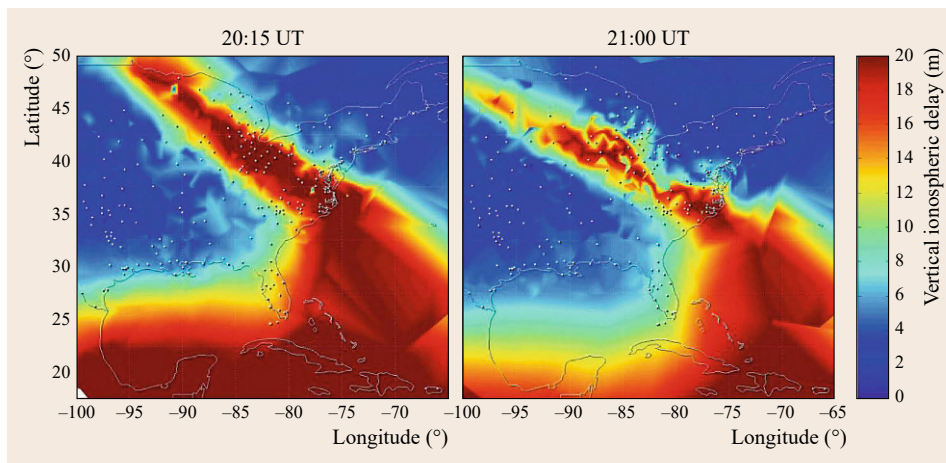


Fig. 31.8 Large-scale ionospheric disturbance over CONUS on 20 November 2003 (after [31.51])

This experience with PPDs at Newark, along with other experiences of unintentional jamming affecting GBAS ground stations and aircraft (e.g., see [31.48] for the problems caused by an indoor GPS signal repeater broadcasting strong signals visible to landing aircraft), suggests changes in the way that future GBAS ground systems are fielded. First, if at all possible (though not possible at Newark), reference receiver antennas should be placed further away (≈ 500 m or more) from roadways with significant traffic, and they should be spread out further to prevent a single relatively weak jammer from affecting more than one reference receiver at a time. Future ground system designs will support larger antenna separations, but the limited real estate available for siting at many airports will remain a significant constraint.

Ionospheric Spatial Decorrelation

Under normal conditions, the difference in ionospheric delay on smoothed pseudorange measurements made within 5–100 km of each other is a minor component of the total error budget for GBAS users and is conservatively bounded by the broadcast σ_{vig} term used to compute σ_{iono} in (31.8). In CONUS, the typical (1 s) spatial variation in zenith (i.e., vertical, at 90° elevation) ionospheric delay at the GPS L1 frequency is about 1 mm/km, and the value of σ_{vig} used to bound ionosphere is 4 mm/km to add margin to cover days with high levels of ionospheric activity [31.49]. However, during strong ionosphere storms or other severe anomalies within the ionosphere, this value can grow much larger and can threaten GBAS user safety. Because each GBAS ground station views the ionosphere from one location on Earth and does not normally share information with other locations, an ionospheric anomaly can arrive at the vicinity of a ground station and potentially cause hazardous errors before it would

be detected by GBAS ground and airborne monitoring.

The possibility of ionospheric spatial gradients large enough to be threatening was first discovered by analyses of Wide Area Augmentation System (WAAS) reference station data in 2002. In October and November of 2003, a very strong coronal mass ejection (CME) from the Sun created severe ionospheric anomalies that were noticed by WAAS and were analyzed after the fact by the continuously operating reference station (CORS) network of about 400 stations in CONUS at that time (now there are more than 1000 stations). Several years of WAAS and CORS observations in CONUS were collected and analyzed, with the result being a *threat model* that both describes the dynamics of these events from the GBAS viewpoint in simplified terms and provides bounding parameters on the variables in the model such that behavior outside the model is deemed to have negligible probability (see [31.50] for a general description of threat models and how they are used).

Figure 31.8 shows the ionospheric anomaly that generated the largest spatial gradients that have ever been discovered in CONUS or elsewhere in the middle latitudes (similar analyses have been done for Germany, Australia, and other locations). This occurred in the afternoon hours (local time) on 20 November 2003, during the period of coronal mass ejections mentioned above. In this figure, a zone of very high vertical ionosphere delay (in red) exists in between two zones of much lower delay (in blue). Thus, at the boundaries between the high and low-delay zones, very large spatial gradients occurred. The overall pattern of high delay moved roughly westward over time and eventually broke up into more irregular features, as shown in the plot for 21:00 Universal Time (UT) compared to 20:15 UT.

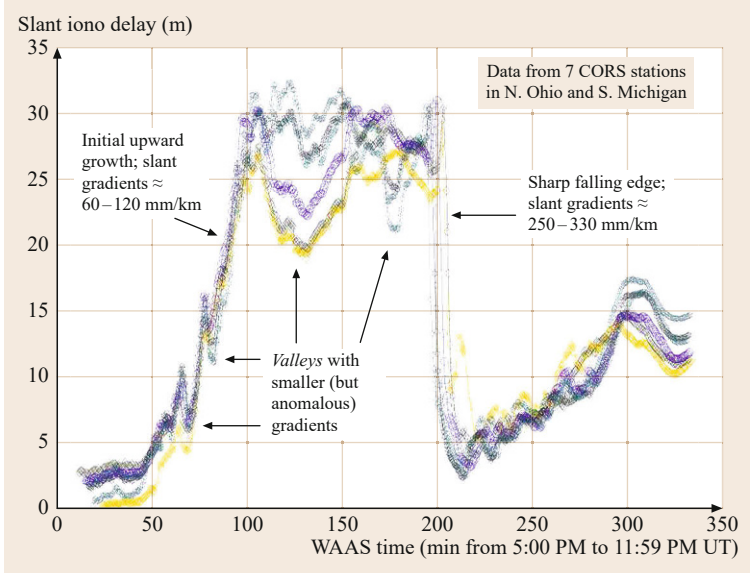


Fig. 31.9 Change in ionospheric delay observed on SVN 38 at seven adjacent stations in CONUS on 20 November 2003 (after [31.51])

Figure 31.9 examines the event shown in Fig. 31.8 by plotting the slant ionospheric delay over time as observed by seven CORS reference stations located close to each other in Northern Ohio and Southern Michigan that are tracking the same GPS satellite (space vehicle number SVN 38). This shows the rapid rise in delay caused by the leading edge of the high-delay zone as it passed over. The resulting spatial gradients between these stations were very high (60–120 mm/km) compared to typical levels of 1–5 mm/km [31.49]. The observed ionospheric delays remained anomalous and unsteady during the period when the high-delay zone affected the measurements. When the trailing edge of this zone reached the measurements a little before 21:00 UT, a sudden, very large drop in delay appears at all seven stations, creating spatial gradients between the stations of as large as 330 mm/km. This same event caused gradients as large as 412 mm/km between other pairs of stations in Northern Ohio.

Based on observations of this event and several others that also created anomalous gradients (but not this severe), a threat model covering what was observed (and validated to be due to ionospheric events) was developed and is shown in Fig. 31.10 [31.51, 52]. This threat model provides bounds on the parameters of a simplified physical model of an ionospheric spatial gradient affecting a GBAS station and nearby users. This model, shown in Fig. 31.11, assumes that the gradient is generated by a constant, linear change in delay between high and low (or low and high) levels, and this gradient wedge is moving with constant speed relative to the ground. Example numbers that fall within the threat model bounds are shown in Fig. 31.11, but any

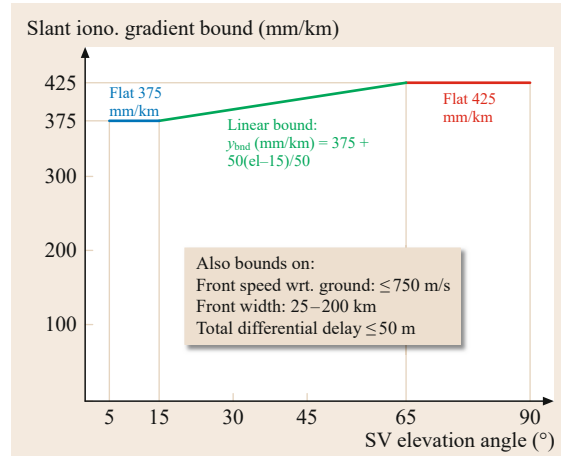


Fig. 31.10 Ionospheric gradient threat model established for CONUS (after [31.51])

numbers falling within these bounds are deemed to be possible (credible); thus user integrity must be demonstrated against all permutations of parameters within the threat space.

Figure 31.10 shows the most critical threat model parameter, which is the maximum slant ionospheric spatial gradient as a function of satellite elevation angle. Based on observed data, it varies from 375 mm/km at low elevation angles to 425 mm/km at high elevation angles. Note that the latter number bounds the observed largest event of 412 mm/km with a small amount of margin for measurement error [31.52]. Other bounds are also listed, including the gradient propagation speed relative to the ground (no greater than 750 m/s, but smaller

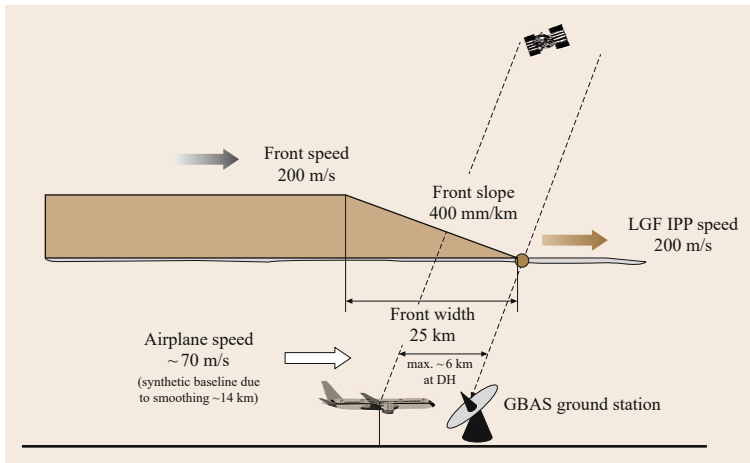


Fig. 31.11 Simplified linear wedge model of ionospheric spatial gradient (after [31.51])

speeds are harder to detect and thus more threatening), the width of the zone in which the delay is changing (no less than 25 km), and a limit on the total differential delay (width times gradient) of 50 m. The limit on total differential delay means that some permutations of gradient and width that would otherwise fall within the threat model are eliminated because their product exceeds 50 m and thus are considered noncredible.

While the CONUS threat model is thought to cover all mid-latitude GBAS sites, regions outside CONUS should conduct their own data analyses to confirm that no larger gradients exist. If only smaller gradients are found, a less-conservative threat model bounded by these lower gradients could be used. However, because of the rarity of the events that cause extreme gradients and the low likelihood of observing very large gradients in a small geographic area, the use of the CONUS threat model of Fig. 31.10 is recommended for all mid-latitude regions that do not discover gradients exceeding it [31.53].

When the CONUS threat model is implemented as shown in Fig. 31.11 and then applied to GBAS, it is quickly evident that the worst-case user differential range error is very large. The (simplified) equation that relates ionospheric spatial gradients to user differential range error is given by [31.9, 49]

$$E_{\text{iono}} = F_{\text{PP}} \times g_v \times (x_{\text{air}} + 2tv_{\text{air}}), \quad (31.17)$$

where E_{iono} is the resulting differential pseudorange error, g_v is the ionospheric spatial gradient in vertical (zenith) terms, t is the smoothing filter time constant (100 s for GAST-C GBAS), x_{air} is the ground-to-user separation, and v_{air} is the horizontal aircraft approach velocity (i.e., velocity of approaching the airport and the GBAS ground system). F_{PP} is the standard ionospheric obliquity factor that converts between zenith

and slant delay, but it is not needed here because gradients in the threat model are already expressed in *slant* (g_s) terms, where $g_s = F_{\text{PP}} \times g_v$.

Applying the maximum gradient ($g_s = 425 \text{ mm/km}$) with possible values of x_{air} (6 km for very large airports) and v_{air} (70 m/s is typical of jet aircraft) results in a (worst-case) differential error of 8.5 m on a single satellite, which is very large and would be difficult to handle with the existing VPL equations because these are compared to an alert limit of 10 m in the position domain (not the range domain). The vast majority of gradients approaching this size would be detected by one or more of the ground station monitors described in Sect. 31.3.3, such as the code-carrier divergence (CCD) monitor, that are sensitive to the time rate of change of ionospheric delay. However, it is possible for a gradient moving with respect to the ground to be counteracted by the motion of the satellite with respect to the ground, resulting in very little change of delay with time and thus very little to trigger the existing ground monitors.

Since very large differential range errors are possible and are not guaranteed to be detected by the ground station, a different technique for demonstrating the safety of Category I precision approaches under worst-case ionospheric conditions was needed. Two things resulted:

1. A relaxed requirement on the tolerable error limit (called TEL) based on the obstacle clearance surface (OCS) definitions for Category I precision approaches [31.54]
2. A new ground system integrity algorithm known as *geometry screening* that strategically inflates the broadcast VPL parameters (including the ephemeris decorrelation parameter P , σ_{vig} , and/or $\sigma_{\text{pr_gnd}}$) to ensure that any satellite geometries that could violate TEL are unavailable and thus cannot be used.

The procedures used to implement geometry screening in real time within GBAS ground systems are complicated and difficult to describe in simple terms. Detailed descriptions of two different approaches to the task are included in [31.55, 56]. The following summarizes the key steps in geometry screening:

1. Using the known set of approved satellites now and in the near future (e.g., the next 10 min), derive the set of possible user satellite geometries. This requires some assumptions on which subsets of satellites have been approved by the ground but may have been discarded (or unusable) by users (presumed to be approaching aircraft).
2. Using a simulation of the model in Fig. 31.11 with all possible satellite geometries, user approach geometries, and threat model parameters, determine the largest possible ionospheric-induced error in vertical user position (denoted as *MIEV*) for each possible user satellite geometry that would be deemed available by users (because the user VPL is below the normal Category I alert limit of 10 m). Note that *MIEV* also depends on the assumption of how many satellites can simultaneously be affected by the worst-case gradient (all combinations of two satellites are normally tested).
3. If *MIEV* exceeds TEL (about 28 m at the Category I approach threshold) for any possible user geometries, implement broadcast parameter inflation using trial increases of P , σ_{vig} , and/or $\sigma_{\text{pr_gnd}}$. Continue increasing a subset of these parameters until all possible user geometries become unavailable (VPL now exceeds the alert limit given the inflated broadcast parameters).

Implemented in this manner, geometry screening succeeds in protecting Category I GBAS users against worst-case ionospheric spatial gradients. Because of the conservatism involved in protecting each and every permutation of the threat combined with every possible user geometry, the result is significantly lower user availability. If geometry screening were not needed, GBAS Category I user availability would easily exceed 99% and might approach 99.9% at some airports. With geometry screening implemented based on the CONUS threat model and testing of all combinations of two satellites impacted at the same time, availability can fall below 99% for ground-to-approach-threshold separations of 1–3 km and below 98% for larger separations.

Given the lessons learned from GAST-C, the design of GAST-D GBAS to support Category II/III approaches implements several improvements to reduce the impact of anomalous ionospheric spatial gradients and improve the effectiveness of ground and airborne

monitoring [31.57]. First, as mentioned above, GAST-D positioning is based on a 30 s smoothing time constant, which significantly reduces the possible differential range error per (31.17). Second, CCD monitoring is required in user equipment as well as within the ground system. This is advantageous because airborne users are moving relative to the ground and thus can detect gradients that the ground might be blinded to (and vice versa). Combined with the use of D_V in the VPL calculations, this substantially increases the likelihood of detecting ionospheric divergence caused by anomalous spatial gradients.

Finally, GAST-D ground systems are required to implement new spatial gradient monitoring so as to guarantee that very large gradients that affect ground receiver will be detected regardless of any temporal *blinding* effects. To achieve this, differential carrier-phase test statistics between reference receiver antennas carefully sited to provide specific separations and directions of observability are needed. Several related algorithms have been proposed and are collectively called ionospheric gradient monitoring, or IGM [31.58, 59]. IGM is difficult to implement due to siting restrictions (see Sect. 31.3.6), small variations in reference receiver antenna errors that must be calibrated out to the extent possible, and the fact that even very large gradients only create small signatures over the short baselines used by IGM.

However, once IGM is implemented, it allows a large relaxation of the geometry screening required, and the remaining screening is done by each aircraft instead of within the ground system. Since each aircraft knows its own satellite geometry, the ground system need not cover all possible airborne geometries. That, combined with the reduced level of gradient that can escape undetected by IGM, leads to a significantly lower impact of geometry screening on precision-approach availability.

31.3.6 Equipment and Siting Considerations

Several aspects of ground system siting have already been discussed in previous sections. Siting focuses on choosing the best locations for the reference receiver antennas (to support monitoring while minimizing errors) and the VDB transmitter antenna (to cover the airborne user region with adequate, but not too strong, signal levels [31.8]). As noted above, reference receiver antenna siting follows these principles:

1. Where possible, separate the antennas by at least 100 m to minimize multipath error correlation among reference receivers, which weakens the ability of MRCC to mitigate individual receiver errors

- (the residual correlation at each site should be estimated and accounted for).
2. Where short-baseline ionospheric gradient monitoring (IGM) is implemented to support GAST-D, antenna separations on the order of 150–300 m are needed [31.58, 59].
 3. Where RF interference from nearby roadways or other sources is a threat, separate the antennas further to the degree possible to minimize the possibility of multiple receivers being affected simultaneously by the same interferer.

In addition, reference receiver antennas need to be located a sufficient distance away from nearby obstructions as to limit multipath errors to the bounding error models deemed acceptable from offline analysis. From years of trial-and-error and multipath error observations at several airports, siting guidelines to achieve this have been developed [31.60]. The concept of one or more *clear zones* that are free of significant multipath reflectors comes from the siting of ILS transmitters. An inner *clear zone* of perhaps 100–200 m in radius must be clear of all obstructions, including aircraft or other vehicles, while relatively small reflectors may be allowed in larger outer zones.

These guidelines take advantage of the use of multipath-limiting antennas, or MLAs, in GBAS ground systems. These devices go beyond normal GNSS antennas to establish a very strong roll-off between the gain pattern at low but positive elevation (where low-elevation satellites should be tracked) and low but negative elevation (which is the source of ground multipath). The first generation of MLA used in GBAS was a dual-element antenna with a helibowl facing toward zenith and a multi-element dipole for lower elevations that established the required gain roll-off. These two elements required two different receivers and *cross-over* software logic to combine their outputs into one *virtual* receiver for downstream GBAS processing [31.61]. The more-recent generation of MLAs uses a single multi-element dipole to track both high-elevation and low-elevation satellites [31.62], avoiding the need for two receivers per antenna and the resulting cross-over calibration. While not perfect, these antennas work very well in reducing both specular (single-reflection) and diffuse (multireflection) multipath to small levels that can be empirically measured and bounded by the broadcast σ_{pr_gnd} as long as the above siting guidelines are followed.

One major advantage of GBAS siting with respect to ILS is that GBAS sites do not have to occupy specific locations near runway ends and that one GBAS ground station can support all runway ends. This benefit is limited by the need to find multiple *clear zones*

and by the need to limit the separation between the geographic centroid of the reference receiver antennas and the landing thresholds of the multiple runways being covered. The effects of anomalous ionospheric spatial decorrelation, in particular, get worse with increased ground-to-user separation. While the *geometry screening* used to mitigate this threat for Category I approaches can support any separation, the resulting performance (availability) degradation becomes severe for separations greater than 4 or 5 km.

Finding sufficient space on airport property to site multiple reference receiver antennas while meeting both GBAS and external airport constraints is a challenge. At some airports, such as at Newark, the only possible locations may not meet all GBAS requirements. To account for this, GBAS can adjust several key performance parameters on a site-specific basis. One example is the broadcast σ_{pr_gnd} values that bound the errors of ground-generated pseudorange corrections. Ideally, the same values (as a function of satellite azimuth and elevation) would be broadcast at all sites. However, sites with less-than-ideal multipath performance can adjust this model by broadcasting higher values in bins of azimuth and elevation where reference receiver multipath errors are greater (due to nonideal siting or any other cause). If the errors in certain bins are much higher than ideal, these bins can be *masked*, meaning that corrections are not broadcast for satellites that occupy these bins. *Masking* should only be applied to a small subset of azimuth bins at very low elevation angles (e.g., just above the 5° system elevation mask angle) to avoid significant user performance degradation.

31.3.7 Typical GBAS Errors and Protection Levels

Variants of GBAS that support Category I precision approaches are now fielded at many airports around the world. Most of these are at mid-latitude locations where ionospheric behavior is less severe and better understood, but several sites in equatorial locations (such as Rio de Janeiro, Brazil) have been fielded and are under study.

A good source for recent and near-real-time performance reporting from several GBAS installations is the William J. Hughes FAA Technical Center LAAS website [31.18]. The FAA Technical Center maintains its own LAAS ground station prototype at Atlantic City, NJ as well as providing data from commercial Honeywell SLS-4000 ground stations at Newark, NJ, Houston, TX, Moses Lake, WA, and Rio in Brazil. Using a web interface, it is possible to plot vertical and lateral user errors (based on a static *pseudo-user* antenna not far from the ground station) and vertical and

lateral protection levels at various distances from the ground system centroid and at the approach threshold for each runway supported by the system.

Figure 31.12 illustrates typical GBAS performance in CONUS by plotting vertical accuracy (measured by GBAS versus known from a survey) from the pseudo-user receiver sited near the Newark, NJ (EWR) and Houston, TX (Intercontinental, IAH) airport GBAS sites. These results are conservative because they are dominated by the error in the pseudo-user receiver, which is worse than a typical airborne receiver in that its antenna is on or near the ground and is not an MLA like the ground-station antennas. Even so, typical vertical accuracy is well within 0.5 m with only occasional excursions beyond 0.5 m. The magnitudes and patterns of errors at Newark and Houston are similar, suggesting that GBAS user performance is roughly the same for most mid-latitude locations. This level of nominal accuracy, combined with the *smoothness* of typical error variation (i. e., multipath-induced time correlation over a 150 s approach interval), provides approach guidance to aircraft that is objectively superior to that of ILS [31.63].

Both of these figures cover a week of measurements starting at midnight UT on 3 August 2014, and ending at midnight UT on 10 August 2014. The daily repeti-

tion of the pattern of errors is evident. This is due to multipath repeating every sidereal day (23 h 56 m), when the configuration of GPS satellites returns to the same locations in the sky. Since the position of the pseudo-user antenna relative to reflecting objects is also (mostly) fixed, multipath geometries approximately repeat every sidereal day and produce similar position errors. Significant exceptions to this rule occasionally appear. For example, an error spike just exceeding (negative) 1.5 m appears at Newark around 1600 Coordinated Universal Time (UTC) on 5 August that is not repeated on other days, and the same is true (with a smaller error) at Houston around 1600 UTC on 4 August. These unrepeated error spikes could have several causes but are most likely due to multipath from moving objects (including, possibly, aircraft moving near the pseudo-user antenna).

Figure 31.13 shows the computed GBAS vertical protection levels (VPLs) as estimated by the ground system at each of the runway ends supported by the Newark/EWR and Houston/IAH GBAS systems, respectively. Note that these plots cover only a single 24 h period of repeatable GPS satellite geometries on 3 August 2014. Because VPLs vary mostly with GPS satellite geometry, they will closely repeat from sidereal day to day.

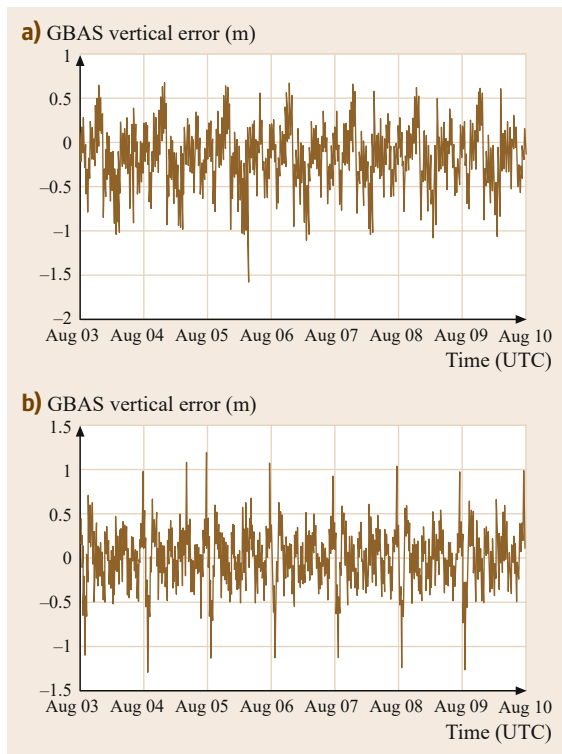


Fig. 31.12a,b GBAS vertical accuracy at Newark (a) and Houston (b) from 3–10 August 2014

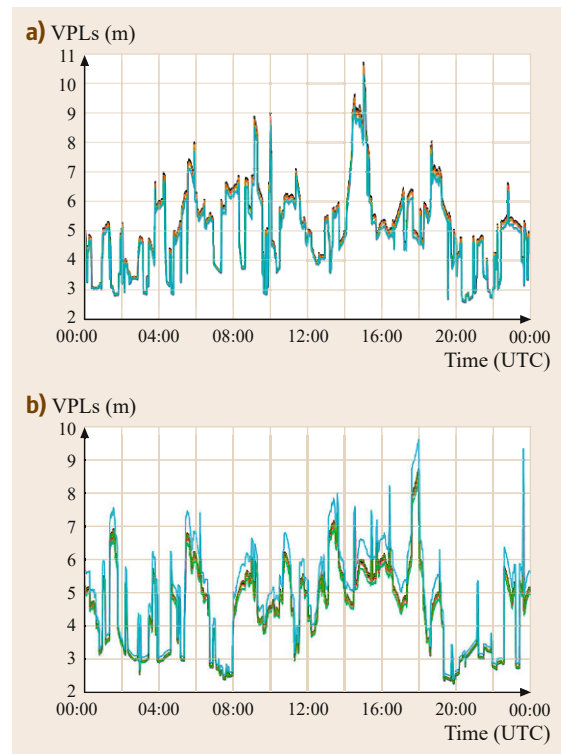


Fig. 31.13a,b GBAS vertical protection levels (VPLs) at Newark (a) and Houston (b) on 3 August 2014

The variation in VPL seen in these figures results partly from changes in the quality of the satellite geometry for positioning as measured by weighted vertical dilution of precision, or **VDOP** (Chap. 1) and partly from the deliberate inflation of σ_{vig} as part of *geometry screening* to protect against worst-case ionospheric gradients (Sect. 31.3.5). VPL values above 7–8 m generally indicate the presence of significant σ_{vig} inflation, which occasionally leads to brief losses of Category I precision approach availability when VPL grows to exceed the 10 m Category I VAL. As shown in Fig. 31.13a, this occurred at Newark/EWR for a brief period around 15:00 UTC for all five runway ends supported by GBAS. Since the degree of σ_{vig} inflation is driven by satellite geometry rather than any particular knowledge of the ionospheric state, this condition will typically persist day after day until the satellite constellation itself changes (e.g., an unhealthy satellite is brought back into service).

31.3.8 Existing GBAS Ground Systems and Airborne Equipment

As noted above, GBAS ground and airborne equipment that supports Category I precision approaches has

been certified and available for several years. The most prominent GBAS ground system on the market is the Honeywell *SmartPath* SLS-4000, which has been fielded at several sites in the US and Europe as well as Rio de Janeiro in Brazil and which generated the data shown in the previous section [31.64]. Other GBAS ground systems include the Thales DGRS 610/615 Reference Station and the NPPF Spektr LCCS-A-2000, which has been fielded at many airports within Russia [31.65].

On the airborne side, the first equipment to be approved for use with GBAS was the Rockwell Collins GLU-925 multimode receiver (MMR), which combines GPS/GBAS (sometimes denoted as *GLS* for *GPS-based landing system*) with ILS and microwave landing system (**MLS**) receiver components in order to support all sources of precision-approach guidance within a single unit [31.66, 67]. Honeywell (RMA-55B) and Thales (TLS-755) now also offer MMRs that are GPS- and GBAS-capable. Current equipment has only been approved for Category I precision approach, but the developing standards for GAST-D GBAS mentioned earlier provide a pathway to upgrade this equipment to Category II/III approach capability.

31.4 Augmentation via Ranging Signals Pseudolites

31.4.1 Origins and Use in Local-Area DGNSS

Pseudolites are terrestrial devices that transmit GPS or GNSS-like signals to nearby users in order to either enhance the performance of GNSS satellite users or completely replace the need for satellites. One of the first uses of pseudolites was to support the testing of GPS and user equipment functions during the very early days of GPS (the late 1970s), when no or very few satellites were in orbit [31.68]. By the early 1990s, as GPS user equipment became smaller and more portable, small and lightweight pseudolites also became practical and became a key component of early DGNSS systems.

One prototype DGNSS system aimed at providing centimeter-level accuracy (via carrier-phase DGPS) and integrity sufficient to support Category II/III landings was known as the integrity beacon landing system, or **IBLS** [31.3]. The layout of IBLS is shown in Fig. 31.14. Its most unique feature is the use of a pair of pseudolites (*integrity beacons*) sited along each approach path. These pseudolites broadcast weak, carrier-only GPS-like signals (received on antennas mounted on the bottom of the aircraft) that create a *bubble* through which each approaching aircraft flies. The rapid change

in aircraft-to-bubble geometry created by this allows the aircraft to reliably resolve carrier-phase integer ambiguities to both the pseudolites and the GPS satellites. Carrier-phase receiver autonomous integrity monitoring (**RAIM**) at the aircraft is the primary source of integrity monitoring [31.69]. The nearby ground system provides pseudorange and carrier-phase corrections for both satellites and pseudolites but is not responsible for the degree of integrity monitoring described above for GBAS. The quality of pseudorange measurements can be much weaker as well – the primary need for

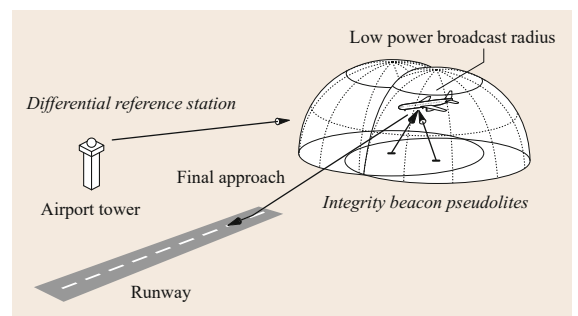


Fig. 31.14 Integrity beacon landing system (IBLS) concept diagram

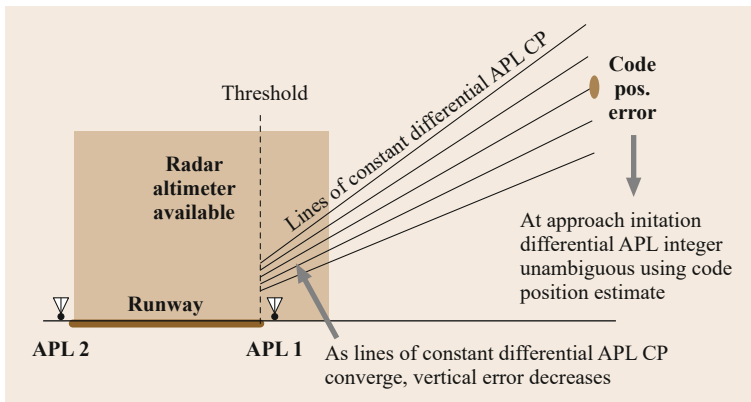


Fig. 31.15 Intrack airport pseudolite (APL) concept diagram (after [31.10])

pseudorange accuracy is to ensure the reliability of the carrier-phase integer ambiguity resolution procedure.

While IBLS worked very well and was demonstrated by multiple aircraft flight tests in the early 1990s [31.3], its requirements for pseudolites along each approach direction (analogous to ILS) and its focus on verifying integrity at the aircraft rather than within the ground system made it unpopular with the FAA and other civil navigation service providers. The IBLS concept was modified to address these concerns in what was known as the *Intrack airport pseudolite (APL) landing system* that was demonstrated at Moffett Field Naval Air Station in the late 1990s. The Intrack airport pseudolite (APL) concept is illustrated in Fig. 31.15. It includes two pseudolites placed at both ends of each runway, but both runway ends are served rather than just one (approaches are supported from either direction). The pseudolites transmit GPS-like pseudorange and carrier-phase signals on unused PRN codes. Approaching aircraft can employ algorithms similar to those in IBLS but do not expect to resolve integer ambiguities. Instead, if *floating* integer values are utilized, the orientation of the two pseudolites along the direction of approach results in improved vertical position accuracy and integrity (where it is most needed), while lateral accuracy and integrity are unaffected. Airborne RAIM is included in this concept, but unlike IBLS, the focus of integrity monitoring is within the ground system that provides differential corrections.

While the Intrack-APL approach requires fewer pseudolites than does IBLS, the need for two pseudolites per runway was seen as excessive for a system that was to serve all runways and to be much easier to site than ILS. The advent of the specialized, multipath-resistant ground system antennas or *MLAs* as described above provided improved pseudorange accuracy and reduced the need for the improvements provided by the Intrack APL layout [31.61, 62]. As a result, the role of

pseudolites in GBAS became that of an additional GPS-like ranging signal broadcast from the ground that was designed to fill in for occasional gaps in GPS satellite coverage. By the early 2000s, even this level of pseudolite augmentation seemed unnecessary, which is why pseudolites are not a feature of today's fielded GBAS systems.

31.4.2 New-Generation Pseudolite Systems for Commercial Applications

In recent years, pseudolite systems designed to more heavily augment (or even replace GNSS) satellites have been developed, particularly for applications where sky visibility is significantly restricted. Open-pit mining is one such application, as equipment operating on the floor of a deep mine is far below the ground's surface and may be unable to see a sufficient number of satellites above the walls of the mine to support accurate positioning.

One pseudolite system developed by Novariant, Inc. to address this scenario is known as *Terralite XPS* and is described in [31.2]. It transmits its own XPS ranging signals in the X-band, between 9.5 and 10 GHz, to avoid interfering with L-band and other commercial transmissions in industrial, scientific and medical (ISM) bands. The combination of XPS signals from multiple pseudolites and at least some L1 and L2 signals from GPS satellites supports three-frequency carrier-phase differential GNSS positioning with accuracies on the order of 10–30 cm. As with the pseudolite systems previously discussed, a differential reference station is needed to provide corrections (raw measurements, in this case) for the L1, L2, and XPS signals received at the reference station to all users. Integrity monitoring is provided within the reference station (along the lines of GBAS) to improve positioning robustness. The number of pseudolites fielded in and around the mine can be adjusted to achieve the needed visibility in the depths of the mine.

In the last several years, pseudolite systems designed to operate mostly or completely independently of GNSS satellites have been introduced. One example has been developed by Locata Corp. of Australia. It is based on individual *LocataLites* that are combined within a network (*LocataNet*) that synchronizes itself wirelessly, which in principle avoids the need for a traditional reference

station. The *LocataLites* transmit on two separate frequencies in the 2.4–2.4835 GHz ISM band, with each frequency being transmitted on two PRN codes. While a *LocataNet* constructed of multiple *LocataLites* can be combined with GPS satellites, it is also capable of operating independently in places where GPS satellites are not available, such as indoors [31.70, 71].

31.5 Outlook

This chapter has summarized the key aspects of ground-based augmentation systems. The GBAS architecture is described in detail as an example of local area differential GNSS (LADGNSS) augmentation systems. Although most LADGNSS systems do not need to meet the integrity and reliability (continuity and availability) requirements of civil aviation as supported by GBAS, the hardware and software components of GBAS are good illustrations of what is possible with LADGNSS.

Fielding pseudolites to augment or even replace GNSS satellites has significant advantages for applications where GNSS-equipped users do not have a full and clear view of the sky. The advent of multiple GNSS constellations makes it possible to receive sufficient

satellite signals even in obstructed locations, but there will likely remain scenarios where pseudolite augmentation remains worthwhile.

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APPENDIX B

Differential GNSS: Accuracy and Integrity

Sam Pullen and Jason Rife

4.1 Introduction to DGNSS

Differential GNSS (DGNSS) was originally conceived in the 1980s as a means of removing satellite-navigation errors that are highly correlated spatially. The basic concept is to install one or more GNSS “reference receivers” at known locations and have these reference receivers broadcast estimates of GNSS satellite errors to users, who can then remove these error estimates from their own measurements. Since the largest error source on the GPS C/A-code prior to May 2000 was the deliberate clock-error distortion known as selective availability (S/A), DGNSS was first motivated by the desire to remove this artificially induced error source [1]. Now that S/A no longer exists (see [2]), DGNSS benefits users by removing almost all of the remaining spatially correlated errors that occur due to such causes as satellite clock and ephemeris error and ionospheric and tropospheric delays. DGNSS also provides a means to monitor GNSS measurements for satellite faults or other anomalies that might cause errors large enough to threaten user integrity, or safety of operations, if the measurements are not detected and removed in a timely manner.

This chapter explains the fundamentals of DGNSS, including the means by which DGNSS is implemented in practice and the expected level of accuracy resulting from DGNSS. This chapter then proceeds to describe several categories of failures and anomalies that can affect the integrity of satellite navigation and briefly explains how they can be dealt with as part of DGNSS implementation. Chapter 10 provides more details regarding the implementation of differential GPS for worldwide civil-aviation navigation.

4.2 Fundamentals of Differential GNSS

Most users of satellite navigation are so-called “stand-alone” users, meaning that they perform position determination solely from the ranging measurements made from GNSS satellites. These measurements contain errors due to satellite imperfections, delays imparted on the signals as they pass through the atmosphere, and errors due to the users’ equipment and nearby environment. The first two of these error categories changes relatively little over separations of tens to hundreds of

kilometers. Therefore, estimates of these errors, or “corrections,” broadcast by receivers at known, fixed locations can be used to almost completely cancel out satellite and atmospheric errors. This is the idea behind DGNSS. While this chapter will focus mostly on the simpler “local-area” version of DGNSS, in which scalar corrections (for all errors combined) are generated at one nearby location, it will also briefly describe the “wide-area” version of DGNSS that utilizes a widespread network of reference receivers and provides “vector” corrections for individual error sources to support users over regions of thousands of kilometers.

Figure 4.1 shows a simplified, two-dimensional diagram of a version of DGNSS intended to support users in the local vicinity (within 10–50 km) of a single reference receiver (i.e., “local-area” DGNSS). In this figure, the vectors $\mathbf{R}^{(i)}$ extend from the reference receiver to $i = 1, 2, \dots, N$ satellites in view, and the vector $\mathbf{b}$ extends from the reference receiver to the single user shown in the picture (this vector is often called the “baseline”). The scalars $R^{(i)}$ and b represent the magnitudes of these vectors. Figure 4.1 is used to define the notation used in the analyses that follow.

In standard DGNSS implementations, the reference receiver and antenna shown in Figure 4.1 are in fixed locations. The location of the reference receiver antenna is carefully established in advance by GPS surveying techniques to within 1–2 cm (see Chapter 14) so that any errors in the estimated location of the antenna are negligible compared to the DGNSS errors described in Section 4.2.1. The use of a fixed reference station distinguishes DGNSS from another multireceiver technique known as “relative GNSS,” in which each receiver is positioned relative to a preselected “master” receiver, even though some or all of these receivers may be

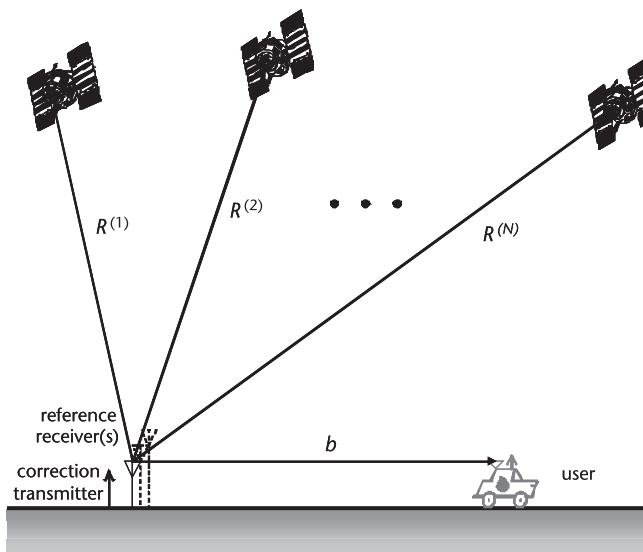


Figure 4.1 Local-area DGNSS geometry.

moving. Relative GNSS thus cannot take advantage of near-perfect knowledge of the absolute location of the “master” receiver. However, the fact that most error sources discussed in Section 4.2.1 are highly correlated spatially means that, in a manner similar to DGNSS, the impacts of these errors are significantly reduced when relative GNSS positioning is performed (see [3]).

4.2.1 Error Sources and Degree of Spatial Correlation

Table 4.1 summarizes the principal error sources for users of the GPS Standard Positioning Service (SPS) [2], meaning “stand-alone” navigation based on L1 C/A-code pseudorange measurements (see [1, 3]). Where error sizes differ between pseudorange and carrier-phase measurements, “PR” in this table refers to pseudorange measurements, while “ ϕ ” refers to carrier-phase measurements.

Among the error sources listed in Table 4.1, all but multipath and receiver noise are strongly correlated spatially and are thus greatly reduced by the application of DGNSS. Only multipath is not affected, as it is statistically independent between reference and user receivers unless their antennas are very close together (i.e., $b \leq 20\text{--}30\text{m}$ in Figure 4.1). In fact, because of this independence, the use of DGNSS actually increases the total impact of multipath error because reference-receiver multipath (and receiver-noise) errors are added to those of the user. For this reason, it is important to minimize the impact of multipath on DGNSS reference receivers by careful siting and selection of receivers and antennas (e.g., see [4]). With reasonable care, this penalty is easily overcome by the error reduction achieved by the removal of well over 90% of, in rough order of magnitude, ionospheric, satellite clock, satellite ephemeris, and tropospheric errors [1, 3].

It is important to note the differences in spatial and temporal correlation among the first four error sources in Table 4.1 that are mitigated by DGNSS. All four of these error sources change relatively slowly over time, limiting the required update rate of the correction messages (see Section 4.2.3) and allowing slightly dated corrections to be projected forward in time and still be used, provided that the integrity time-to-alert requirements are still met (see Section 4.2.4 and Chapter 10). At a given time, satellite clock errors are perfectly correlated for all users and can be removed almost completely (the only limitation is the latency, or age, of

Table 4.1 Approximate 1-Sigma Errors for Stand-Alone and Local-Area DGPS Users

Error Source	<i>1σ Range Error for Stand-Alone Users</i>	<i>1σ Range Error for Local-Area DGPS Users</i>
SV clock error	1–2m	<0.05m
SV ephemeris error	1–3m (corrected by single-frequency model)	0.001–0.05m
Ionospheric delay error	1–7m	0.1–0.3m
Tropospheric delay error	2–3m (uncorrected) 0.1–0.5m (corrected by atmospheric model)	0.01–0.05m
Multipath (reference and user)	PR: 0.5–1.5m ϕ : 0.005–0.015m	PR: 0.5–2m ϕ : 0.005–0.02m
Receiver noise (reference and user)	PR: 0.2–0.35m ϕ : 0.001–0.003m	PR: 0.2–0.5m ϕ : 0.001–0.005m

the broadcast corrections—see Section 4.2.4). On the other hand, ephemeris errors, or errors in describing the true orbit of a GPS satellite, are not quite perfectly correlated because the projection of the satellite orbit error onto the line of sight from any receiver varies slightly with receiver location. The same is true of atmospheric errors (ionospheric and tropospheric delays) due to the fact that the atmospheric characteristics that generate signal delays are not precisely the same at different locations. The following paragraphs describe these three imperfectly correlated error sources in more detail.

The detailed analysis of residual DGNSS ephemeris error in [1] develops a bounding (worst-case) relationship between three-dimensional satellite orbit error (δR) for a given satellite and residual (post-DGPS) range error (ϵ_{eph}) as follows:

$$\epsilon_{eph} = \frac{\|b\| \delta R}{R} \quad (4.1)$$

where R is the distance between reference receiver and satellite (the distance from user receiver to satellite is essentially the same) and b is the baseline vector. For a typical local-area DGPS baseline, such as $\|b\| = 10$ km, and the smallest value of R ($\approx 20,180$ km), which occurs for a GPS satellite directly overhead, an ordinary three-dimensional satellite orbit error of 10m translates into a worst-case DGPS range error of only 0.005m. This is a worst-case result because it assumes the worst-case relative geometry between satellite, reference receiver, and user receiver (see [1, 5]).

During periods of non-negligible solar activity, ionosphere effects are now (in the absence of S/A) the largest source of error for stand-alone GPS users. Ionization within the upper atmosphere delays code-phase measurements and advances carrier-phase measurements by an equal amount, leading to errors of several meters or more in pseudorange measurements and code-carrier divergence in single-frequency code-carrier smoothing (see [3, 6]). The amount of ranging error that results varies significantly with the degree of solar activity and the elevation angle (θ) through which a given satellite is observed. Because this angle relates to the length of the signal that must pass through the ionosphere, satellites lower in the sky (i.e., smaller elevation angles) incur higher ionosphere delay than satellites higher in the sky. This effect is modeled by the so-called obliquity factor, which is derived based on approximating the ionosphere as a thin shell that concentrates its entire “delaying” impact at a single atmospheric altitude h_I . The resulting obliquity factor (OF) definition is [3, 7]:

$$OF = \left[1 - \left(\frac{R_E \cos \theta}{R_E + h_I} \right)^2 \right]^{-0.5} \quad (4.2)$$

where R_E is the mean radius of the Earth (6378.136 km), and the thin-shell height h_I is typically taken to be 350 km (a simpler approximation is defined in ICD-GPS-200C [8]).

The obliquity factor resulting from (4.2) ranges from 1.0 at 90 degrees elevation to just over 3.0 at 5 degrees elevation. Thus, satellites visible at 5 degrees elevation

will have approximately three times the ionospheric error as satellites visible very high in the sky. However, this approximation is only as good as the thin-shell model it is based upon. While that model appears to hold quite well under normal ionospheric conditions, significant deviations have been observed during ionospheric storms. These storms can cause severe spatial gradients that can magnify residual ionospheric errors for local-area DGPS users by a factor of 10 or more. Carrier smoothing of pseudorange errors, which is commonly applied by DGNSS users, magnifies this error because, as noted above, carrier-phase measurements are advanced by the same amount that pseudorange measurements are delayed (see [9, 28]).

Tropospheric errors are caused by signal delays due to the density of the neutral (noncharged) atmosphere within 10 km of the ground. The vast majority of tropospheric delay is denoted as the hydrostatic or “dry” component and is due to the refractivity of dry gases in the lower atmosphere. The remainder of the delay (roughly 10%) comes from the “wet” component and is due to the presence of water vapor in the lower atmosphere. The amount of water vapor in the atmosphere is highly variable; thus most of the short-term variation in the total tropospheric delay comes from the wet component (see [3, 9]). Tropospheric delays are significantly smaller than ionospheric delays under active solar conditions, vary much less over time, and affect code and carrier measurements identically.

The fact that tropospheric delays are generally well-behaved makes it relatively easy for all classes of GNSS users to remove most of their impact by using atmospheric models to predict the delay. These models typically take atmospheric pressure, temperature, and water-vapor partial-pressure data as inputs, but long-term average values for particular locations or regions can be used in place of real-time measurements with a relatively small loss of accuracy (see [3, 9, 10]). As with ionospheric error, a geometric factor $m(\theta)$ is needed to adjust for the user’s elevation angle. A very simple model for this is $1/\sin(\theta)$ [3], but models that are more accurate for small θ are preferred, such as the one given for use with the RTCA WAAS MOPS tropospheric model for $\theta \geq 4$ degrees [10]:

$$m(\theta) = \frac{1.001}{\sqrt{0.002001 + \sin^2 \theta}} \quad (4.3)$$

Tropospheric error correction models such as the ones cited in [9, 10] can be used by stand-alone users, but this is not a standard practice because tropospheric errors are not the dominant error source for standalone users. Wide-area DGNSS users (such as SBAS/WAAS users—see Chapter 10) do use these models to remove predicted tropospheric delays for their approximate locations. This makes sense because wide-area DGNSS users are spread over very large regions with widely different weather conditions, and wide-area “vector” corrections for different error sources are constructed in such a way that they do not include localized tropospheric effects to the extent possible (see Section 4.2.2). On the other hand, local-area scalar DGPS corrections include a very good representation of the tropospheric delay in a given locality; thus application of these corrections removes almost all tropospheric error from user measurements under normal weather conditions. The

most extreme weather conditions from the DGNSS user point-of-view would be the presence of sharp weather fronts and/or thunderstorms, which, for example, place the DGNSS reference station under cool, dry conditions while the user is under warm, humid conditions. A recent study of actual storms of this type (see [11, 12]) suggests that DGPS range errors of as large as 0.3–0.5m could occur over baselines as short as 5–15 km under worst-case conditions.

Having covered the four error sources that are removed by local-area DGNSS due to strong local spatial correlation, it is time to consider the effects of errors that are independent between user and reference receivers. Under nominal conditions, multipath is the largest error source for DGPS users because, rather than being canceled out by the application of DGPS corrections, it is enhanced somewhat by the combining of statistically decorrelated reference and user errors. The levels of multipath error shown in Table 4.1 assume “clean” or “moderate” reflecting-surface conditions around user and reference receivers and/or the use of at least some multipath-mitigating technology in the receivers or antennas (see [3, 4, 13]). Larger errors are possible under conditions with many or large reflecting surfaces nearby, as are sometimes encountered in urban areas (see [14]). Receiver noise is a function of received signal-to-noise power (see [3, 15]). User and reference receiver noise errors are normally reduced to relatively small values by carrier smoothing of C/A-code measurements, as described in [3]. The values shown for receiver noise errors in Table 4.1 assume that at least a default level of carrier smoothing (e.g., a time constant of 20 seconds or more in a first-order smoothing filter) is present. Longer time constants, such as the 100 seconds that is used in the Local Area Augmentation System (LAAS) (see Chapter 10) have the advantage of further reducing receiver noise and also attenuating high-frequency multipath errors.

Now that all major error sources have been considered, it is possible to estimate the total error budget for stand-alone and DGPS users under nominal conditions. Combining the error magnitudes listed in Table 4.1 and considering other small error sources that affect DGNSS users (such as the centimeter-level errors in knowledge of the reference-receiver location) suggests that typical one-sigma pseudorange errors for stand-alone GPS users are approximately 3–5m, compared to approximately 0.5–1.0m for local-area DGPS users. As mentioned before, because multipath dominates the local-area DGPS error budget under typical conditions (i.e., not considering the possibility of anomalies within one of the other error sources), further multipath mitigation beyond what is assumed in Table 4.1 has a direct effect in lowering total DGPS errors, whereas this is not the case for stand-alone users since other error sources not under the user’s control (e.g., ionospheric delays) are the dominant factors.

For applications such as surveying and precision farming that require centimeter-level accuracy, standard (pseudorange-based) local-area DGPS is insufficient. However, a variation of local-area DGNSS known as carrier-phase DGNSS (CDGNSS) [also known as real-time kinematic (RTK) GNSS positioning], routinely achieves decimeter-to-centimeter-level accuracy by providing carrier-phase in addition to code-phase corrections. The key to the use of CDGNSS is solving for carrier-phase integer ambiguities, which allows the very high-accuracy carrier-phase measurements (see Table 4.1) to be used as ranging observations. Details regarding

the algorithms that can be used to solve for carrier-phase integer ambiguities are discussed in Chapter 14 (also see [3, 14, 16]).

4.2.2 Local Versus Regional DGNSS Corrections and DGNSS Networks

Most of the discussion in this chapter refers to local-area DGNSS, which is the most common application of DGNSS. As shown in Figure 4.1, this application of DGNSS has one or more users applying corrections derived at and received from a single reference station, which contains one or more closely spaced reference receivers for the purposes of redundancy and measurement averaging. LAAS reference stations, for example, typically include four reference receivers with antennas spaced at distances on the order of 100m. Since corrections are generated from essentially one observing location, they are transmitted and applied as *scalar* corrections, meaning that one scalar value represents the pseudorange correction for a given satellite, and this single number covers all of the spatially-correlated error sources described in Section 4.2.1. This procedure works best when all users of these corrections are close to the reference station. As noted above, users within several tens of kilometers are best-served, but users as far as several hundred kilometers away can achieve substantial error reduction and safety improvement via local-area DGNSS, as evidenced by the success of the U.S. Coast Guard DGPS/radio beacon system fielded in the 1990s and since expanded into the “nationwide DGPS” (NDGPS) system, to support marine and other users (see [1, 17]).

Because the Coast Guard DGPS/radio beacon system employs many reference stations spread along the coastlines of the United States (with a few inland sites), it is an example of a DGNSS network. From a user perspective, the Coast Guard system operates just like single-reference-receiver local-area DGNSS because users normally apply only the corrections broadcast by the nearest (or easiest-to-receive) station. However, in other applications, measurements made by networks of reference receivers are used in combination to improve user performance and reliability, even though the resulting user corrections may appear to be from a single source. Integrated reference-receiver networks are better able to observe and correct for ionospheric and tropospheric spatial variations compared to what can be achieved at a single reference site. Regional networks that support CDGNSS are one common example of this approach (see Chapter 14 and [16]).

DGNSS systems that must support users spread over large regions, such as entire countries or continents, typically expand upon this “network” concept and make use of what is known as “wide-area” DGNSS. Unlike the single-reference-station system shown in Figure 4.1, or the NDGPS system with its many reference stations that each produce independent scalar corrections, wide-area systems combine the measurements of many reference stations spread out to cover the entire intended service area (or as much of it as possible, if some of it is oceanic). These measurements are combined at a so-called “master station” that generates a single set of correction messages applicable to users throughout the service area.

Broadcasting one set of corrections valid over a large region implies several key differences from local-area DGNSS. One is that communications between reference stations and the master station must be rock-solid. Also, while a well-built reference-station network can tolerate occasional outages of individual reference

stations, the master station must be sufficiently internally redundant that the probability of master-station outages is much smaller than the intended maximum reliability (or *availability*—see Chapter 10). Most fundamentally, the form of the corrections changes from scalar values for individual satellites to *vector* corrections: multiple values, which describe individual elements of the error sources that affect each possible user measurement.

The means by which corrections are implemented in space-based augmentation systems (SBASs), including the Wide-Area Augmentation System (WAAS) described further in Chapter 10, are a good example of the concept of vector DGNSS corrections. SBAS provides two separate sets of corrections, in two different formats, rather than the single scalar correction of local-area DGNSS. One set of SBAS message types broadcasts individual correction components for satellite-generated errors, including separate corrections for the one satellite clock error state and the three axes of satellite ephemeris error, for all GNSS satellites covered by a given SBAS at a given time. In addition, a “fast” correction message that combines clock and ephemeris corrections into one value for each satellite is broadcast at more frequent intervals to minimize latency (see Section 4.2.4) [10]. Meanwhile, a completely separate set of SBAS message types broadcasts ionospheric-delay corrections based on a grid of mostly 5×5 degree latitude/longitude points at the assumed ionosphere thin-shell height of 350 km (see [10, 18, 19]). SBAS users must follow the elaborate procedures laid out in [10] to combine these elements into measurement corrections applicable at their location and time (an example of this calculation is included in the software receiver presented in Chapter 5). The necessity for this can be seen from the fact that, in the case of WAAS, the same set of correction messages must be applicable to users in southern Florida, northern Minnesota, the Arizona desert, and off the west coast of the United States, even though these locations see different sets of satellites from different angles and see very different segments of the ionosphere.

Because wide-area DGPS corrections are generated to support large regions instead of being “specialized” for locations in the vicinity of a reference station, wide-area DGPS accuracy is significantly worse than local-area DGPS, although it is still much better than stand-alone GPS. The U.S. Federal Aviation Administration evaluates the performance of WAAS in quarterly “Performance Analysis Network” (PAN) reports, which are available online. A recent WAAS PAN report [20], covering January through March 2008, shows 95% (roughly 2σ) satellite clock/ephemeris errors of between 0.7 and 3.0m (most below 2m) after WAAS corrections are applied, depending on the (static) observing location and the satellite being observed, while 95% ionospheric residual errors after WAAS corrections range from 0.3 to 2.0m (most under 1m). The reference-to-user separation boundary, beyond which wide-area DGPS is likely to be more accurate than local-area DGPS, is estimated to be 200–250 km, but these figures underestimate the *integrity* advantages of wide-area DGPS, which are described in more detail in Section 4.3 and in Chapter 10 (also see [19]).

4.2.3 Means of Distributing DGNSS Corrections

Given the explosion in communication technologies that has occurred over the past 10–15 years, DGNSS corrections are now distributed over almost every

possible means of communication, including over the Internet (for example, see [21]) and over mobile-phone networks in support of A-GNSS technology (see [3, 22, 56]). However, most real-time DGNSS users continue to rely on some form of RF transmission.

Many means of transmitting DGNSS corrections via RF are described in [1]. One of these is the pre-existing marine radio beacon direction-finding technology that has been adapted to broadcast NDGPS signals over hundreds of kilometers. These radio beacons operate in the 283.5–325 kHz band and broadcast local-area corrections in the format defined by the Radio Technical Commission for Maritime Services (RTCM) Special Committee (SC) 104 (see [1, 23, 24]). This format is used by many local-area DGNSS systems around the world and has been adopted by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). It consists of many different message types to transmit pseudorange corrections (PRCs), range-rate corrections (RRCs), reference station and satellite information, and a variety of other data types that may be useful depending on the characteristics of a particular DGNSS. Each message type is made up of a set of 30-bit “words,” each word being composed of 24 data bits and six parity bits. Furthermore, each message type begins with the same structure for the first two 30-bit words, and these two initial words define the broadcasting station identifier along with a “modified Z-count” that unambiguously gives the time that the message was transmitted (see [1]). It should be noted that the most recent published version of the RTCM-104 format, Version 3.1 [24], is not compatible with the latest version of the earlier format, Version 2.3 [23], as many changes were made in Version 3 to enhance CDGNSS applications. Version 3 also makes room for support of GLONASS, Galileo, and potentially other future GNSS constellations (see Chapter 17).

The original RTCM-104 data format, published in 1985, served as a model for the development of the subsequent Ground-Based Augmentation System (GBAS—see Chapter 10) data transmission formats. GBAS (including LAAS) correction information is broadcast at VHF in the band used for Instrument Landing System (ILS) localizer transmissions (108.0–117.975 MHz). This choice was made to allow aircraft to receive correction broadcasts with existing ILS avionics. Each 25-kHz interval from 108.025 to 117.950 MHz (inclusive) represents a usable center frequency, and since D8PSK modulation is used, each such center frequency has eight assignable time slots for broadcast messages [25]. One such slot is intended to be used by a single GBAS installation.

As with the RTCM SC-104 data format, the GBAS message structure encompasses several message types, of which Message Type 1 is the most important because it is updated twice per second and includes PRC, RRC, error bounds, and other integrity information. The other message types are updated less frequently. Message Type 2 contains information on the ground station location and on tropospheric and ionospheric error bounds, while Message Type 4 provides data that defines the approach supported by a given GBAS installation. Additional “optional” message types are defined to, for example, relay expected loss of satellite visibility (Message Type 5) [25].

While it is possible to distribute wide-area DGNSS corrections via terrestrial RF transmissions [the Ground-Based Regional Augmentation System (GRAS),

explained in Chapter 10, is an example of this], the best way to provide coverage of large regions is to broadcast corrections via satellite. As described in Chapter 10, SBAS systems (including WAAS) relay corrections and integrity information to users via satellites in geostationary (GEO) orbit (also see [10]). These messages, broken down into many different message types, are encoded as 250-bps navigation data streams on L1 C/A-code ranging signal broadcasts coming from each SBAS GEO satellite. Because encoding data on L1 C/A-code signals enforces a far lower data rate than the VHF broadcasts used by GBAS, yet SBAS is charged with providing vector corrections and error bounds to cover users located across vast regions, careful scheduling of individual SBAS message types is required to meet the six-second time-to-alert that applies to CAT I and “near-CAT-I” or “LPV” modes of precision approach (see Chapter 10).

4.2.4 Managing the Latency of DGNSS Corrections

While the lower data rate of SBAS corrections means that SBAS corrections suffer from much more latency than do GBAS corrections (or local-area corrections in general), all DGNSS systems need to adapt to the reality that users will receive and apply DGNSS corrections to their measured pseudoranges some time after the corrections were generated. In the meantime, the “zero-latency” correction, meaning the correction that applies at the current moment in time, has likely changed, if for no other reason than to keep up with changes in the satellite clock. It is for this reason that, at a minimum, RRCs are sent to users in addition to PRCs. With this information plus the time-tag t_C of the correction message (e.g., the modified Z-count in the RTCM and RTCA message formats) indicating when the PRC and RRC were generated, DGNSS users can easily compute a linear correction to update the PRC to apply to the user’s observation time t :

$$PRC_{upd} = PRC + RRC(t - t_C) \quad (4.4)$$

This approach is used by both GBAS and SBAS to remove first-order latency effects, but higher-order approaches may also be used (as in [26], which applies a quadratic time correction).

Whichever means of updating for latency is selected; the fact that users are applying dated reference-receiver information poses a potential vulnerability if GNSS satellite clock errors become much larger than normal and change dynamically in a manner that is not well-modeled by the latency-correction method. In the case of the linear correction applied in (4.4), if anomalous GNSS clock errors are limited to ramps with constant slope over time, these errors will be removed by the estimation of the ramp error magnitude in the RRC values broadcast by DGNSS reference stations. However, anomalous clock events limited to perfect ramps are unlikely; other changes, such as steps, accelerations, and jerks (acceleration rates) may also be present. In these cases, any practical latency correction is likely to leave significant residual error. While satellite clock faults are infrequent, they are among a class of anomalies that must be detected and excluded in order to insure user integrity at the 10^{-5} -per-operation level or better. Section 4.3 describes

how satellite faults and other anomalies can be mitigated by reference stations supporting DGNSS.

An additional consideration for latency that is related to both integrity and continuity is missed correction messages. If DGNSS users depend on reference stations to detect and exclude faulted measurements, missing one or more correction messages exposes them to potential faults that might have occurred since the time-tag of the most recent received correction message. For this reason, and because a time gap longer than a few seconds significantly degrades the accuracy of the linear latency correction given in (4.4), constraints apply regarding how many missed messages can be tolerated before operations must be aborted or downgraded in capability. The *time-to-alert* component of the integrity requirements for safety-critical users is typically the driving factor that determines how many consecutive missed messages are allowed (see Chapter 10 for more detailed discussion of this topic).

4.3 DGNSS Integrity Threats and Mitigations

One major advantage of DGNSS is the ability of reference stations to provide integrity to users in a manner that is more precise and less dependent on satellite geometry redundancy than is the primary alternative, which is known as receiver autonomous integrity monitoring (RAIM) (see [27–29]). Providing integrity for DGNSS users involves mitigating the following classes of faults and anomalies:

1. *Faults within GNSS*: This category includes failures within individual GNSS satellites and failures or errors in the control segment that manages a given GNSS constellation, such as the GPS Operational Control Segment (OCS).
2. *Faults within reference station equipment*: This category primarily includes failures within individual GNSS reference receivers as well as anomalous multipath at reference receiver antennas. It also includes potential faults in the communication methods used to relay DGNSS corrections and integrity information to users.
3. *Signal propagation anomalies*: This category includes anomalous spatial delay decorrelation when GNSS signals pass through the ionosphere or the troposphere on their way to reference and user antennas. The result of such anomalies is measured pseudorange delay at the reference receiver that is significantly different than the delay measured by users. Other impacts of anomalous propagation, such as ionosphere “scintillation,” are much more likely to cause loss of lock (or detection by one of the monitors looking for GNSS faults) and thus lead to continuity breaches (meaning unexpected loss of service) as opposed to loss of integrity (or a safety hazard—see Chapter 10).

Sections 4.3.1–4.3.3 cover each of these failure or anomaly categories separately.

4.3.1 Integrity Threats and GNSS Faults

This section addresses the five GNSS satellite and/or control segment faults defined by the FAA LAAS ground facility (LGF) specification [30]. This list includes all failure modes of significance to stand-alone or differential GNSS that have been seen, plus one that, to the authors' knowledge, has never been seen (satellite-generated code-carrier divergence). A brief description of each of these faults follows, along with a summary of the means by which DGNSS can mitigate the condition.

4.3.1.1 Satellite Code Signal Deformation

This fault mode involves the deformation of the code signal broadcast by a GNSS satellite relative to the ideal code signal expected by a GNSS receiver attempting to track it. Gross deformation of the signal would make the signal untrackable because receivers could not correlate to the flawed broadcast signal. These deformations do not constitute an integrity threat. However, more subtle deformations that retain the general shape of the desired signal can be tracked—they could distort the correlation peak as viewed by the receiver and thus result in hazardous errors. For DGNSS, if reference and user receivers track the faulted satellite identically, the resulting error will be identical and will cancel out once the user applies the reference-receiver-derived differential correction. However, the reference and user receivers are typically not identical; thus some differential error remains and could be of hazardous magnitude.

To the authors' knowledge, deformations with the potential to cause hazardous errors have only been observed once, on satellite SVN (and PRN) 19 in 1993 [31]. The fault appeared to cause a significant delay in the C/A-code rising edge chip transition relative to the P(Y)-code chip transition. After the fault was acknowledged by the GPS OCS and corrected by switching the satellite signal transmission electronics from the "A-side" to the "B-side," this anomalous transition delay was replaced with an acceptable level of delay. Note that, in practice, some level of deviation from "perfect" C/A-code exists on otherwise "nominal" satellites, and this "normal" signal deformation must be accounted for in the design of nominal error budgets and detection thresholds against anomalous, threatening signal deformations [31].

Figure 4.2 illustrates how the PRN-19 anomaly was first noticed by civil GPS users and demonstrates the vulnerability of differential users to it. The plot in Figure 4.2 is taken from differential GPS user measurements taken at the Oshkosh air show in August 1993. When PRN-19 was not in view, vertical errors were approximately 1–2m. When PRN-19 came into view at around 6:30 a.m. local time, vertical errors suddenly jumped as high as 8.5m (see [31] for a detailed study of this incident).

Concern over the effect of signal-modulation failures similar to PRN-19 led the aviation community to develop threat models to encompass the PRN-19 failure and reasonable extrapolations of it. Figure 4.3 illustrates the resulting "second-order-step" threat model that was created by RTCA and accepted by ICAO once the PRN-19 anomaly was better understood. This threat model includes the "digital delay (or advance)" fault mode thought to have been observed in the PRN-19 fault

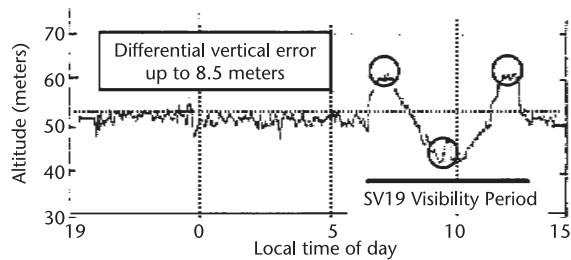


Figure 4.2 Vertical position error resulting from PRN-19 fault.

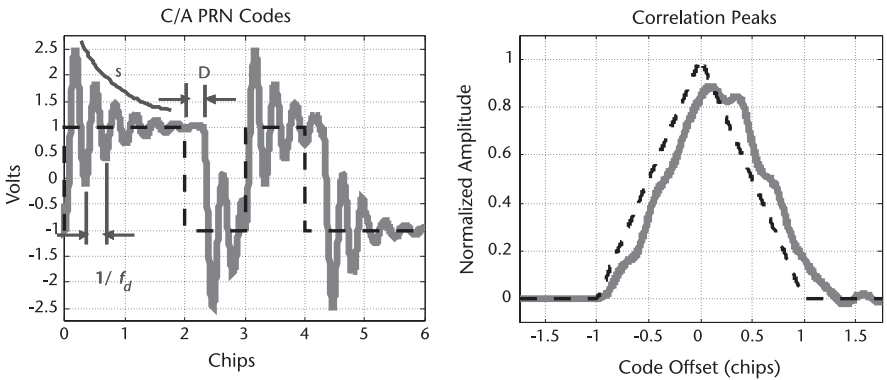


Figure 4.3 Threat model parameters and resulting correlation-peak deformation.

as “Threat Model A” with lead/lag parameter Δ . In addition, it includes a second-order-decay model of analog “ringing” during a code-chip transition as “Threat Model B” with parameters f_d (damped frequency) and σ (decay rate). “Threat Model C” combines both Threat Models A and B so that a single fault may have both digital-delay and analog-ringing characteristics. (This is the case illustrated by the thick, wavy line in Figure 4.3—see [7, 32].) The right-hand plot in Figure 4.3 shows the impact of the “Threat Model C” fault shown on the left-hand plot on the C/A-code correlation peak seen by a GPS receiver.

This class of signal deformation is capable of introducing appreciable errors in differential GPS systems. If the reference and user receivers use the same RF/IF transfer functions, the same discriminator scheme (e.g., early minus late and double delta), and the same correlator spacing, then the error suffered by the user will be the same as the error suffered by the reference. In this case, these errors would cancel in differential processing. However, if the reference and user differ with respect to any of these parameters (RF/IF transfer function, discriminator, or correlator spacing), then the errors will not cancel completely, and hazardous misleading information (HMI—see Chapter 10) may result.

Using the threat parameters described above, the deformed C/A-code signal (e.g., the thick, wavy line shown on the left-hand plot of Figure 4.3 relative to the ideal dashed line) is given by the following equations ([10, 33]):

$$e = \begin{cases} 0 & t \leq 0 \\ 1 - \exp(-\sigma t) \left[\cos \omega_d t + \frac{\sigma}{\omega_d} \sin \omega_d t \right] & t > 0 \end{cases} \quad (4.5)$$

$$\omega_d \equiv 2\pi f_d \quad (4.6)$$

Note that the signal-deformation case shown in Figure 4.3 represents the scenario where $f_d = 3$ MHz, $\sigma = 0.8$ MNepers/sec, and $\Delta = 0.3$. This case does not fall within any of the threat model boundaries defined below, as Figure 4.3 uses an exaggerated scenario to make the characteristics of deformation visually clear.

Table 4.2 gives the outer limits of the three threat-model parameters Δ , f_d , and σ as specified in two ways. The first, and primary, set of limits are from the “official” RTCA/ICAO threat model defined in [10, 30]. A secondary and tighter (meaning more constraining on the possible threat parameters) set of “most likely subset” (MLS) threat model parameters also is shown (see [33]). This second set is what the initial implementation of WAAS (approved for operation in July 2003) was subjected to. Both sets of limits are based on consensus-of-experts expansions from an estimate of the PRN-19 anomaly projected into the domain of the second-order-step threat model. For the most likely subset, the expansion from the PRN-19 case is very limited. This subset does not include the analog-only (Threat Model B) threat possibility. It does include the combined analog-digital threat (Threat Model C), but this threat is limited to a single frequency ($f_d = 10.23$ MHz).

In assessing the overall threat of signal deformation to DGNSS, a simulation is normally employed to search through a discretized set of points within and at the edges of one of these threat models to determine (1) the maximum differential user error in the range domain before any monitoring and (2) the maximum differential user error after taking credit for signal deformation monitoring (SDM) within its time-to-alert (e.g., 3 seconds for a CAT I LAAS Ground Facility—see [34] for a detailed treatment).

Figure 4.4 shows the basic concept behind signal deformation monitoring (SDM). This monitor makes code correlator measurements at multiple “early” and “late” chip offsets as well as at a “prompt” measurement. The monitor then forms detection statistics that check the correctness of the shape of the code correlation peak. These detection statistics can take the form of a collection of “ Δ -test” and “ratio test” statistics [32], each of which has its own threshold. These thresholds

Table 4.2 Signal Deformation Threat Model Parameter Bounds

	<i>Full RTCA/ICAO Threat Model</i>	<i>MLS Threat Model</i>
Threat Model A (Digital Lead/Lag Only)	$-0.12 \leq \Delta \leq 0.12$	$-0.04 \leq \Delta \leq 0.04$
Threat Model B (Analog “Ringing” Only)	$\Delta = 0$ (N/A) $4 \leq f_d \leq 17$ MHz $0.8 \leq \sigma \leq 8.8$ MNepers/sec	None (N/A)
Threat Model C (Digital Lead/Lag plus Analog “Ringing”)	$-0.12 \leq \Delta \leq 0.12$ $7.3 \leq f_d \leq 13$ MHz $0.8 \leq \sigma \leq 8.8$ MNepers/sec	$-0.04 \leq \Delta \leq 0.04$ $f_d = 10.23$ MHz $1.8 \leq \sigma \leq 7.8$ MNepers/sec

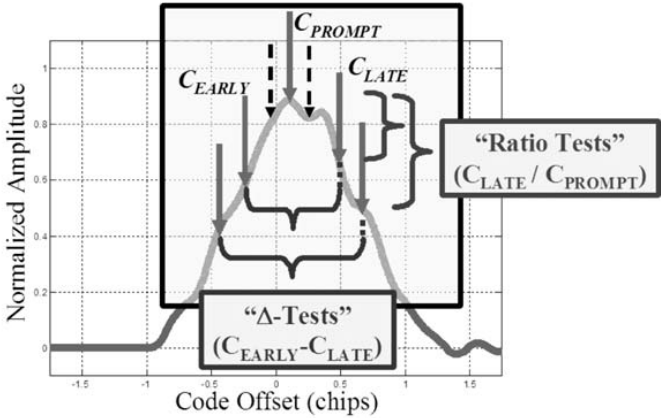


Figure 4.4 Illustration of multiple-correlator signal deformation monitoring.

are determined to provide an acceptably low level of false alarms under nominal conditions when the code correlation peak is influenced by nominal signal deformation (see [31]), receiver noise, and code multipath. In this approach, all Δ -tests and ratio tests must be passed at each epoch for the monitored signal to be declared healthy. More recent approaches “fuse” multiple test statistics into a single SDM test statistic [35, 36].

Note that, in the LAAS implementation, the raw correlation-peak observations shown in Figure 4.4 must be averaged or smoothed over a period similar to that of the 100-second carrier-smoothing time constant in order to reduce receiver noise and multipath down to acceptable levels. Therefore, careful analysis (and, in some cases, simulation) is required to demonstrate that all signal-deformation threats within the threat models given in Table 4.2 are mitigated within the time-to-alert if they generate potentially hazardous range-domain errors. The methodology for performing this analysis is detailed in [34], which introduces an approach called a time-varying maximum error range requirement (MERR). This approach has the useful property of relating the definition of the not-to-exceed error in the range domain (MERR) to the time-to-alert requirement. The “time-varying MERR” concept can be applied to all threats except for ionosphere anomalies, which are too large to be bounded in the range domain.

4.3.1.2 Satellite Low Signal Power

This fault involves the broadcast of satellite signals at power levels below the specified minimum levels. For GPS, the minimum received signal power levels are given in [8] (e.g., -160.0 dBW for C/A-code). In practice, GPS satellite broadcast signal power is and has been consistently several decibels above these levels. As reported in a study for the GPS Joint Program Office in 2002 [37], instances of significant violations of these minimum power levels are rarely (if ever) noticed, and our best understanding is that this continues to be the case today.

A threshold test on the measured C/N_0 in DGNSS reference receivers is described in [38] as a means of detecting low signal power (also see [15]). Through rare, signal power fades of a few decibels are important and should be detected. Deep fades (tens of decibels) do not constitute an integrity threat, because the reference and user receivers would simply lose lock. Shallow fades, on the other hand, could introduce cycle slips, and a few such slips could constitute an integrity threat. In addition, low satellite power could be indicative of other potential problems with the affected satellite. When an observable fault (such as low signal power) is detected on a given satellite, that satellite should be excluded from use, even if there is no immediate direct threat to integrity, because of the indirect threat to integrity posed by using satellites known to be in an anomalous state.

Low signal power can also appear as a consequence of local phenomena such as receiver failures, or anomalous reference-antenna multipath, and in these cases, direct integrity hazards are possible due to the effects of these other anomalies. In such “multisymptom” cases, the presence of low signal power in addition to other, more hazardous fault modes makes life easier for DGNSS integrity monitoring in that a separate monitor not targeted at the underlying fault (in this case, the C/N_0 monitor) might detect the unfolding anomaly before the “targeted” monitor does.

4.3.1.3 Satellite Code-Carrier Divergence

This is defined as a lack of synchronism between the code and carrier waveforms transmitted by the satellite. The effect is to cause a difference between the apparent range as indicated by code and carrier measurements. As measured by ground-based receivers, satellite-generated code-carrier divergence may differ from ionosphere-generated divergence. The ionosphere causes code delay and carrier advance to have equal magnitude (and opposite sign—thus “delay” and “advance”). Satellite code-carrier divergence refers to divergence of any type (not necessarily equal and opposite, and without an upper bound).

Unlike the other four satellite failures described in this section, satellite code-carrier divergence has never occurred, to the authors’ knowledge. In principle, it could be excluded based on fault modes and effects analysis (FMEA) directed at such failures in the satellite hardware. Since complete exclusion of such a fault based on FMEA analysis is very difficult in practice, and because no official guidance has been provided, code-carrier divergence is included in the list of possible failures because the effect of such a failure could definitely be hazardous. Most DGNSS systems (including SBAS and GBAS) use carrier-phase smoothing of code-phase measurements, and this process assumes that the code and carrier are synchronous when the signal leaves the satellite.

DGNSS systems that rely on single-frequency carrier smoothing in both reference and user receivers are vulnerable to this threat to the degree that their carrier-smoothing filters are not identical and have not achieved steady-state performance [39]. Monitoring for this threat involves estimating the degree of code-carrier divergence present in reference receiver measurements and comparing it to a threshold that is mostly based on what is typically present due to normal ionospheric divergence [38, 39]. Since experience suggests that satellite-generated code-carrier divergence is extremely unlikely, the combination of satellite clock monitoring

(described in the next section) and code-carrier divergence monitoring is sufficient to mitigate this potential hazard.

4.3.1.4 Satellite Clock Anomalies

Among the five classes of GPS satellite or control-segment faults listed above, satellite clock anomalies the most frequent and best understood. The cesium and rubidium atomic frequency standards that maintain long-term time stability in GPS satellites are known to unpredictably “lose control” as they age, despite careful monitoring and maintenance by the GPS OCS (see [40, 41]). The impact of this instability can be sudden changes in apparent range, range rate, and range acceleration as seen by reference and user receivers. Note that, unlike the code-carrier divergence fault mode defined above, both pseudorange and carrier-phase will move identically under the influence of satellite clock anomalies.

Two examples of satellite clock faults that occurred prior to 1997 are described in detail in [40]. Figure 4.5 shows a more recent clock failure that occurred on SVN/PRN-22 on July 28, 2001, as viewed by the FAA William J. Hughes Technical Center LAAS Test Prototype (LTP) installed at the Atlantic City, New Jersey, airport (see [42]). An initial large jump in clock drift rate was followed by a very fast clock runoff. Most worrisome, this fault was not flagged as “unhealthy” by the GPS OCS until one and a half hours after the onset of the anomaly.

Figures 4.6 and 4.7 provide two examples of less severe (and more typical) satellite clock failures from 2003 [35]. Figure 4.6 shows a clock drift problem on SVN/PRN-27 on May 26, 2003. This drift generated stand-alone user range errors

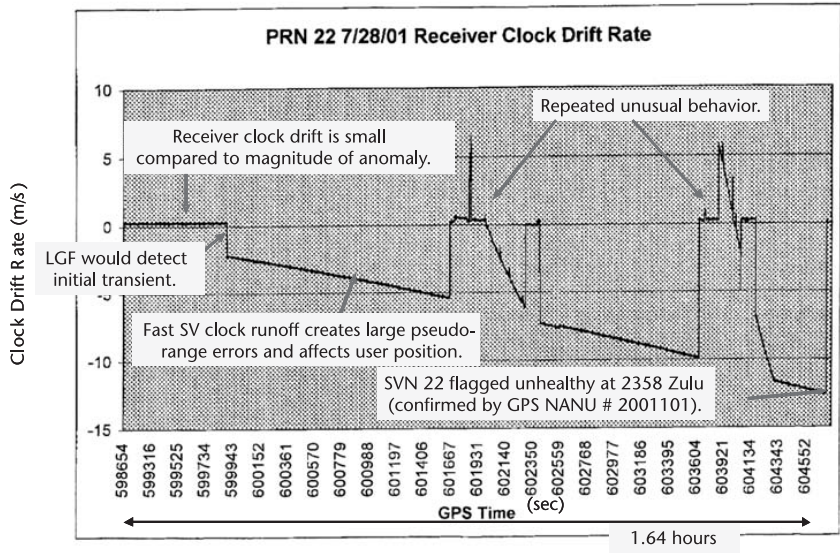


Figure 4.5 SVN/PRN-22 clock anomaly of July 28, 2001. (Figure courtesy of John Warburton, FAATC.)

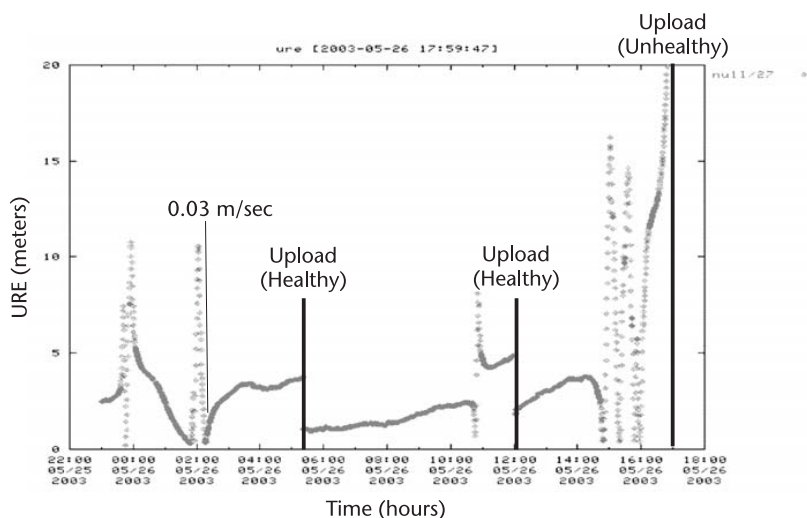


Figure 4.6 SVN/PRN-27 clock anomaly of May 26, 2003. (Figure courtesy of Karl Kovach for IFMEA.)

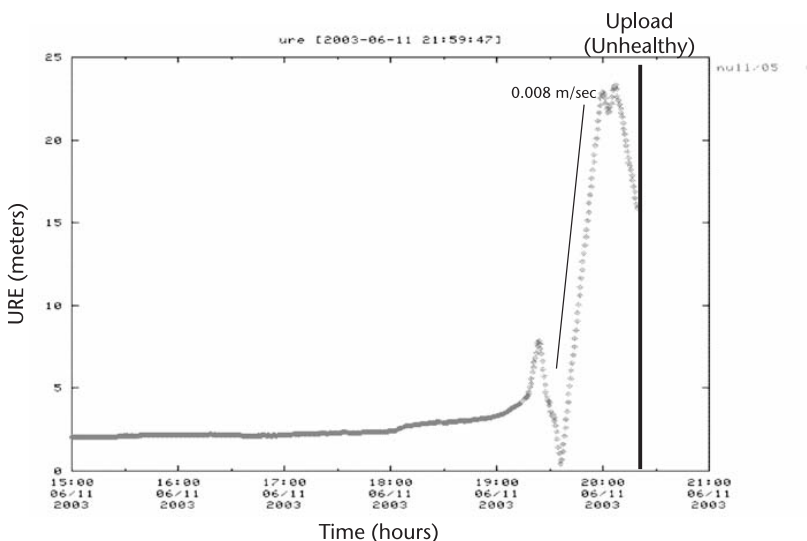


Figure 4.7 SVN-35/PRN-05 clock anomaly of June 11, 2003. (Figure courtesy of Karl Kovach for IFMEA.)

(URE)—shown on the y-axis—for OCS receivers that grew to 15m. Two attempts to correct it with updated satellite-clock-correction messages (in the broadcast satellite navigation data) failed, and the satellite was finally flagged as unhealthy after the URE shot upward and exceeded 20m. According to [40, 41], a URE of 20–30m represents the threshold that OCS uses to decide when a satellite should be flagged as “unhealthy” and taken off-line for further analysis before it is flagged

as “healthy” again. Additionally, the definition of HMI for stand-alone civil users in [2] is a URE from a satellite flagged as “healthy” that exceeds either 30m or 4.42 times the broadcast user range accuracy (URA) parameter. Figure 4.7 shows a simpler but otherwise similar example of clock “run-off” on SVN-35/PRN-05 on June 11, 2003. All three affected satellites in Figures 4.6 to 4.8 were GPS Block IIA satellites operating rubidium frequency standards.

These clock faults represent the most significant threat to stand-alone user integrity for two reasons. First, there is no clear upper bound to the size of possible errors in range, range-rate, and/or range-acceleration. Second, these faults occur with a relatively high frequency compared to other satellite fault modes, and the existing GPS OCS is unable to warn users of such faults within five to 10 minutes. Thus, stand-alone users requiring real-time integrity need to turn to one of several RAIM solutions, such as the one prescribed by RTCA DO-208 [36] for stand-alone aviation users (also see [28]).

For DGNSS users, these clock faults present a more complicated situation. Under ideal conditions, differential users would apply the reference corrections promptly and thus remove any impact of satellite range error changes. Since zero latency is impossible in practice, the degree to which differential users are directly threatened by clock anomalies depends on (1) the delay between reference correction generation and user application of the resulting corrections; and (2) the interpolation mechanism used to correct for this delay, as described in Section 4.2.4. Since the linear-range-rate latency correction given in (4.4) is the one most commonly used, satellite clock errors with significant range-acceleration error components are the most threatening to DGNSS because such accelerations make this method erroneous.

A means to detect the initial range-domain transient that results when a satellite clock becomes anomalous is described in [38]. This method is based on the carrier-

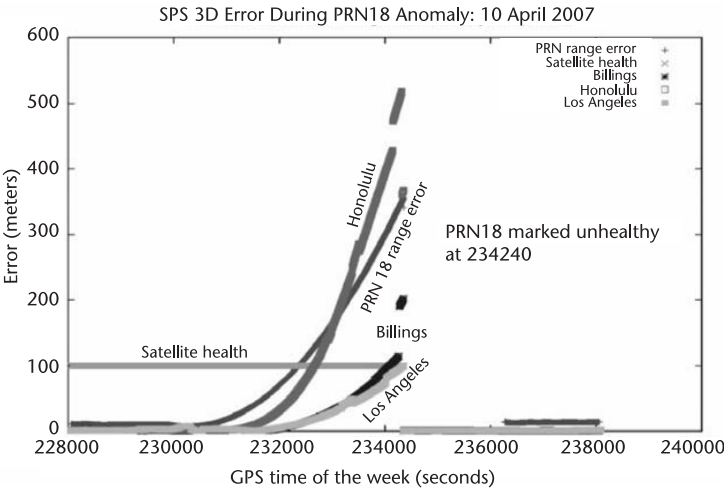


Figure 4.8 Errors resulting from SVN-54/PRN-18 ephemeris failure of April 10, 2007.

phase measurement extrapolation developed to mitigate latency in [26]. When a carrier-phase transient due to a satellite clock anomaly (or many other causes, including receiver cycle slips) occurs, the difference between the phase measurement predicted from previous measurement and the newly observed measurement (that is affected by the anomaly) provides a clear-cut means of detection.

4.3.1.5 Satellite Ephemeris Failures

These faults result in substantially erroneous ephemeris data being broadcast by a GNSS satellite. For GPS satellites, nominal ephemeris errors on a given orbit axis are less than 10m (1σ); thus a three-dimensional satellite orbit error exceeding 100m would certainly qualify as anomalous. Two very different causes of this type of anomaly have been foreseen:

- *Type A fault:* A large ephemeris error following a previously announced (A1) or unannounced (A2) satellite orbit maneuver;
- *Type B fault:* An OCS error in setting the broadcast ephemeris parameters (without a satellite orbit maneuver).

Prior to April 2007, type B faults were thought to create the larger integrity concern because they could occur due to OCS inattention when nothing unusual was happening. In contrast, type A faults were thought to be less likely because of the increased OCS vigilance associated with satellite maneuvers. In fact, no confirmed instance of any type of ephemeris fault as defined here had ever occurred until the recent (and serious) type A fault of April 10, 2007, which is illustrated in Figure 4.8. This plot comes from the SPS PAN report compiled by the FAA Technical Center for that period [43]. In this event, satellite SVN-54/PRN-18 was deliberately maneuvered from one orbit to another while still flagged as “healthy.” This serious blunder on the part of OCS should never have occurred, but it illustrates that all human and human-directed systems are fallible.

As shown in Figure 4.8, the apparent range error on PRN-18 during its unflagged maneuver grew to about 350m, meaning that the three-dimensional satellite orbit error was at least this large. Stand-alone GPS users in the western United States (here represented by stationary receiver sites maintained by the FAA Technical Center) saw three-dimensional position errors of several hundred meters depending on their location and the other (nominal) satellites in their position solutions. These errors persisted until the GPS OCS realized its mistake and set the satellite to unhealthy about 75 minutes after the “Delta-V” that triggered the planned orbit maneuver commenced. Note that the actual thrusting that triggered the orbit maneuver lasted only 44 seconds, after which the satellite was left to drift toward its newly desired orbit location.

As explained with regard to nominal ephemeris errors in Section 4.2.1, the impact of ephemeris anomalies on DGNSS users depends on two geometrical factors. First, as indicated by (4.1), the resulting differential range error increases linearly with reference-to-user separation ($\|b\|$). Second, the component of the three-dimensional satellite ephemeris error vector in space that results in differential range error is that component that projects into the plane that is perpendicular to

the vector connecting the reference receiver (or the geometric centroid between reference receivers) to the user. For example, if the reference-to-user vector (**b**) points due west, only the component of the three-dimensional satellite ephemeris error (projected into east-north-up coordinates centered at the reference site) that falls within the north-south plane results in differential ranging error. The remainder of the ephemeris error is removed by the user's application of differential corrections.

Because there is no way to bound the magnitude of satellite ephemeris errors (particularly for type B faults) or to limit them to specific orbit axes, differential users require at least some degree of monitoring to reduce the ephemeris integrity risk to an acceptable level. This poses no problems for wide-area DGNSS because the regional spread of reference stations makes it possible to directly solve for satellite positions in space independently of the broadcast ephemeris messages (this is required to be able to generate vector corrections for individual ephemeris components) [44]. However, for local-area DGNSS, with reference receivers in only one location, satellite ephemeris monitoring is much more difficult.

Several monitors that are useful in detecting type B ephemeris faults within local-area DGNSS are described in [38, 45]. These methods are based on the "YE-TE" concept, which compares elements of "yesterday's ephemeris" (more precisely, the ephemeris stored from the most recent pass of a given satellite) to the same elements from "today's ephemeris," meaning the ephemeris that is broadcast by a newly risen satellite at the present time. The method described in [38] compares three-dimensional satellite positions in space, while the method in [45] compares several specific ephemeris orbit parameters and produces somewhat lower minimum detectable errors (MDEs).

Detection of type A anomalies, which involve actual satellite maneuvers, is even more difficult because the limited observability from a single reference location is combined with the lack of a valid prior ephemeris to serve as a reference. A differential-carrier-phase-based algorithm for detecting "Type A1" failures is described in [45]. This method attempts to make these maneuvers observable by utilizing the same ephemeris error decorrelation effect that poses a potential threat to users. Carrier-phase differences are used to make these effects visible over reference receiver antenna baselines of 100m to 1 km. In order to detect faults in all directions, two orthogonal baselines are needed within the set of reference receivers supporting nearby users.

Another, simpler approach to detecting type A anomalies is to apply thresholds on the differential range, range-rate, and range-acceleration corrections (note that the latter is not broadcast by LAAS) that are tighter than what is required to assure that the corrections fit within the broadcast message structure. For example, in LAAS, the maximum pseudorange correction that can be broadcast is $\pm 327.67\text{m}$ (see [25]), but a much smaller threshold of $\pm 125\text{m}$ can be applied to this correction without sacrificing continuity or availability. A threshold of $\pm 3.4\text{ m/s}$ can be applied to the range-rate correction, and a threshold of $\pm 0.019\text{ m/s}^2$ can be applied to the estimated range acceleration. These thresholds will detect almost all satellite maneuvers, whether commanded or uncommanded by OCS, but there is a small region of "worst-case" maneuver geometry that has little or no component along the vector between satellite and LGF that could go undetected and potentially (if

large enough) cause HMI. Thus, this approach does not preclude all possible threatening geometries. Its intent is to shrink the “space” of possible HMI events to the degree that the remaining space is of small enough probability that the overall integrity requirement is met (see Chapter 10).

4.3.2 Integrity Threats from DGNSS System Faults

This subsection focuses on DGNSS faults that directly affect receiver measurements. Software errors are not covered here because they are normally handled procedurally in high-integrity systems by the use of RTCA DO-178B [46] practices (not that these are perfect). Errors in the system that transmits corrections are also not covered. They can be managed by a combination of equipment redundancy and/or bit-to-bit comparison of the received broadcast to the data stream input to the transmitter.

4.3.2.1 Reference Receiver Errors and Cycle Slips

This category of errors covers everything that might go wrong inside a reference receiver that would cause it to produce incorrect pseudorange and carrier-phase measurements, which, if not detected and excluded, would corrupt the broadcast differential corrections. The inner workings of GNSS receivers are typically opaque to DGNSS designers. Hence, the implied “threat model” is conservative. It assumes that any magnitude of error in pseudorange or carrier phase is possible on any combination of pseudorange and/or carrier-phase measurements on one or more satellites being tracked. However, reference receiver failures are typically assumed to be statistically independent across reference receivers, meaning that the known presence of a fault on one receiver does not change the probability of a fault on any of the other receivers that appear to be working properly.

In practice, cycle slips are amongst the most common receiver faults, particularly when tracking satellites at low power levels [47]. In this fault, the carrier-phase measurement of the affected satellite(s) jumps by an integer (or half-integer) number of wavelengths of the carrier-phase waveform being tracked (e.g., 19 cm for L1). Usually, if cycle slips are large enough to be potentially hazardous, they are relatively easy to detect using the carrier-phase transient monitor described above for detection of satellite clock anomalies. In addition, if multiple redundant reference receivers are present, the multiple reference consistency check (MRCC) monitor used in LAAS detects faults of hazardous magnitude that are limited to a single reference receiver [30, 38]. MRCC uses B-values that represent differences among the redundant reference receivers to determine if a single reference receiver has failed on one or more of its channels.

Figure 4.9 uses simplified accounting to illustrate how B-values are computed in LAAS. Each reference receiver generates its own pseudorange correction (PRC_i) for a given satellite. Then, the corrections for all four reference receivers are averaged to produce the overall PRC that would be broadcast. The B-value for a given reference receiver j (B_j) represents the difference between this overall PRC and what the “correct” PRC would be if receiver j were known to be faulty. In this case, receiver j would be excluded from the generation of the broadcast corrections,

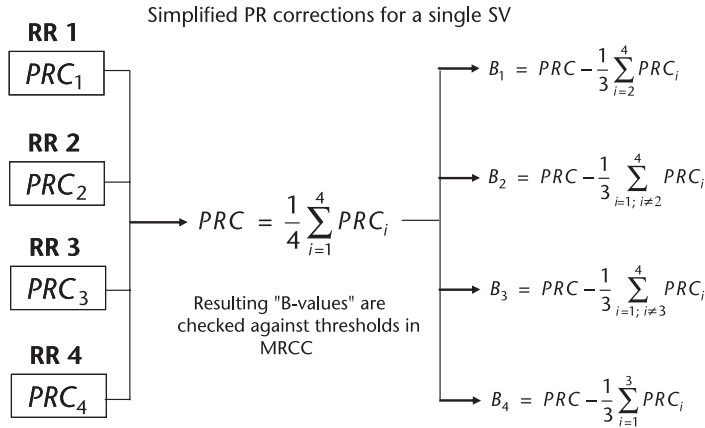


Figure 4.9 Illustration of simplified B-value calculation for LAAS.

and the “correct” PRC would instead be based on the average PRC over the three remaining (nonfailed) receivers. Each B-value thus expresses a measure of the difference between the receiver for which it applies and the consensus of the other three receivers, and if this difference exceeds a threshold, the receiver in question is marked for exclusion (at least with respect to the satellite(s) for which the discrepancy occurs). If one or more satellites fail MRCC, then a series of trial exclusions and recomputations of the remaining B-values is carried out until all remaining B-values fall below the threshold. At that point, the surviving B-values represent validated measurements that can be used to generate differential corrections (subject to passing all other monitors).

4.3.3 Integrity Threats from Signal Propagation Anomalies

These threats result from anomalies in the atmosphere between GNSS satellites and reference or user receivers. As shown in Table 4.1, under most conditions, ionospheric and tropospheric delays experienced by reference stations are almost identical (e.g., to within 10–30 cm) to those experienced by users within 100 km; thus, very little error remains after the application of differential corrections. Rare cases, with much greater differential delays across a 100-km baseline, create potential integrity hazards.

4.3.3.1 Ionospheric Spatial-Decorrelation Anomalies

Nominal one-sigma ionosphere vertical (zenith, referenced to a 90° elevation angle) delay gradients are from 1–4 mm/km in mid-latitude regions of the Earth. This finding is based on many years of experience with differential systems combined with extensive data analysis within the conterminous United States (CONUS) (see [48]). However, ionospheric delay gradients exceeding 400 mm/km have been observed on rare occasions during large geomagnetic storms. These gradients apply

to an arbitrary ray path and are not referenced to a particular elevation angle [49, 50].

Based on this data analysis, a LAAS ionosphere spatial anomaly threat model has been developed for CONUS to assess the impact of large ionosphere gradients on LAAS operations. The geometry of a large gradient is represented in Figure 4.10, where a linear ionosphere-slant-delay gradient is assumed to exist over a region of fixed width between regions of “flat” ionospheric delay (i.e., where the gradients are at nominal levels). This gradient “wave front” moves at constant velocity with respect to the ground.

In Figure 4.10, example values for the various threat-model parameters are shown that approximate a “near-worst-case” condition. Note that the front speed with respect to the LAAS Ground Facility (LGF) is 200 m/s, and the front is approaching from directly behind the aircraft so that the aircraft’s ionosphere pierce point (IPP) is impacted first. LAAS avionics built to the current MOPS [7] are not required to monitor for ionosphere anomalies; thus no help can be expected from user monitoring (even though such monitoring is possible—see [51]). Differential error begins growing before the wave front reaches the IPP, and when the LGF IPP is impacted, the LGF cannot detect the anomaly because the speed of the wave front is approximately the same as the speed of the LGF’s IPP. Thus, the code-carrier divergence (CCD) monitor described in Section 4.3.1 (to detect satellite-generated code-carrier divergence) is of no help in this ionospheric-anomaly scenario.

For single-frequency carrier smoothing, as used by LAAS and most local-area DGNSS systems, the differential pseudorange error (denoted here as ϵ_{iono}) resulting from the ionospheric anomaly modeled in Figure 4.10 is given by:

$$\epsilon_{iono} = g_{iono} (\|b_{air}\| + 2\tau \|v_{air}\|) \quad (4.7)$$

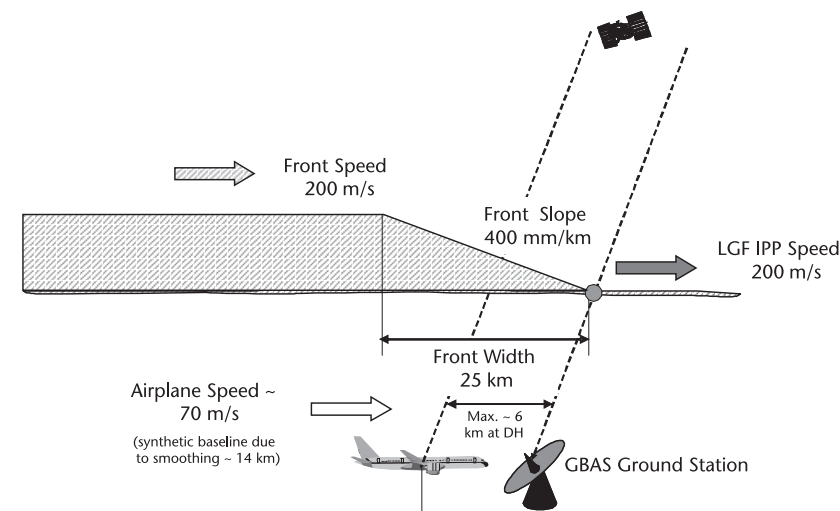


Figure 4.10 Geometry of near-worst-case ionospheric anomaly.

where g_{iono} is the ionosphere spatial gradient (in units of slope), $\|b_{air}\|$ is the baseline distance between LGF and aircraft, $\|v_{air}\|$ is the horizontal approach speed of the aircraft toward the LGF, and τ is the carrier-smoothing time constant (assumed to be the same in both LGF and aircraft, and typically 100 seconds for LAAS). A detailed derivation of this result can be found in [52]. Also note that the obliquity factor is not applied because anomalous gradients are already expressed in terms of slant delay. For the numbers shown in Figure 4.10, the resulting differential range error (on a single satellite) from (4.7) amounts to 8m. This is not disastrous for most DGNSS applications but could be hazardous for LAAS-supported precision approach and landing.

As noted above, extensive data analysis of ionosphere storms in CONUS since 2000 has allowed us to establish upper bounds for the threat-model parameters in Figure 4.10 (see [49, 50]). The plot in Figure 4.11 shows the upper bound on the ionosphere slant delay gradient (in mm/km) as a function of satellite elevation. This bound varies from 375 mm/km at low elevations to 425 mm/km at high elevations. These individual bounds express the largest gradients observed from ionospheric storms in CONUS. These largest gradients occurred in the Ohio-Michigan region during the extremely severe November 20, 2003, ionosphere storm between approximately 2030 and 2115 UT. These bounds also include a small margin (on the order of 10–20 mm/km) for measurement error. Also shown in the text within Figure 4.11 are upper and lower bounds on the width (25–200 km) and speed (0–750 m/s with respect to the ground) of the “wave-front” model shown in Figure 4.10 [49, 50].

To translate this ionosphere threat model into actual user impacts, a simulation methodology has been created that superposes the wave front shown in Figure 4.10 onto a given user satellite geometry. This procedure is described in detail in

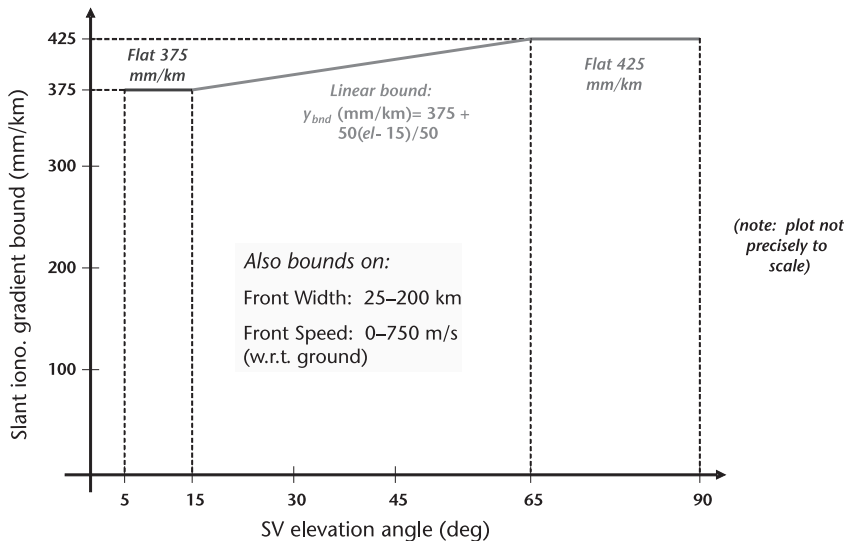


Figure 4.11 Ionospheric anomaly threat model parameter bounds.

[53]. The simulation applies either the worst-case ionospheric anomaly within the threat model or a randomly selected scenario within the threat model to either a single satellite or a pair of satellites in a given user geometry. The worst-case scenario for a given satellite is the maximum gradient for that satellite's elevation angle, and it usually involves the minimum-width (25 km) front. It also includes the front speed and direction shown in Figure 4.10, where the aircraft is impacted first and the front speed nearly matches the LGF IPP speed for the satellite in question, making LGF detection impossible. For the two-satellite-impacted case, two cases are simulated. First, the worst-case anomaly is chosen for the first satellite in the pair, and the effect on the second satellite is then computed. Second, the worst-case anomaly is chosen for the second satellite and the resulting scenario for the first satellite is computed.

The worst-case vertical position error is called the maximum ionosphere error in vertical (MIEV) (position). The MIEV is found as follows. For each satellite and satellite pair in the subject geometry, the differential range error is converted into vertical position error using the known satellite geometry. The MIEV is the maximum position error over all satellites or pairs checked for that geometry. Importantly, the LGF (or the system operator) does not know the user's exact satellite geometry. Hence, it must consider all possible user satellite geometries to determine the overall MIEV at a given location and time.

Figure 4.12 shows a histogram of vertical position errors for the Honeywell LAAS provably safe prototype (PSP) at Memphis airport for a CAT I approach with a decision height 6 km from the centroid of the LGF reference receivers. It is based on simulating a range of possible ionospheric anomaly scenarios within

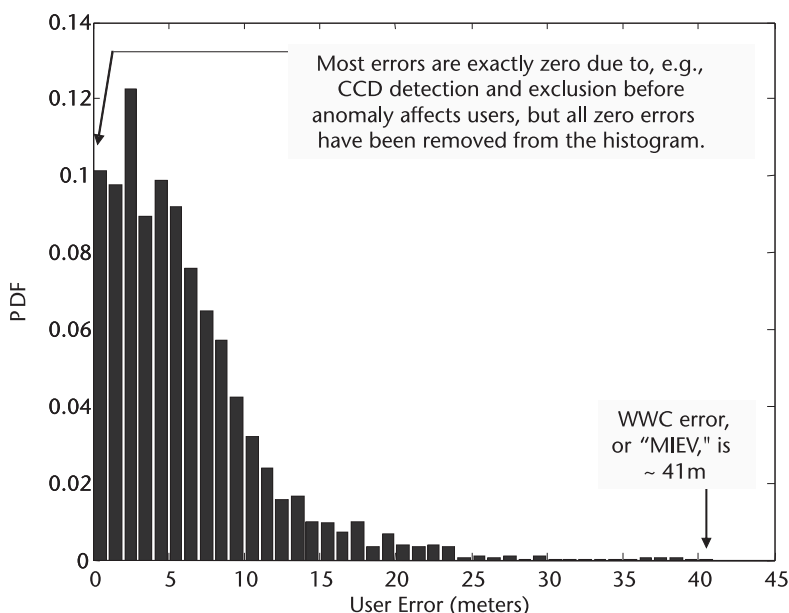


Figure 4.12 Histogram of vertical position errors for Memphis LAAS prototype.

the threat model. While all widths and velocities within the threat model of Figure 4.11 are simulated, only two maximum gradients are simulated (425 and 375 mm/km). Vertical position errors are computed for all satellites and pairs of satellites for the all-in-view user geometry, all “1-satellite-out” user geometries, and all “2-satellite out” user geometries. Simulating the threat model in this fashion results in most errors being identically zero because the LGF code-carrier-divergence monitor detection precedes the growth of any differential error, but these results have been deliberately excluded from the histogram. Even so, the vast majority of the resulting vertical errors are below 10m, although the very worst-case error (under the worst-case combination of ionospheric anomaly conditions, user geometry, and timing) is about 41m.

Several options exist for mitigating the risk of ionospheric spatial anomalies:

- Demonstrate that, for a given user class or set of applications, the probability of ionospheric anomalies severe enough to threaten user safety is acceptably low. If this can be done, no additional mitigation is required.
- Utilize signals on multiple GNSS frequencies to perform “divergence-free” and/or “ionosphere-free” smoothing, as described in detail in [54]. These techniques remove all or most of the differential ionospheric error between reference and user receivers and thus greatly reduce the magnitude of this threat.
- While only using a single GNSS frequency, add ionospheric-gradient monitoring to users as well as to reference receivers and broadcast information to users to allow them to “screen out” satellite geometries for which the worst-case ionosphere-induced positioning error would be hazardingly large. This is the approach taken by a future upgrade of LAAS to support “GAST-D” CAT II/III service (see [51]).
- If none of the above are practical, the reference receivers must perform satellite geometry screening without the benefit of airborne monitoring and without knowledge of the exact user geometry. This is the case for the present version of LAAS supporting CAT I precision approach. In this method, the LGF determines the MIEV over all possible user geometries (typically down to two satellites removed from the set of satellites approved by the LGF), and if this MIEV exceeds the allowable worst-case error for this threat [55], the LGF must inflate one or more broadcast parameters that affect the airborne vertical protection level (VPL) such that all geometries with unacceptably high MIEV become *unavailable* [that is, VPL exceeds the tolerable vertical alert limit (VAL)] [7].

Two methods for implementing the technique proposed in the fourth bullet by real-time determination of inflation factors for combinations of the broadcast σ_{vig} , σ_{pr_gnd} , and/or the ephemeris P-value (see [25]) are given in [50, 53]. Because of the conservatism inherent in protecting against the worst possible ionospheric anomaly and the worst possible airborne satellite geometry, the resulting increase in VPL significantly degrades the achievable CAT I precision-approach availability using the existing “GAST-C” version of LAAS.

4.3.3.2 Tropospheric Spatial-Decorrelation Anomalies

As described in Section 4.2.1, tropospheric delays on GNSS signals are functions of local atmospheric pressure, temperature, and humidity. Thus, anomalous decorrelation of troposphere delays results from large differences in these weather parameters between the LGF and the user. As noted in that section, studies of tropospheric decorrelation for LAAS [11, 12] suggest that differential range errors as large as 0.3–0.5m can result from conditions where the LGF and the user are on different sides of a strong weather front (e.g., during severe thunderstorms) that separates warm, humid air from cold, dry air. While the resulting gradient is too small to be reliably detectable within GNSS measurements, the weather conditions under which such an event could occur are observable by other means (e.g., weather instruments, human observation of severe weather being present). Also, since this magnitude of worst-case differential error is an order of magnitude smaller than what is possible for ionospheric anomalies, special efforts to mitigate it are not required unless multiple-frequency measurements are available to mitigate ionospheric anomalies.

The approach recommended for LAAS in [12] is to include an independent one-sigma gradient of 5 mm/km to cover worst-case tropospheric spatial decorrelation. Since ionospheric and tropospheric anomalies are deemed independent, this 5 mm/km factor would be root-sum-squared (RSS'ed) with the 4 mm/km that is used to bound nominal (not anomalous) one-sigma ionospheric decorrelation in the broadcast σ_{vig} term (see [25, 48]), resulting in a “nominal” broadcast σ_{vig} (prior to any inflation to mitigate ionospheric anomalies) of 6.4 mm/km. This is unusual in that a sigma designed to bound worst-case errors is combined with one designed to bound nominal errors, but it is a conservative approach that requires no further mitigation of tropospheric anomalies.

4.4 Summary

This chapter describes the basic features of both local-area and wide-area differential augmentation of GNSS. DGNSS provides major performance improvements to satellite-navigation users over what is possible with stand-alone use of GNSS. In particular, DGNSS significantly improves both the *accuracy* and the *integrity* of user navigation. By removing error sources that are beyond the control of GNSS users, such as satellite and atmospheric errors, DGNSS moves the focus of error mitigation to error sources, such as multipath and receiver noise, that users (and DGNSS designers) have more control over. DGNSS reference receivers also serve as powerful means of real-time integrity monitoring that greatly exceeds the capabilities of a GNSS alone, even when augmented by user RAIM.

As new, improved GNSS constellations are fielded and existing systems continue to improve, the role of DGNSS may change. Much of the growth of GPS usage since the deactivation of selective availability in 2000 has been among personal and automotive users for whom the performance of stand-alone GPS is more than adequate. In the future, the presence of multiple constellations with higher basic signal accuracy will likely make it possible to support some levels of precision approach with stand-alone GNSS and RAIM (see [28, 29]), which would provide

(almost) worldwide service. However, for local and regional applications, the many new means of passing information from one place to another make it much easier to implement various forms of DGNSS “behind the scenes.” A-GNSS is an example of a use of DGNSS techniques to make GNSS signals easier to track in obscured locations [22, 56]. A-GNSS is also a means of meeting the ever-growing user expectations of GNSS performance. It is safe to say that DGNSS technologies, whether used openly for high-precision, high-integrity applications such as SBAS, GBAS, and surveying as done today, or covertly to boost the accuracy and coverage of next-generation automobile and mobile-phone navigators, will be standard elements of the GNSS designers’ toolbox for as long as GNSS remains in use.

4.5 Data Provided on the DVD

An example of DGNSS corrections has been provided on the DVD accompanying this book in the form of the WAAS option in the fastgps software receiver (to be presented in Chapter 5). Built into this receiver is the option to apply WAAS ionosphere differential corrections by using the 5-degree by 5-degree ionospheric grid point data described above (available at <http://www.nstb.tc.faa.gov/>). An example IGP file taken at the same time as software receiver data set 2 is included on the DVD, and it can be added into the processing loop using the configuration flag described in Chapter 5. The formulas for converting IGP grid data into corrections for individual pseudorange estimates can then be applied within the fastgps receiver (starting in the function WAAS_corrections in the file nav.cpp). This simple functionality is meant to provide a starting point from which others can expand the DGNSS functionality of the software receiver into more of the application areas discussed above.

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APPENDIX C

Real-Time Ionospheric Threat Adaptation Using a Space Weather Prediction for GNSS-Based Aircraft Landing Systems

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Abstract—The use of ground-based augmentation systems (GBASs) is increasing in the national airspace system and also in many nations to support aircraft precision approaches and landing. An anomalous ionospheric event if undetected can cause a potential threat to users of single-frequency-based global navigation satellite system augmentation systems. Current GBAS utilize the pre-defined “worst case” ionospheric threat model in their computation of user position errors to consider all possible ionospheric conditions. This could lead to an excessive availability penalty by adding conservatism on the resulting error bounds. This paper proposes a methodology of real-time ionospheric threat adaptation that adjusts the ionospheric threat model in real time instead of always using the same threat model. This is done by using predicted values of space weather indices for determining the corresponding threat model based on an established relationship between space weather indices and ionospheric threats. Since space weather prediction itself is not reliable due to prediction errors, an uncertainty model was derived from 17 years of historical data. When applied to Category I GBAS in the Conterminous United States, this method lowered the upper bound of the current threat model about 95% of the time during the 17 years (from 1995 to 2011) using the bounded prediction value of the disturbance-storm time index.

Index Terms—Automatic aircraft landing, ground based augmentation systems (GBAS), next-generation air transportation system (NextGen), real time ionospheric threat adaptation, space weather prediction.

I. INTRODUCTION

AS A part of the Next Generation Air Transportation System (NextGen) of the United States, GPS-based aircraft precision approach and landing systems have been developed to get aircraft ‘wheels on runway’ in all weather

and visibility conditions [1], [2]. The US Federal Aviation Administration (FAA) developed and operates the Local Area Augmentation System (LAAS), which is a form of Ground Based Augmentation System (GBAS) that currently supports Category (CAT) I precision approaches [3], [4]. The GBAS ground facility, equipped with Global Navigation Satellite System (GNSS) receivers/antennas at precisely known locations, continuously monitors GNSS signals and broadcasts differential GNSS corrections and integrity information to users. It supports increased runway and airspace capacity by providing highly accurate and reliable three-dimensional aircraft position in real-time. Applications of GBAS either as it is or with modifications for intelligent air transportation including Unmanned Aircraft Systems (UAS) are being studied to support automatic guidance and landing, path planning, and safe separation for collision avoidance [5]–[8].

Aviation communities, including service providers, airlines, and manufacturers, are actively working to develop, install, and spread the use of GBAS. In 2009, the Honeywell SmartPath SLS-4000 achieved the first System Design Approval (SDA) for CAT I operations which allow automatic precision approaches down to a decision height (DH) of 200 ft [9]. Since the world’s first fully operational implementation of a GBAS ground system in Bremen, Germany, GBAS has become operational at many airports in the US, Australia, Spain, Switzerland and Russia. Over one thousand Boeing aircraft including B737s are equipped with GBAS Landing Systems (GLS) as of 2015 and GLS is standard on the B787 and the B747-8 [2]. The next-generation aviation system aims to extend the GBAS capability from CAT I to CAT II/III service which demands a higher level of navigation requirements to guide an aircraft to the runway surface (i.e., zero-visibility operations) [1], [10]. Thus, the GBAS program now focuses on validating standards for a GBAS Approach Service Type-D (GAST-D) which is equivalent to a single-frequency GBAS CAT III service [9].

For safety-critical systems like GBAS, the integrity requirement is the most important and challenging to meet [11], [12]. Integrity is an assurance provided to users that the difference between an unknown true position and a GBAS-derived position estimate is bounded with an extremely high degree of confidence. One of the major concerns for the integrity of single-frequency GBAS is the undetected ionosphere-induced error large enough to threaten the safety

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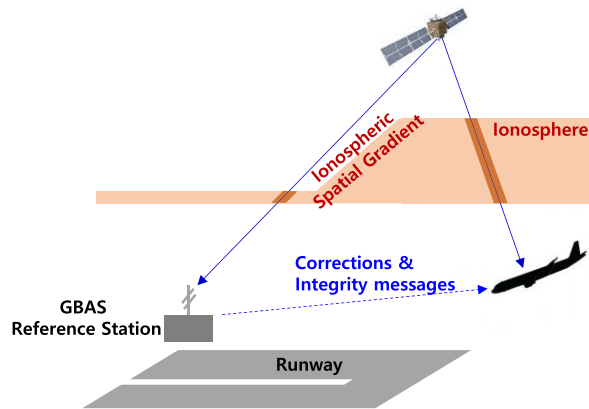


Fig. 1. Illustration of a potentially hazardous situation caused by an ionospheric gradient.

of users. The ionosphere is one of the largest and most unpredictable error sources that can degrade the performance of GNSS. GBAS users therefore apply ionospheric corrections and integrity information included in broadcast messages to compute their position estimates and confidence bounds of these estimates. The ionosphere, however, occasionally has strong variability that causes spatial and temporal decorrelation between reference stations and users. This variability becomes significant in the case of disturbed ionospheric conditions, resulting in decreased positioning accuracy and possible loss of integrity if undetected. A potentially hazardous situation is shown in Fig. 1 which illustrates an aircraft affected by an ionospheric front with an anomalous spatial gradient.

Ionospheric spatial gradients in the slant domain (i.e., along the actual path between satellite and receiver) of as large as 413 mm/km over baselines of 40 – 100 km have been observed in the United States during ionospheric storms since April 2000 [13]. Extreme gradients of this magnitude can pose a potential integrity threat to GBAS users because the residual range error at the CAT I DH can be as large as 8 meters if undetected by the GBAS ground facility. It required the development of a worst-case ionospheric threat model for GBAS in the Conterminous U.S. (CONUS). The threat model is applied for the simulation of worst-case ionospheric errors against which the users should be protected. These hypothetical errors can be mitigated to acceptable levels by inflating one or more integrity parameters broadcast to users [13], [14].

The upper bounds of 425 mm/km at high elevation and 375 mm/km at low elevation for the CONUS threat model were determined based on the largest gradients observed in Northern Ohio during the same ionospheric storm on 20 November, 2003 [13]. This storm was the most extreme event that occurred during the peak of the last solar cycle in CONUS. Threat observations populated in the current threat model were observed and identified on only four days within an 11-year period of the last solar cycle. Regardless of very low likelihood of extreme storm events, GBAS always assumes the worst ionospheric condition and mitigates worst-case ionospheric errors. This could lead to an excessive availability penalty.

A method to eliminate a threat caused by large ionospheric spatial decorrelation is to directly compute and remove ionospheric errors using GPS dual frequency measurements. As a major focus of the GPS modernization program, new civil signals (i.e., L2C and L5) are being phased in as the United States (US) Air Force launches new GPS satellites [15]. However, it requires deploying a sufficient number of satellites which broadcast L5 signals in an Aeronautical Radio Navigation Service (ARNS) band. Moreover, a transition from single frequency GBAS to dual frequency GBAS involves a long process of safety assessment and system design approval. These constraints make this method difficult to implement in the near future.

An approach we propose in this paper is to reduce the conservatism of the current threat model by utilizing an external source of space weather prediction. We can possibly lower the bound of the threat model if predictions of ionospheric activity indicate that ionospheric conditions are less severe than the pre-defined worst-case bound. This approach is possible if the level of ionospheric activity is classifiable and predictable (at least over periods of tens of minutes to hours) from measurable space weather conditions and the prediction is sufficiently reliable.

Space weather prediction technologies have been greatly advanced and matured in recent years. Several organizations including the Space Weather Prediction Center (SWPC) from the National Oceanic and Atmospheric Administration (NOAA) [16], the National Aeronautics and Space Administration (NASA) Space Weather Laboratory [17], as well as academic research groups provide reliable and enhanced prediction information in terms of accuracy, availability, and accessibility. They utilize space weather observations obtained from the existing space-based and ground-based systems such as the Advanced Composition Explorer (ACE) satellite [18] and the U.S. Geological Survey (USGS) magnetometers [19].

To utilize space weather prediction for forecasting ionospheric conditions, a precondition that should be verified is a strong relationship between space weather indices and ionospheric activity. Mendillo *et al.* [20] found that enhancements in total electron content (TEC) of the ionosphere coincided with increases in geomagnetic activity. Balan and Rao [21] also showed a correlation between geomagnetic storm intensity and the strength of ionospheric storms by examining TEC and peak electron density data at both low- and mid-latitudes. Lee *et al.* [22] examined a correlation between disturbance, storm time (Dst) and the standard deviation of ionospheric spatial gradients and the resulting correlation coefficient was very high during both nominal and ionospherically active days. However, the use of this information to potentially aid GNSS augmentation systems and users has not been thoroughly investigated. If the worst ionospheric threat can be related in advance to predicted space weather conditions, and the predictions are reliable to the required level of integrity, it would allow service to be enhanced.

This study presents a methodology of real-time ionospheric threat adaptation that adjusts the ionospheric threat model in real time instead of always using the same ‘worst-case’

threat model. We originally proposed the idea of utilizing space weather information for the real-time ionospheric threat adaptation in [22], and fully develop it in this paper by using 17 years of space weather data. The concept could be realized by establishing a relationship between space weather indices and ionospheric gradients, deriving an uncertainty model of space weather prediction error, bounding those prediction errors, and finally selecting threat models which are functions of bounded space weather prediction indices. This methodology when applied to GNSS-based aircraft landing systems would improve system availability, while requiring a minimal change to the existing ground facilities. The availability benefit is achievable because the lowered bound of the threat model would reduce or remove the inflation of the integrity parameters and consequently lead to the smaller confidence bounds of user position estimates. Section II introduces available space weather indices and selects a suitable index for real-time threat adaptation. A relation between the selected space weather index and the worst case ionospheric threat is then defined. Section III derives an uncertainty model of space weather prediction using historical data, and describes a method of bounding prediction errors to the required level of system integrity. Methods of utilizing pre-analyzed information regarding bounded prediction errors to determine appropriate threat model bounds are proposed in Section IV. Expected performance is evaluated in Section V by conducting an availability simulation. Section VI concludes this paper.

II. RELATION BETWEEN SPACE WEATHER AND IONOSPHERIC GRADIENTS

A. Space Weather Indices

Real-time ionospheric threat adaptation utilizes external information on space weather conditions to determine the corresponding threat model bounds on a periodic basis (e.g., every few minutes). The first step required to realize this concept is to select a suitable space weather index (or indices) that is strongly correlated with the ionospheric threats of concern while also considering accessibility, fast update rate, short latency, long lead time, etc. Many organizations provide space weather indices in the form of ‘real time’ and/or ‘prediction’ values. Table I lists three global space weather indices: disturbance, storm time (Dst), planetary K (Kp), and interplanetary magnetic field (IMF) Bz, which are known to be strongly correlated to ionospheric activity. The update rates of both real-time and prediction values and the lead time of prediction for indices provided by different organizations are presented in this table. ‘Lead time’ indicates the length of time between the broadcast of predicted data and the period for which the prediction is intended to be valid. As an example, the University of Colorado [23] provides predicted Dst updates every 10 minutes for the following hour at about 10 minutes past the hour. Therefore, the length of time from prediction generation to the future time that the predicted data references is about 50 minutes. In other words, the maximum ‘lead time’ in which we can take advantage of the prediction is roughly 50 minutes.

TABLE I
GLOBAL SPACE WEATHER INDICES

Para-meters	Real time/ Prediction	Organization	Update rate	Lead time
Dst	Real time	WDC, Kyoto Univ. [24]	Hourly	
		USGS [19]	1 min / 1 hour	
	Prediction	Univ. Colorado [23]	10 minutes	50 minutes
		NiCT, Japan [25]	Hourly	50 minutes
Kp	Real time	GFZ Potsdam [26]	3 hours	
		SWPC [16]	3 hours	
	Prediction	SWPC (WingKp) [16]	15 minutes	1 hour / 4 hours
IMF Bz	Real time	SWPC [16]	1 minute	

Among space weather indices listed in Table I, predicted data are provided for both Dst and Kp indices while only real-time data is available for IMF Bz. In general, longer lead times and shorter update rates are desirable for the purpose of this study. Thus, we select the predicted Dst data from the University of Colorado at Boulder [23] whose lead time and update rate are 50 minutes and 10 minutes respectively. The predicted Kp data with longer lead times of 1 hour/4 hours are provided by SWPC. However, the amount of predicted Kp data is limited because these data are archived for only a week after data generation. In order to derive an uncertainty model of predicted indices (which will be discussed in Section III), a large amount of data is necessary. The predicted Dst data from the University of Colorado are available for about 21 years (from 1995 up to the present time).

Real-time values of the hourly Dst index are available starting from 1957 at the World Data Center (WDC) for Geomagnetism at Kyoto University in Japan [24]. These ‘real time’ Dst values are typically revised after a few months and replaced with ‘provisional’ Dst. After about two years, the ‘provisional’ Dst is replaced with ‘final’ Dst. In this study, we assume that ‘final Dst’ represents the true value of Dst at the indicated times. Therefore, ‘final Dst’ values are used in Section III to derive an uncertainty model for the predicted values. Both final and predicted values of Dst from 1995 to 2011, inclusive, or a total of 17 consecutive years (this gives a total of 894,096 data points, as predicted values of Dst have a resolution of 10 minutes) are available.

B. Worst Case Threat as a Function of Space Weather Index

This section defines the worst case threat (in terms of bounding ionospheric gradient) as a function of the values

TABLE II
DATES INVESTIGATED FOR THE CURRENT CONUS THREAT
MODEL AND SPACE WEATHER INDICES [13]

Day (UT mm/dd/yy)	Kp	Dst
04/06/00	8.3	-287
04/07/00	8.7	-288
07/15/00	9.0	-289
07/16/00	7.7	-301
09/07/02	7.3	-177
10/29/03	9.0	-350
10/30/03	9.0	-383
10/31/03	8.3	-307
11/20/03	8.7	-422
07/17/04	6.0	-76

TABLE III
ADDITIONAL DATES SELECTED AND SPACE WEATHER INDICES [27]

Day (UT mm/dd/yy)	Kp	Dst
08/12/00	7.7	-235
09/17/00	8.3	-201
03/31/01	8.7	-387
04/11/01	8.3	-271
04/12/01	7.3	-236
11/06/01	8.7	-292
11/24/01	8.3	-221
11/21/03	6.7	-309
11/08/04	8.7	-374
11/09/04	8.7	-214
11/10/04	8.7	-263

of the selected space weather index Dst. We first analyze the relationship between the ‘final’ Dst and ionospheric gradients. Anomalous ionospheric gradients observed in CONUS during the last solar maximum period (2000 – 2004) were used for this study. The ten dates from which data were collected and analyzed to generate the current CONUS threat model are listed in Table II along with Kp and Dst indices [13]. Eleven additional dates were selected by applying predetermined criteria (days where the daily maximum value of Kp is greater than six or that of Dst is less than -200 nT [27]) to the data from 2000 to 2004, as shown in Table III. In order to identify large ionospheric gradients, we used the Long Term Ionospheric Anomaly Monitoring (LTIAM) software package developed to build, validate and update threat models over the life cycle of the system by monitoring ionospheric behavior continuously [27]. This tool focuses on estimating ionospheric delays and ionospheric gradient magnitudes and automatically detecting gradients large enough to be hazardous to users.

Fig. 2 shows the resulting threats (anomalous gradients) observed on the days listed in Tables II and III. Observations of individual events populate the ionospheric spatial gradient threat space, with gradient shown on the y-axis and the corresponding daily maximum value of ‘final’ Dst shown on the x-axis. The threat points identified previously (from the days in Table II) and included in the CONUS threat model are marked with circles. The maximum gradient among these points in the current model determined a constant upper bound of 425 mm/km with no Dst dependence. The newly discovered threat points from this data analysis are denoted with triangles.

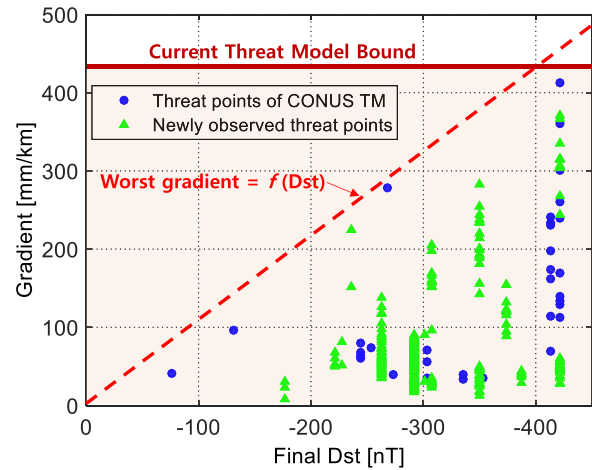


Fig. 2. Current LAAS CAT-I threat model bound which has the value of constant 425 mm/km regardless of space weather index (solid line) and newly defined worst-case ionospheric threat model as a function of ‘final’ Dst (dashed line).

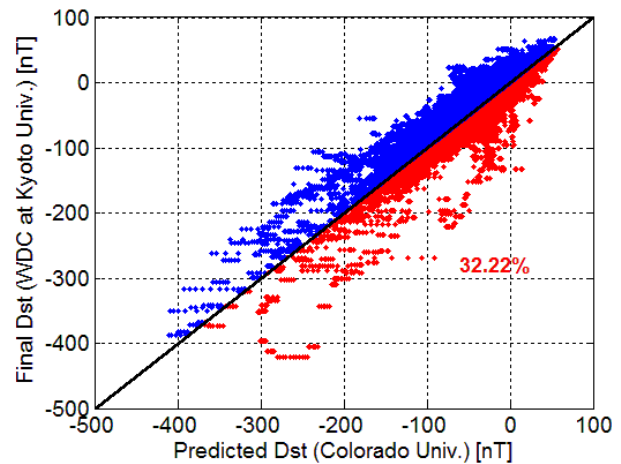


Fig. 3. Comparison of ‘final Dst’ vs. predicted Dst for data collected from 1995 to 2011. Approximately 32 percent of the predicted Dst values do not bound the final Dst values.

These include both additionally observed threat points by LTIAM from the dates listed in Table II and threat points discovered from the dates listed in Table III. Based on the identified threat observations, the maximum gradient which bounds all ionospheric spatial gradients as a function of the ‘final Dst’ is determined and is shown as the dashed line.

III. UNCERTAINTY MODEL OF SPACE WEATHER PREDICTION

A. Space Weather Prediction Errors

Space weather prediction is not free from errors that cause the predicted values to deviate from true values. Prediction errors exist due to several factors: inaccurate and inappropriate input measurements (e.g., solar wind measurements) to a prediction model; inaccuracies in a model due to a limitation on modeling magnetosphere; and the complex behavior of the space weather [28]. Fig. 3 shows the comparison of ‘final Dst’

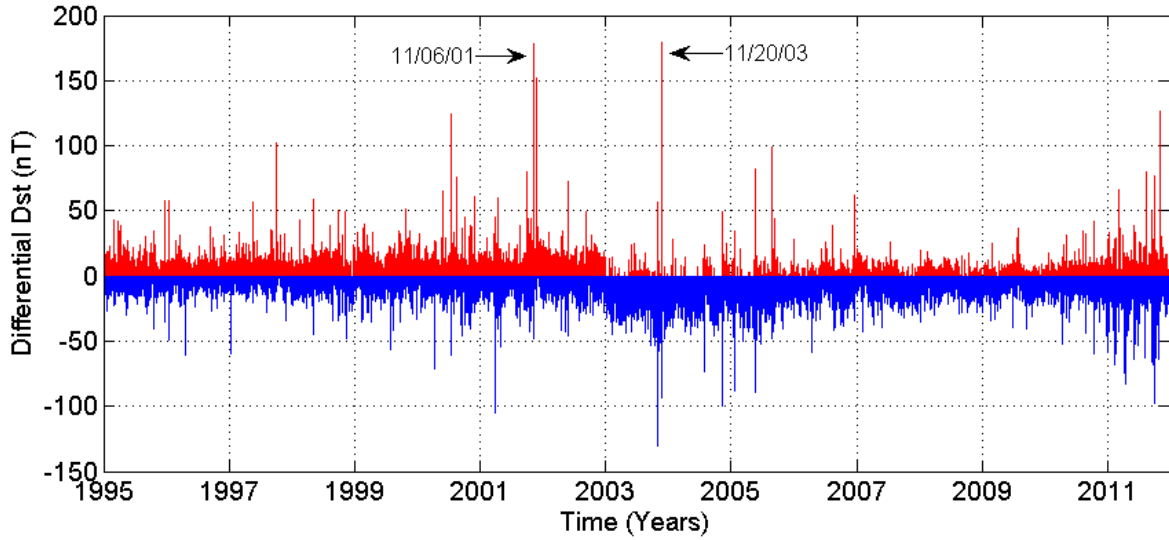


Fig. 4. Variations of computed DDst values over the seventeen consecutive years between 1995 and 2011. While most of the DDst values are close to zero, relatively large DDst values were observed from days on which ionospheric storms occurred (note that DDst values of 178.2 nT and 178.9 nT occurred on 6 November 2001 and 20 November 2003, respectively).

versus predicted Dst for the total number of 894,096 data points collected from 1995 to 2011.

The predicted Dst values provided by the University of Colorado at Boulder are plotted on the horizontal (x) axis, and the ‘final Dst’ values provided by WDC at Kyoto University are plotted on the vertical (y) axis. Again, we assume that the ‘final Dst’ represents the true Dst. A linear relationship between the predicted Dst and the ‘final Dst’ is shown in the two-dimensional scatter plot. However, the predicted Dst does not always bound the ‘final Dst’. In particular, approximately 32 percent of the predicted Dst values (those plotted in the lower right triangle) are larger than the corresponding ‘final Dst’, meaning that the prediction was optimistic and could introduce safety concerns if used directly.

To estimate the prediction uncertainty, we first determine the prediction errors, which are represented by ‘differential Dst’ (DDst) and are computed by subtracting the ‘final Dst’ from the predicted Dst at each epoch. Fig. 4 shows the variations of computed DDst values over the seventeen consecutive years between 1995 and 2011. While most of the DDst values are close to zero, relatively large positive DDst values were observed from days on which ionospheric storms occurred. Note that DDst values of 178.2 nT and 178.9 nT occurred on 6 November 2001 and 20 November 2003, respectively. Previous studies analyzed severe ionospheric disturbances observed during a geomagnetic storm on 6 November 2001 [29], [30]. During the superstorm on 20 November 2003, the largest ionospheric gradient in solar cycle 23 was observed in Northern Ohio [13]. While the final Dst reached -422 nT on 20 November 2003, a predicted Dst value of only -243.1 nT was reported; thus resulting in the largest DDst value of 178.9 nT in the seventeen years. If a bound on worst possible ionospheric gradients is derived based on a Dst predicted to be much less severe than the actual Dst, users could not be protected from potential threats. Therefore,

an uncertainty model for the predicted Dst values needs to be established.

B. Statistical Modeling of Space Weather Prediction Uncertainty

By using computed DDst values, a statistical analysis of prediction uncertainty is performed. First, DDst values are divided into five bins of predicted Dst in order to allow for variable behavior under different levels of ionospheric intensity while maintaining a sufficient number of samples per bin to obtain reliable statistics as in (1)

$$\begin{aligned} \text{bin 1: } & 100\text{nT} > \text{predicted Dst} \geq 0\text{nT} \\ \text{bin 2: } & 0\text{nT} > \text{predicted Dst} \geq -25\text{nT} \\ \text{bin 3: } & -25\text{nT} > \text{predicted Dst} \geq -75\text{nT} \\ \text{bin 4: } & -75\text{nT} > \text{predicted Dst} \geq -175\text{nT} \\ \text{bin 5: } & -175\text{nT} > \text{predicted Dst} \geq -500\text{nT}. \end{aligned} \quad (1)$$

The boundaries of the bins in (1) were determined based on the confidence intervals for the mean ($\hat{\mu}_{DDst}$) and the standard deviation ($\hat{\sigma}_{DDst}$) of DDst in each bin. If DDst has a Gaussian distribution, a two-sided t-interval for μ_{DDst} and a χ^2 -distribution-based confidence interval for σ_{DDst} can be calculated with the $1-\alpha$ confidence level as shown in (2) and (3), respectively [31]:

$$\begin{aligned} \mu_{DDst} - \delta & \leq \hat{\mu}_{DDst} \leq \mu_{DDst} + \delta; \\ \delta & = \frac{t_{\alpha/2, n-1} \sigma_{DDst}}{\sqrt{n}} \end{aligned} \quad (2)$$

$$\begin{aligned} L & \leq \hat{\sigma}_{DDst} \leq U; \quad L = \sqrt{\frac{(n-1)\sigma_{DDst}^2}{\chi_{\alpha/2, n-1}^2}}; \\ U & = \sqrt{\frac{(n-1)\sigma_{DDst}^2}{\chi_{1-\alpha/2, n-1}^2}} \end{aligned} \quad (3)$$

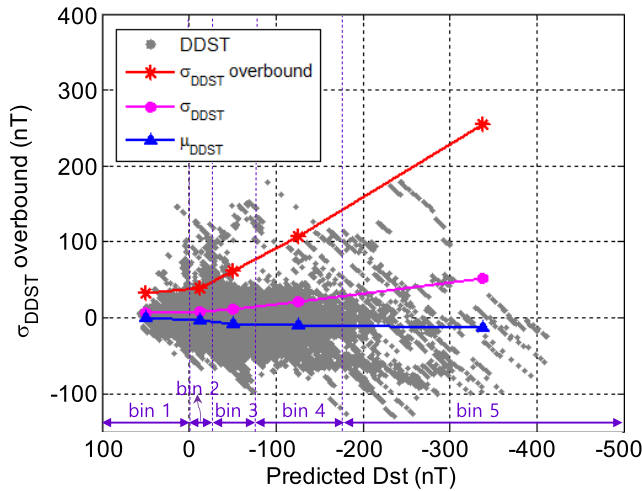


Fig. 5. Estimated mean, standard deviation, and overbounded standard deviation of DDst for each bin.

where μ_{DDST} and σ_{DDST} are the sample mean and sample standard deviation computed using the n samples of DDst in each bin. The upper and lower boundary values of each bin were chosen to have both the margin of the $\hat{\mu}_{DDst}$ estimation error, δ , and the margin of the $\hat{\sigma}_{DDst}$ estimation error, $(U - L)/2$, to be less than 1 nT with a confidence level of $1 - 10^{-7}$. A larger number of samples would allow us to obtain reliable statistics by contributing to a smaller confidence interval. However, the size of bins should not be increased excessively to collect more samples because it results in mixing different distributions under various ionospheric conditions. The sensitivity of the number and the boundary values of bins to prediction uncertainty modeling will be further investigated in future work when more data especially under severe ionospheric conditions become available.

Second, the DDst samples are nominalized by using the sample mean and the sample standard deviation of DDst in each bin. The estimated mean (the curve with triangles) and one sigma values (the curve with circles) of DDst are shown with a scatter plot of DDst in Fig. 5. The assumption of a Gaussian distribution was applied only to determine the bins of predicted Dst in (1), but the DDst values are not normally distributed. Lastly, the ' σ_{DDST} overbound' (the curve with asterisks) is thus computed for each bin to take into account the non-Gaussian tails of the normalized DDst distribution. Detailed steps for the σ_{DDST} overbounding method are described in the following paragraphs.

Fig. 6 shows a folded cumulative distribution function (CDF) for normalized DDst values (the curve with dots) in log scale. The folded CDF is a graphical representation obtained by folding down the upper half of the cdf where probabilities are greater than one half. In other words, one minus probabilities are plotted on a y-axis for the part with probabilities from 0.5 to one. This modified-CDF plot looks like a PDF plot in that both lower and upper parts of the distribution trend toward a probability of zero, but the plot shows the cumulative probabilities that we need to bound in the tails instead of the probability density values. Thus, this plot drawn in log scale makes it easy to confirm that the tails are properly

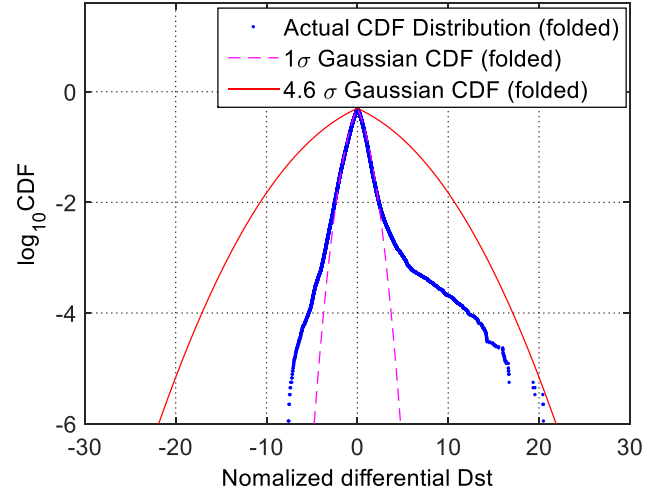


Fig. 6. Folded cumulative density function of normalized DDst.

bounded in the CDF domain, which is where the bounding requirement applies. The CDF bounding method overbounds error distributions reliably and conservatively as shown by previous studies and is currently used for the certification of GNSS augmentation systems [32]. The normalized DDst values are computed by removing their means and dividing them by their standard deviations, which were computed separately for each bin. It is clearly seen that the distribution (the curve with dots) derived from the computed DDst shown in Fig. 5 has non-Gaussian tails. The prediction uncertainty is modeled as a Gaussian distribution which is commonly used in GNSS augmentation systems because of its simplicity for defining the error distribution with only two parameters (its mean and standard deviation). Thus, the non-Gaussian tails must be appropriately overbounded by a Gaussian distribution with an inflated standard deviation.

It is noteworthy that the actual distribution in Fig. 6 has thicker and broader right side non-Gaussian tails, where the predictions were optimistic, compared to the left side tails. If a zero-mean Gaussian distribution were assumed to model the prediction uncertainty, the nominal sigma (1σ) of a zero-mean Gaussian distribution (the dashed curve) would have to be inflated to cover the non-Gaussian tails of the actual distribution, especially non-Gaussian tails in the right side which may raise safety concerns. The inflation factor (f) bounding the distribution to the level of a probability of $1 - 10^{-6}$ is determined as shown in Fig. 6 to take into account worst-case prediction errors and the inflated distribution is also shown in the same figure (solid line). The ' σ_{DDST} overbound' is then computed as $|\mu_{DDST}| + f \cdot \sigma_{DDST}$ for each bin by applying an inflation factor of approximately five as shown in Fig. 5 (the curve with asterisks). It is seen that the determined ' σ_{DDST} overbound' increases as the absolute value of the predicted Dst increases, implying that we need to consider larger uncertainty on prediction as the predicted Dst decreases.

C. Bounding Prediction Errors for Assurance of Aviation Safety

The resulting ' σ_{DDST} overbound' from Section III-B is then used to compute bounded prediction errors to the required level

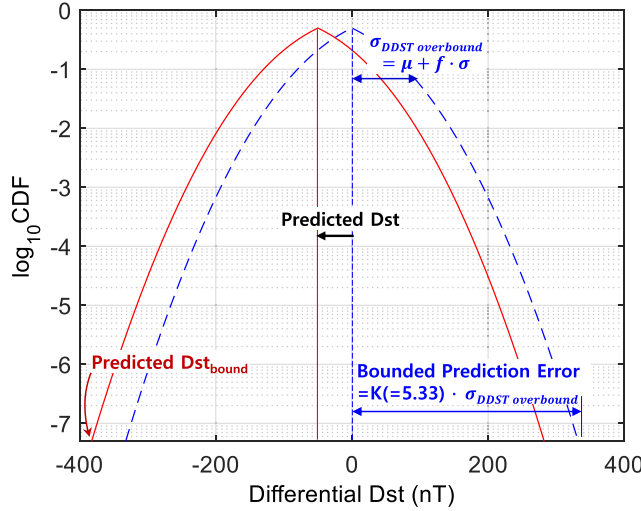


Fig. 7. A graphic example of computing Predicted Dst_{bound} for a bin 3 ($-25 \text{ nT} > \text{predicted Dst} \geq -75 \text{ nT}$) with a probability of $(1 - 10^{-7})$.

of integrity by multiplying σ_{DDST} by a K factor. Here, the K factor is defined to satisfy (4), where z has a standard normal distribution and x denotes the required level of integrity. In this study, we use a K factor of 5.33 to meet the required level of integrity of $1 - 10^{-7}$

$$P(-K \leq z \leq K) < x. \quad (4)$$

We then determine bounded predicted Dst, or the 'predicted Dst_{bound}', by subtracting the bounded prediction errors from the predicted Dst, as shown in (5)

$$\text{Predicted Dst}_{\text{bound}} = \text{Predicted Dst} - K \cdot \sigma_{DDST} \text{ overbound}. \quad (5)$$

Fig. 7 shows a graphic example of computing the predicted Dst_{bound} for a 'bin 3' ($-25 \text{ nT} > \text{predicted Dst} \geq -75 \text{ nT}$). The dashed curve represents a folded CDF with one sigma value of σ_{DDST} overbound. The bounded prediction error (double-headed arrow) is then determined by multiplying the K factor by the computed σ_{DDST} overbound. Lastly, the predicted Dst is applied by moving the dashed CDF curve to the left with the magnitude of the predicted Dst. The Predicted Dst_{bound} can be read from the solid CDF curve where the curve meets the corresponding CDF probability of $(0.5 \cdot 10^{-7})$.

Fig. 8 shows the 'predicted Dst_{bound}' of given predicted Dst values for each corresponding level of integrity from 0.68 ($K=1$, curve with asterisks) to $1 - 10^{-7}$ ($K=5.33$, bolded curve with circles). The bounded predicted Dst with a level of integrity of $1 - 10^{-7}$ (where K is equal to 5.33) is shown as the bolded curve with circles. This means that the 'final Dst' shall not exceed the 'predicted Dst_{bound}' with a probability of $1 - 10^{-7}$ for given predicted Dst values.

IV. REAL TIME THREAT ADAPTATION

A. Threat Model Determination Based on the Bounded Predicted Dst

Values of bounded predicted Dst with an integrity probability of $1 - 10^{-7}$ are used to determine corresponding threat

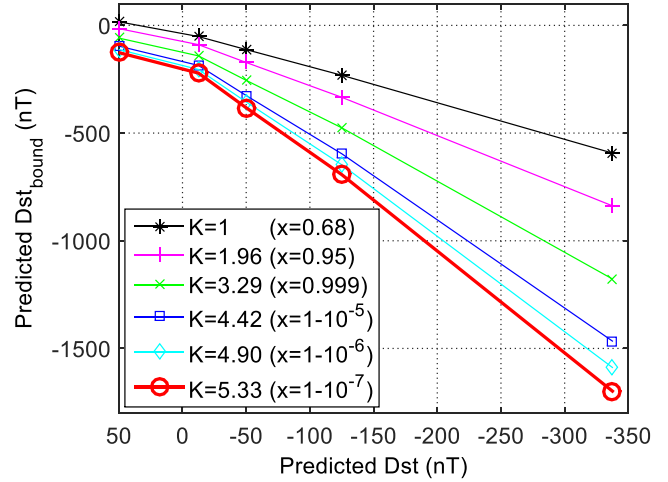


Fig. 8. Predicted Dst_{bound} for each corresponding level of integrity from 0.68 when K factor is 1 (curve with asterisks) to $1 - 10^{-7}$ when K factor is 5.33 (curve with circles). Predicted Dst_{bound} is determined by subtracting the bounded prediction errors from the corresponding predicted Dst.

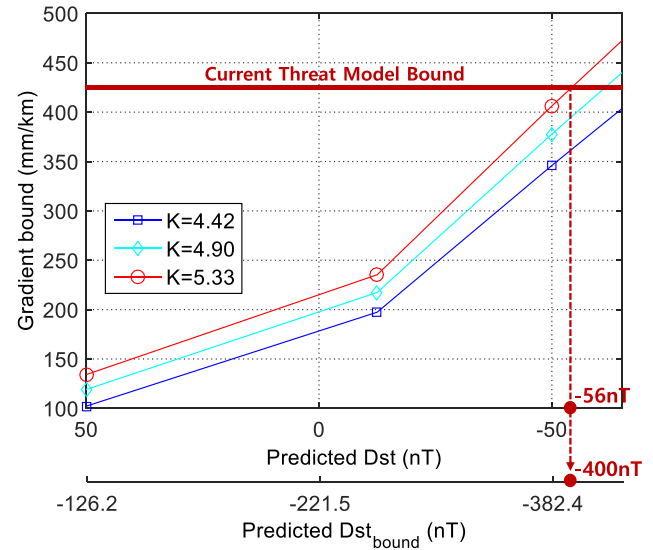


Fig. 9. Gradient bound as a function of predicted Dst and predicted Dst_{bound} for different integrity levels. A predicted Dst of -56 nT corresponds to a bounded predicted Dst of -400 nT with 10^{-7} confidence (dashed arrow). The upper gradient bound of 425 mm/km in the CONUS threat model can be lowered if the predicted Dst is greater than -56 nT .

bounds in real time based on pre-defined worst-case gradient as a function of final Dst. In Section II-B, the worst gradient was determined to have the value of 425 mm/km when the final Dst is -400 nT or lower. Using our prediction uncertainty model, a predicted Dst of -56 nT corresponds to a bounded predicted Dst of -400 nT with 10^{-7} confidence. This suggests that the upper gradient bound of 425 mm/km in the CONUS threat model can be lowered if the predicted Dst is greater than -56 nT (within the window of applicability of the prediction).

Fig. 9 represents the gradient bounds determined as a function of predicted Dst and corresponding predicted Dst_{bound} for several different integrity requirements (K-values) in consideration of the prediction uncertainty. The bolded line with circles shows the determined gradient bound with an integrity probability of $1 - 10^{-7}$ ($K = 5.33$ from the standard

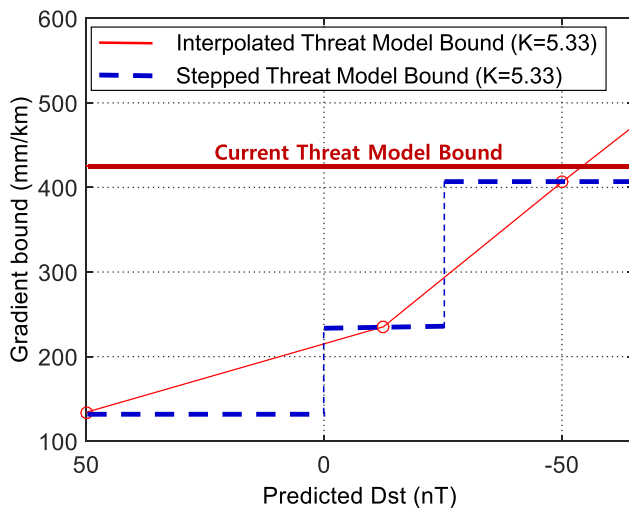


Fig. 10. Linear interpolation method and Stepped (bin-based) gradient bound method for practical operation of real-time threat adaptation. For the former case, a revised gradient bounding any value of predicted Dst greater than or equal to -56 nT can be determined by interpolation. For the latter case, a total of three gradient bounds of 135 mm/km, 235 mm/km, and 406 mm/km would be used depending on the predicted Dst value.

Gaussian distribution). As expected, the current constant gradient bound of 425 mm/km can be lowered significantly when the predicted Dst value is greater than -56 nT.

B. Approaches for Practical Application of Real-Time Ionospheric Threat Adaptation

The adaptive gradient bounds shown in Fig. 9 are represented based on a linear interpolation approach between the determined center points of each defined bin of predicted Dst used to derive these bounds. Therefore, great care must be taken in the practical application of real-time ionospheric threat adaptation. This paper suggests two potential approaches for applying these results in practice. First, linear interpolation is the simplest way to formulate a continuous threat bound, and this is simply represented in Fig. 10. A revised gradient bounding any value of predicted Dst greater than or equal to -56 nT can be determined by interpolation. However, linear interpolation contains uncertainties because it cuts ‘in between’ the center points that represent each bin of predicted Dst data. As a result, the predicted Dst bound (shown in Fig. 8) derived for a single bin of data is not guaranteed to hold for a linear interpolation within the bin. Therefore, the safety of this linear interpolation approach needs further validation.

Fig. 10. Linear interpolation method and Stepped (bin-based) gradient bound method for practical operation of real-time threat adaptation. For the former case, a revised gradient bounding any value of predicted Dst greater than or equal to -56 nT can be determined by interpolation. For the latter case, a total of three gradient bounds of 135 mm/km, 235 mm/km, and 406 mm/km would be used depending on the predicted Dst value.

A second method is to adopt the stepped threat slope bounds determined for each bin of predicted Dst. We now consider the determined gradient bound of each bin as the gradient bound for the whole range of the corresponding bin of predicted Dst.

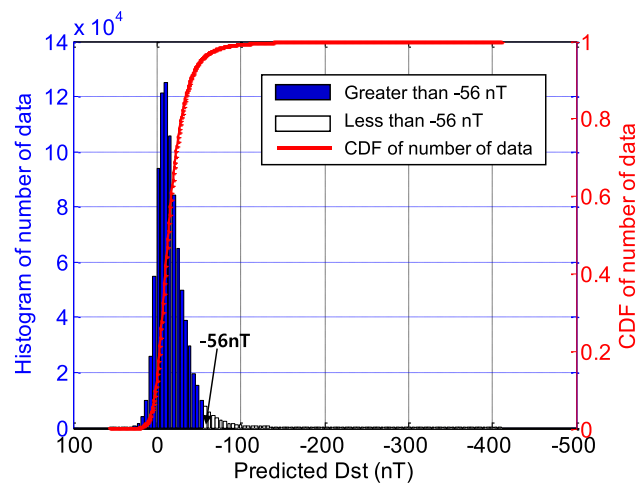


Fig. 11. Histogram and CDF of the number of data points as a function of predicted Dst. Approximately 95 percent of predicted Dst values were greater than -56 nT from 1995 through 2011. This suggests that real-time ionospheric threat adaptation would allow the worst-case gradient bounds to be lowered about 95 percent of the time.

For example, a gradient bound of 135mm/km would apply for the whole range of the corresponding bin of predicted Dst greater than 0 nT, as shown in Fig. 10. As a result, a total of three slope bounds of 135 mm/km, 235 mm/km, and 406 mm/km would be used depending on the predicted Dst value. This approach enables users to select a corresponding threat model in real time from one of several pre-determined models. Further consideration of the best methodology for applying real-time ionospheric threat adaptation is required.

V. AVAILABILITY ANALYSIS OF REAL TIME THREAT ADAPTATION FOR CONUS THREAT MODEL

To see how much benefit can be obtained from the lowered gradient bound using real-time threat adaptation, the distribution of predicted Dst over the 17-year data period was investigated. Fig. 11 shows the histogram and CDF of number of data points as a function of predicted Dst. The left-hand-side vertical axis represents the number of data points, while the right-hand-side vertical axis represents the corresponding CDF. One notable result from this figure is that approximately 95 percent of predicted Dst values were greater than -56 nT from 1995 through 2011, suggesting that real-time ionospheric threat adaptation would allow the worst-case gradient bounds to be lowered about 95 percent of the time.

VI. CONCLUSION

The real-time ionospheric threat adaptation method developed in this paper was shown to successfully reduce conservatism contained in current GBAS systems which make no use of external information regarding ionospheric conditions. Using an appropriate predicted space weather index indicating ionospheric conditions sometime in the near future, it was possible to adjust the ionospheric threat model bounds in real time while assuring the required level of integrity. This has been achieved in four steps in this study: 1) finding a suitable space weather index; 2) establishing a relationship

between the space weather index and ionospheric gradients; 3) analyzing the uncertainty of the space weather prediction; and, 4) determining adaptive threat model bounds based on the bounded space weather prediction index. The performance of the revised, adaptive threat model was assessed for the CAT I GBAS in CONUS. The upper bound of the current CONUS threat model (425 mm/km) was lowered 95% of the time even though prediction error bounding with an integrity requirement of $1 - 10^{-7}$ considerably inflated the value of predicted Dst_{bound} and weakened the credit that can be taken for Dst predictions.

Using this real-time adaptation methodology, we can improve the level of availability of GBAS operations and its other intelligent air transportation applications including UAS autonomous navigation. This possibility may extend to single-frequency-based Satellite-Based Augmentation Systems (SBAS) as well. It is also applicable to the GBAS differentially corrected positioning service (DCPS), which provides differentially corrected latitude, longitude, velocity, and time for a range of applications beyond precision approach and landing. As space weather predictions become more available and reliable, their benefits to the GNSS-based aircraft landing system performance should continue to grow. For further study, more detailed evaluation of the performance and availability benefits from using adaptive ionospheric threat modeling is planned.

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APPENDIX D

Guidance, Navigation, and Separation Assurance for Local-Area UAV Networks: Putting the Pieces Together

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Jiyun Lee
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ABSTRACT

This paper examines the guidance methodology needed to implement networks of autonomously-flown unmanned aerial vehicles (UAVs) controlled by centralized ground stations (GSs). The intended operations would take place within a local area with a diameter of less than 10 km for most applications but potentially as large as 50 - 100 km. UAVs in these networks are envisioned to be potentially quite small and inexpensive but capable of automated flight orientation and stability with guidance updates provided by the GS at 0.5 to 2 second intervals. The GS also provides GNSS differential corrections and integrity information to support sub-meter-level 95% navigation accuracy with 10^{-7} error bounds in the 3 - 10 meter range. Position and timing solutions for each UAV are relayed back to the GS and support both operational (route planning) and tactical (path updating) guidance. This guidance needs to insure safe separation between UAVs within the network and (depending on the airspace used) separation from "out-of-network" UAVs as well as manned aircraft.

The proposed guidance approach centers around "zones of influence" surrounding each UAV that include allowances for navigation error, UAV guidance error, and ground-system guidance error. The amount of error allocated to each error source depends upon the degree of error correlation between each UAV and its neighbors as well as the required probabilities of safe separation that must be maintained. The ground system maintains and updates zones of influence for each UAV within its operational area and guides each UAV it controls to remain within a "zone of operations" to insure that all UAV movements it commands avoid collisions with other vehicles or the ground. This paper provides examples of how this is done and how adjustments are made to reflect changes in navigation performance and the influx of UAVs operating outside the network.

1.0 Introduction to UAV Network Concept

A large number of applications have been proposed for unmanned aerial vehicles (UAVs). Today, some of these applications, such as taking pictures and monitoring particular locations on the ground, have been implemented to a limited degree with remotely-piloted UAVs operated singly in or small groups. However, requiring each UAV to be controlled by a human pilot who must carry out the UAVs mission while monitoring for and maintaining safe separation from other vehicles greatly constrains the number of vehicles that can participate safely and cost-effectively. Obtaining the full benefits of these applications will most likely involve UAVs operating autonomously and coordinating their activities in large groups. This is particularly true for data-collection and monitoring over large areas.

Several examples of applications that are suited for networks of autonomous UAVs are presented in [1]. The simpler of these use the potential cost-effectiveness of autonomous UAV networks to obtain results more quickly and cheaply than existing methods using piloted aircraft or remotely-piloted UAVs. Photography and other forms of passive data collection are good examples, as the data is either not needed in real time or is independent of mission planning. For example, piloted aircraft are used today in major metropolitan areas to monitor road traffic conditions during busy periods. UAV networks could do this job better and more cheaply simply by allowing both denser and more widespread coverage. The outputs of UAV monitoring would be used in near real time to display traffic conditions and warn of accidents and bottlenecks, but the changes to traffic conditions would not require real-time changes in UAV positions or monitoring patterns. Thus, high-level changes to UAV guidance, such as repositioning and UAV air traffic control could be handled by ground personnel, although effective autonomous guidance would be much more cost-effective.

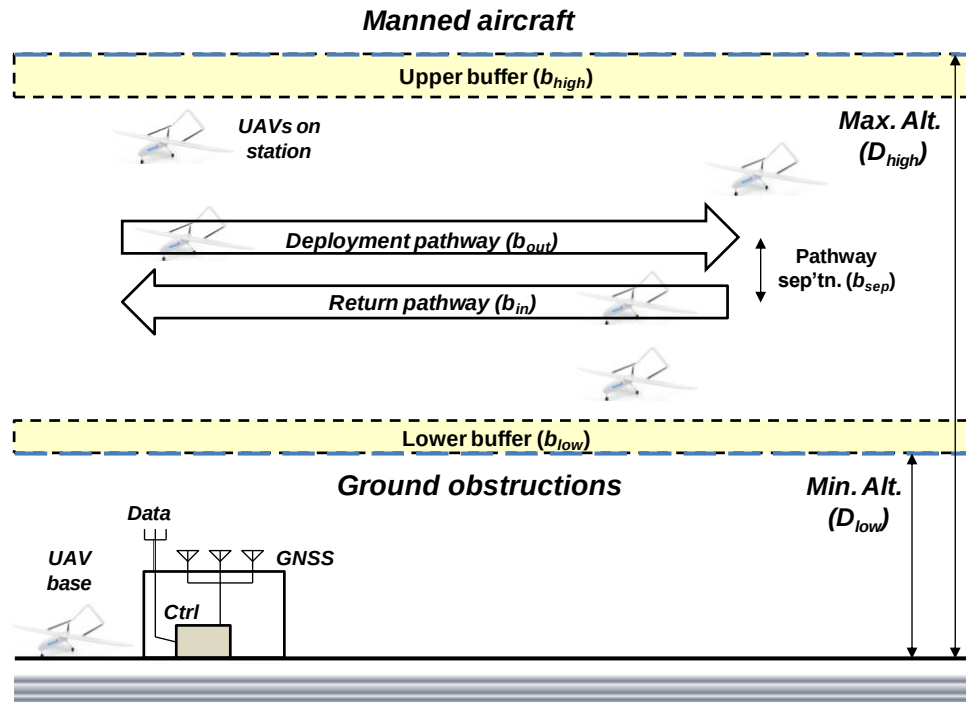


Figure 1: Local-Area UAV Network - Conceptual Diagram [1,2]

Other applications described in [1], such as reconnaissance and surveillance, would place much greater demands on human guidance and would therefore require autonomy guidance for most, if not all, guidance functions. In a surveillance application such as monitoring for potential lawbreaking at a large shopping center or subdivision of houses, UAVs would be spread out in a standard patrol pattern most of the time. When suspicious activity is detected, it would be desirable to reposition several UAVs in real time to get a better view of the area that generated alert to confirm if it is suspicious and, if so, to follow the object of concern until security personnel can arrive. On a small scale, this repositioning could be handled by humans, but as the scale expands to kilometers, most of it will need to be done automatically.

This paper expands on the local-area UAV network concept outlined in [1,2] to explain how autonomous guidance of the type described here can be implemented. Section 2.0 provides an overview of this concept, including the use of local-area differential GNSS (LADGNSS) navigation [1] and the derivation of safe separation standards [2]. Section 3.0 describes how the navigation and guidance error models for individual UAVs are combined with the separation standards to generate multiple "zones of influence" (ZoIs) for each UAV that represent the region around each UAV that must be kept clear to avoid collisions. Section 4.0 describes how the current activities of each UAV are reflected in "zones of operation" (ZoOs) that represent the region within which each UAV is allowed to maneuver while performing a particular activity. Section 5.0

describes how zones of influence and operation work together under nominal ("status-quo") conditions to assure that the overall mission is carried out safely. Section 6.0 describes how these zones are used to manage guidance under off-nominal conditions. Section 7.0 addresses the complications of sharing airspace with other users, including other UAV networks (with separate controllers) and manned aircraft. Section 8.0 summarizes the paper and described the next steps in refining this guidance methodology.

2.0 Local-Area UAV Network Concept

Figure 1 illustrates the concept of local-area UAV network operations developed in [1,2]. The control station shown at the lower left is the source of local-area differential GNSS corrections and integrity information as well as real-time guidance for each UAV in the network. The LADGNSS and guidance information are separate data messages combined in the same outbound transmission. The guidance function also requires feedback from each UAV in real time, including its current position and velocity. Therefore, a two-way datalink is required and is used to relay GNSS information (such as position-domain protection levels) as well as position and velocity from UAVs to the control station. The maximum operational range of a single network of this type is limited by many factors, including the effective range of the datalink and the range beyond which LADGNSS errors grow unacceptably or become too difficult to reliably detect [1].

Most individual UAVs are “on station,” meaning that they are stationary or nearly so and are observing the ground and/or the nearby environment. Under normal conditions, UAVs on station are spread out enough to ensure safe separation among themselves, manned aircraft, and ground obstructions while providing enough density to perform the observation mission assigned to them. Each UAV “flies itself” in the sense that it is responsible for its own attitude control, station-keeping, and path-following (when the GS commands a movement to a new location).

Several events might require one or more UAVs to divert from their normal stations. Because the endurance of each UAV is limited, the ground control station (hereafter simply referred to as “ground station,” or “GS”) must recover, refuel, and re-launch UAVs periodically at a site near the ground station. To support this, specific pathways in space are defined to separate deploying and returning UAVs from those on station. These pathways can also be used to transition UAVs from one “on-station” location to another if called for by normal mission operations or the need to reinforce a region where an alert has been generated. While most recoveries are planned in advance based on GS monitoring of the endurance of each UAV, failures of individual UAVs may require sudden, unexpected recovery. For example, a UAV that suddenly loses partial engine power may be able to be recalled along the recovery path if it can still control itself and fly safely. If all power is lost, the GS must determine where the vehicle can land and guide it to land in the safest possible location that is physically reachable. In general, “landing in place” will be the most common form of recovery when safe, guided flight becomes impossible.

Another need for repositioning arises from unexpected degradation of navigation or guidance quality, both of which are monitored by the GS using the UAV-to-ground datalink. If, for example, the LADGNSS measurement quality suddenly degrades significantly on one or (likely) more UAVs, the distances required for safe separation increase correspondingly, and this may require multiple UAVs to autonomously move in such a way as to avoid each other under new, tighter, geometry constraints. The new separation requirements will be reflected in updated, larger zones of influence (ZoIs) for each affected UAV, as described in Section 3.0. The GS must use these revised ZoIs to quickly determine the maneuver that restores acceptable safety with the least overall disruption to the mission (see Section 6.0).

The largest challenge to automated GS guidance is probably the unexpected intrusion of manned aircraft or UAVs not controlled by the GS (called “out-of-network” UAVs, as opposed to the “in-network” UAVs controlled by the GS). The most complex problem is the arrival of multiple out-of-network UAVs in the same operating region as the in-control UAVs. Without the ability to

control intruding out-of-network UAVs, the GS needs some means to gain information about the location and intentions of out-of-network UAVs so that it can execute maneuvers to maintain safe separation in a reasonable amount of time. The same requirement (with a higher level of criticality) exists with manned aircraft, but usually no more than one manned aircraft will intrude at any given time.

This concept of autonomous UAV operations assumes “uncontrolled airspace” in the terminology of air traffic control. That is, each UAV is free to fly around as it chooses or is guided to without being required to follow the commands of external human controllers. In Figure 1, the airspace where UAVs may operate is separated from manned aircraft (including uncontrolled and controlled varieties of manned airspace) by an upper altitude limit. While it is unlikely that manned and unmanned aircraft can be separated completely in this manner, this division allows us to focus on the challenges of autonomously operating many UAVs in the same airspace. It would be almost impossible (and certainly not cost-effective) to attempt to provide real-time human control of multiple non-cooperating UAV networks in the same region and to replicate this everywhere that UAVs fly. If this were attempted, it would need to address the reality that non-cooperating UAVs may attempt to occupy the same airspace and therefore need external supervision to fairly separate them, as opposed to the operators of each system being tasked to allocate airspace in real time.

3.0 UAV Zones of Influence (ZoIs)

3.1 Definition of Zones of Influence

The concept of a “zone of influence” comes from the networked-UAV separation criteria derived in [2]. Figure 2 (from [2]) shows how the UAV and target (potential collision object) errors are defined. The uncorrelated components of these errors combine to define a buffer zone that must remain unoccupied for collisions to remain sufficiently improbable based on the risk assessment methodology in [2] (for other examples of risk-based approaches, see [3,4]). The error sources relevant to a given in-network UAV are (a) navigation error; (b) path-following error; and (c) guidance error. “Navigation error” represents the deviation of the reported position from the true position. “Path-following error” represents the guidance (control) error due to the UAVs inability to fly its own desired path (the path determined locally by the UAV to follow the GS guidance). “Guidance error” represents the UAV guidance (control) error due to imperfections in GS guidance, including primarily the error in representing the ideal path determined by the GS to the UAV. In practice, guidance error is small and is hard to distinguish from path-following error, but it is defined separately because it affects all UAVs in a

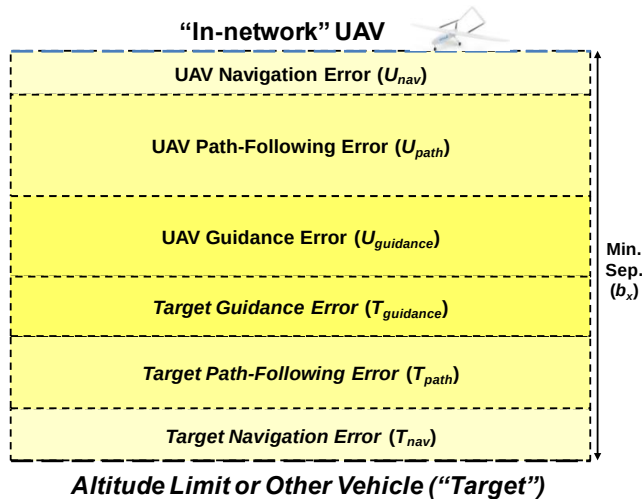


Figure 2: Elements of Required Separation [2]

manner different than path-following error and can be distinguished from path-following error under some circumstances, including sudden maneuvers.

To form a zone of influence for a particular UAV relative to a particular target, the uncorrelated components of the six error sources in Figure 2 are convolved to construct ellipsoidal (3-D Gaussian) error models, which are then extrapolated to the required separation probability for the particular target being considered. These individual errors are typically zero-mean and thus concentric around the estimated position of the UAV, but are not necessarily so. Also, these errors are not represented separately beyond the notional one-sigma level. Instead, conservative one-sigma representations of each error source (i.e., Gaussian distributions that bound rare-event errors using one-sigma values that larger than the nominal one-sigma values) are convolved together to form a single one-sigma bounding ellipse, and this ellipse is extrapolated to bound the separation probability required for a given target.

Since each ZoI reflects collision risk relative to a particular type of target, each UAV actually possesses multiple ZoIs at any given time, and these ZoIs change with time as the UAV and nearby vehicles move. For example, a single UAV "on-station" has a ZoI relative to neighboring in-network UAVs, including those "on-station" and those moving for any reason. It has a separate ZoI with respect to the ground, a separate ZoI with respect to the upper altitude limit, and at least one separate ZoI for each out-of-network UAV that is nearby, if any. These ZoIs are not the same for two reasons [2]. First, the required probabilities of safe separation are generally different for different classes of targets. Second, the error models themselves differ because the degree of error correlation differs. In particular, both navigation and path-following errors are highly correlated

Error Source	Bounding Sigma (meters)
User navigation	0.2
User path-following	0.6
User guidance	0.3
Target navigation	0.2
Target path-following	0.6
Target guidance	0.3
RSS	1.0

Very highly correlated

Highly correlated

Figure 3: Example 3-D Error Budget for Two In-Network UAVs [2]

Error Source	Bounding Sigma (meters)
User navigation	1.5
User path-following	2.0
User guidance	1.0
Target navigation	3.0
Target path-following	4.0
Target guidance	N/A
RSS	5.7

Potentially correlated, but assumed independent

Figure 4: Example Vertical Error Budget for One In-Network UAV Relative to Manned Aircraft [2]

between in-network UAVs in close proximity to each other because GNSS and LADGNSS errors are highly correlated and because disturbances such as wind are also correlated. The degree of correlation that can be assumed with regard to out-of-network UAVs and manned aircraft is lower and depends on the degree to which the GS knows the characteristics of these other aircraft. Finally, non-moving targets such as the upper and lower altitude limits (protecting manned airspace and ground obstructions, respectively) don't have the same error sources and thus require different models (see [2]).

Figures 3 and 4 illustrates this situation using example error numbers from [2] for two scenarios. In Figure 3,

approximate bounding one-sigma errors are given for the separation of two UAVs in the same network. These numbers are very low because each error source is highly correlated between two UAVs that are using the same GNSS, the same differential corrections, the same guidance commands, and are experiencing the same external disturbances (since they need to be near each other for separation to be relevant). Note that the individual ZoIs of in-network UAVs relative to each other are based on the three error sources for a single UAV. The RSS of the three error sources for each UAV in Figure 3 is about 0.7 meters; thus all in-network UAVs have ZoIs relative to each other based on extrapolating from this RSS rather than the RSS of all six error sources (the latter would be "double-counting").

Figure 4, in contrast, shows example correlation-adjusted bounding error sigmas between an in-network UAV and a manned aircraft that might lie just above the upper altitude buffer shown in Figure 1. The errors here are much higher than in Figure 3 because, while there might be significant correlation between UAV and nearby aircraft errors (especially if both use the same GNSS), this cannot be taken for granted; thus error independence must be assumed. Also, the full burden of separation must be assumed by the UAV when the potential target is outside the network; thus the RSS of all five relevant errors shown in Figure 4 must be used to derive the ZoI for the UAV in this case. Since the resulting RSS of 5.7 meters is much larger than the one of 0.7 meters that applies to the case in Figure 3, the resulting ZoI will also be much larger.

Assuming zero-mean Gaussian error models can be relied upon to bound actual errors at the separation probabilities required, the computation of ZoIs for each separation scenario mirrors that of zero-mean (or "fault-free") protection levels for GNSS navigation [6]. In this case, the magnitude of the ZoI in a given position axis can be modeled as:

$$ZoI_x = K_{ffmd} \Sigma_x$$

where Σ_x represents the bounding one-sigma error in dimension x generated by convolving the individual error sources from Figure 2, and K_{ffmd} represents the scalar multiplier needed to extrapolate a bounding one-sigma value to the required separation probability based on the standard (zero-mean) Gaussian distribution. Applying this equation to the numbers in Figures 3 and 4 and the relevant separation probabilities for these two scenarios from [2] further emphasizes the difference between them. For two in-network UAVs, the suggested probability of 10^{-4} for each UAV gives $K_{ffmd} \cong 3.8$ from the standard Gaussian distribution, and multiplying this by the 3-D bounding error RSS for each UAV of 0.7 meters gives a ZoI of about 2.7 meters for each UAV in 3-D (meaning

the combination of horizontal and vertical dimensions). The more demanding probability of 10^{-7} for a UAV relative to manned aircraft gives $K_{ffmd} \cong 5.3$, and multiplying this by the vertical RSS of 5.7 meters from Figure 4 gives a ZoI in the vertical axis of about 30.2 meters (the 2-D horizontal ZoI would be about 25 meters) – an order of magnitude larger than the ZoI between in-network UAVs.

The key to understanding the impact of ZoIs on UAV guidance is that ZoIs between UAVs and all potential collision targets simultaneously and separately apply, rather than the largest ZoI always being the governing one. The ZoI representing separation from manned aircraft or the upper altitude limit (call this "ZoI_{air}") is typically the largest, but it is only a significant limiting factor on UAV guidance for UAVs operating near this upper limit. The same is true of the somewhat smaller value of ZoI with respect to UAVs operating close to the lower limit (call this "ZoI_{gnd}"). The primary constraint on most UAVs not close to either altitude limit will be the ZoI relative to other UAVs ("ZoI_{UAVin}"), particularly out-of-network UAVs ("ZoI_{UAVout}") if any are present.

For any UAV location and position axis, one of the above ZoI will dictate the separation that most constrains the guidance of that UAV. This is called the *limiting ZoI*, and it is the basis for determining Zones of Operation for airspace allocation, as explained in Section 4.0. To clarify this concept, consider the case with no out-of-network UAVs so that three ZoIs apply to each in-network UAV in the vertical dimension: ZoI_{air} = 30 m, ZoI_{gnd} = 20 m, and ZoI_{UAVin} = 2.5 m. If a given UAV is operating near the upper altitude limit, the 30-meter value of ZoI_{air} is the limiting ZoI for vertical positioning. If, instead, the UAV is far from the upper limit but is instead near the lower altitude limit, the 20-meter value of ZoI_{gnd} is limiting. Otherwise, the limiting ZoI is the 2.5-meter vertical ZoI between UAVs in the same network.

3.2 Real-Time Updating of ZoIs

Conservative "floor" values representing each ZoI that applies to in-network UAVs under nominal operating conditions can be computed ahead of time and used in designing the nominal guidance strategy, including the locations of "on-station" UAVs and the best pathways for launch, recovery, and transition of UAVs between stations. "Pre-optimization" of each local-area UAV network installation is vitally important to insure that normal operations support the desired mission objective without presenting any significant guidance burden to the GS. In addition, all likely anomaly and alerting scenarios can be simulated during pre-optimization to ensure that sufficient margin exists to handle them, both in terms of GS and datalink capability and airspace capacity.

The ZoI "floor" values for each target represent conservative bounds on typical UAV behavior, meaning that it is expected (based on simulation, previous experience, and initial on-site test operations) that these values exceed the actual ZoI values most of the time (preferably at least 90% of the time). These values can therefore be used by the GS in real time unless some condition changes that requires one or more ZoIs to be inflated. As noted above, under nominal conditions, the GS should be able to handle all guidance operations routinely, with lots of margin for contingencies.

One status change that affects ZoI is a degradation in the protection levels that are used to derive the navigation-error component of ZoI. A single UAV may experience this when one or more satellites are temporarily masked by the UAV or nearby terrain. If a problem occurs with GNSS itself, such as the unexpected loss or exclusion of signals from a GNSS satellite, all UAVs using that satellite for positioning (likely all UAVs in the network) will experience similar protection level increases and thus ZoI increases. The GS receives protection level updates from each UAV on a regular basis (at least once every 5 s) and receives an out-of-sequence alert when the protection level jumps by more than a certain percentage or grows to exceed a certain threshold; thus the GS can update its ZoIs quickly and then determine if repositioning is required to regain safe separation (this should be rare unless unusually large increases occur). Note that, while GNSS protection levels are normally computed for the rare-event probability to which safe separation must be assured, the one-sigma value of the protection level is used here to allow convolution with the other guidance errors that make up ZoI.

While GNSS navigation error statistics are relatively easy to monitor using protection levels, statistics of estimated guidance errors are also maintained by the GS to monitor for changes that would affect ZoIs. The UAV-to-ground datalink that provides protection levels for each UAV to the GS also provides estimated true position and velocity as well as the commanded position and velocity vectors derived by each UAV for station-keeping or path-following. The GS can therefore keep track of a moving average of the residuals between desired and achieved vehicle states for each UAV, and it uses this to update the path-following error distribution for that UAV if needed. This takes the form of a threshold test, in which the "floor" value for path-following error is used unless the threshold is exceeded, after which the path-following error sigma is progressively increased to track the test statistic. If the test statistic exceeds a certain upper threshold, the guidance quality becomes sufficiently suspect that recovery and replacement of that UAV is triggered by the GS. In addition, test statistics for each in-network UAV based on the difference between UAV-generated paths and the original GS guidance are derived

and combined to generate a running estimate of the overall guidance quality of the GS.

4.0 UAV Zones of Operation (ZoOs)

As stated before, the high-level goal of GS guidance is to maximize mission performance while maintaining sufficiently low risk of in-network UAV collisions with external vehicles or ground objects. The ZoIs computed and maintained for each UAV support the latter objective. To support the former objective, it is natural to define "zones of operation" or "ZoOs" for each UAV corresponding to the current activity being conducted by each UAV and the approximate location of each UAV, which determines which of its ZoIs are limiting. Each ZoO represents a rectangular volume surrounding (and containing) the limiting ZoIs and represents an allocation of airspace by the GS to the UAV included within it. The ZoO extends beyond the ZoI to provide maneuvering room for the UAV, allowing the UAV to move around to some degree without significantly affecting separation.

The amount of maneuvering room or "margin" that lies between the ZoI and ZoO boundaries is an important design parameter. This additional space is used to respond to disturbances or to optimize the performance of the mission. In addition, margin is needed to allow for delayed reaction of the GS to contingencies that require actions to maintain separation, such as another UAV that "blunders" into the ZoO of a given UAV. As with human air traffic controllers, time is needed both for the GS to decide on the appropriate response and to communicate it to affected UAVs. Increasing this margin eases the guidance and datalink requirements on the GS at the cost of lower airspace utilization, as larger ZoOs (give the same ZoIs) provide room for fewer UAVs in the same volume of space. Note that, when UAVs are maneuvered, it is acceptable for ZoOs to overlap as long as these events are infrequent and as long as the ZoIs inside them are not violated.

Figure 5 shows an example of how ZoOs are placed around limiting ZoIs for a network of UAVs focused on ground observations. In this figure, four UAVs are shown "on station" near the lower altitude limit to be as close as possible to the ground. Two other UAVs are shown in the process of deployment to an "on-station" location and recovery back to base. For the "on-station" UAVs, vertical separation is limited by the nearby lower altitude limit. Horizontal separation is theoretically limited by other UAVs, but this limit is not stressed due to the low density of UAVs "on station" (note that the figure is not drawn to scale, or the difference between vertical and horizontal ZoIs would be greater). Because the deployment and return pathways are deliberately located far from the upper and lower altitude limits, UAVs in these pathways have ZoIs limited only by other UAVs.

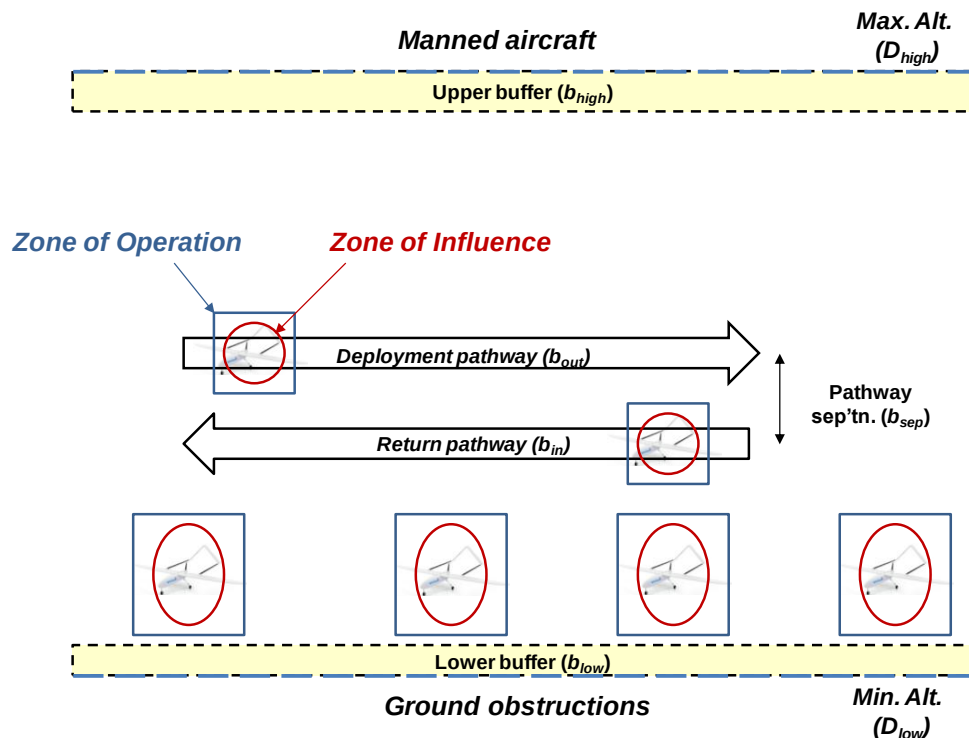


Figure 5: Zones of Operation and Influence for Example Geometry of UAVs under Nominal Conditions

5.0 UAV Guidance Under Nominal Conditions

As noted several times previously, the GS should be able to maintain operations indefinitely under nominal conditions with minimal burden on its algorithms, processing, datalink capacity, and available airspace. The ZoO concept is defined primarily for nominal conditions to make guidance and planning straightforward. Under this concept, as explained in Section 4.0, every individual UAV operation or activity is assigned a ZoO whose volume significantly exceeds the dominant ZoI for the location where the activity takes place. This not only preserves room for maneuvering each UAV around the center of the ZoO without a "repositioning" operation, but it also provides margin in time and space for the GS to react when anomalies or unexpected events occur.

Figure 6 uses the example UAV geometry of Figure 5 and illustrates common vehicle maneuvers under typical conditions. Maneuver (1) is the recall of an "on-station" UAV when it nears the end of its endurance (e.g., battery charge). While sufficient endurance remains, the affected UAV is boosted out of its on-station position and into the return pathway, where it proceeds back to base for refurbishment. In maneuver (2), the remaining UAVs on station are shifted horizontally as needed to cover the gap in observability (if any) caused by the absence of the recalled UAV that was recalled. Maneuver (3) shows the deployment of a recharged UAV from the base to replace the recalled one. Note that, if deployment and recall are

essentially simultaneous, or if the remaining UAVs are sufficient to perform the observation mission, repositioning of the other UAVs is not necessary. In any case, none of these maneuvers should any significant burden on the GS, datalink, or UAV equipment.

6.0 UAV Guidance: Reaction to Unexpected Events

When unexpected (or at least infrequent) events occur, the GS uses the margin built into guidance and planning under nominal conditions to react before the mission or safety are unduly compromised. The burden placed on the GS depends on the severity of the change, whether any advance warning was available, whether one, a few, or many UAVs must be repositioned, and how quickly a response is needed.

As with nominal maneuvers, most foreseeable faults and anomalies should not immediately lead to hazardous conditions. Figure 7 illustrates this with two examples of faults that can almost always be resolved without any threat of loss of separation. The first fault type is an unexpected loss of the primary (GS to UAV) datalink. Unless the UAV has internal telemetry that indicates a fault on-board the UAV, the reason for this loss is unknown at the time that it occurs. As long as the UAVs were positioned appropriately before this datalink loss, the wisest course of action is to "hold position" and wait a short, pre-defined interval for the datalink to be restored. Note that datalink loss prevents the GS from commanding

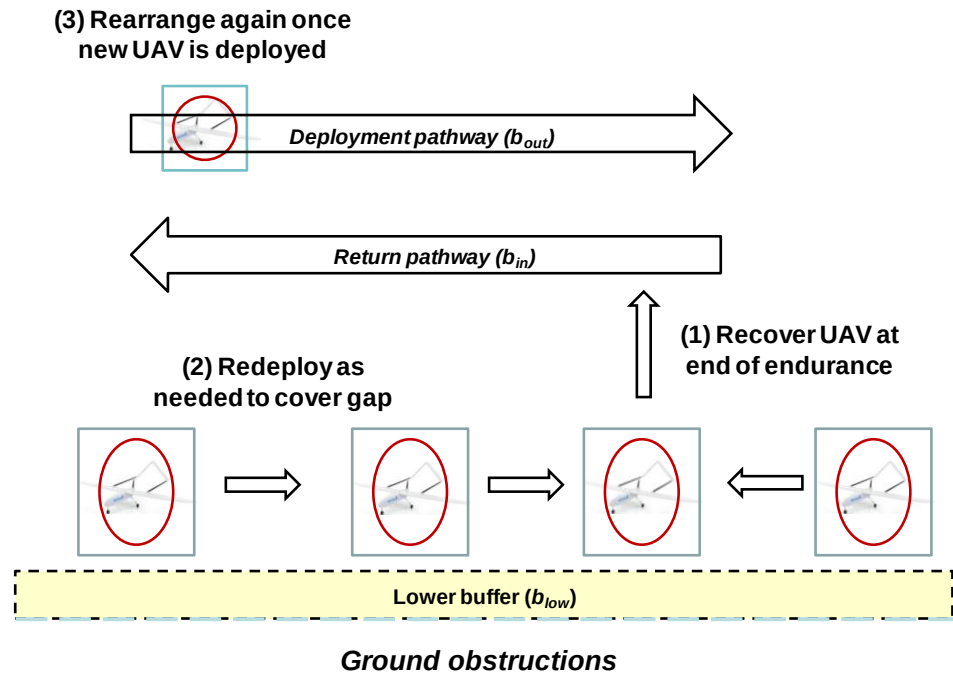


Figure 6: Typical UAV Guidance Actions under Nominal Conditions

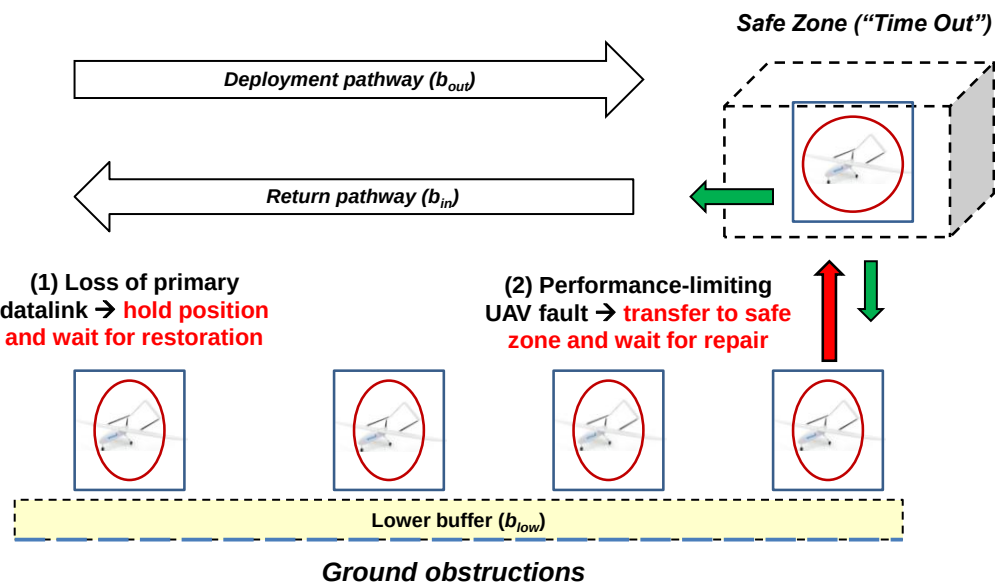


Figure 7: Example UAV Guidance Actions under Anomalous Conditions

the UAV; so the UAV must have this contingency pre-programmed. The most common cause of datalink loss is intermittent RF interference; thus waiting a few seconds for restoration will usually resolve the problem.

The second fault type includes faults on individual UAVs that limit performance such that the pre-existing ZoI and ZoO are no longer valid but do not make the device unflyable or uncontrollable (note that a datalink loss due to a UAV failure is an example). In this scenario, the

primary recourse is to have the GS (or the vehicle itself, if the datalink is down) command the affected UAV to move to a "safe zone" where the UAV can wait for repair to occur. Figure 7 shows this as a designated subset of airspace, but any relatively empty region where the applicable ZoIs are loose enough to provide room for the faulty UAV is fine. The UAV can hold position there for a certain time until the fault disappears, is corrected, or appears to be permanent. If the fault goes away, the UAV can be returned to its former position. If not, the UAV

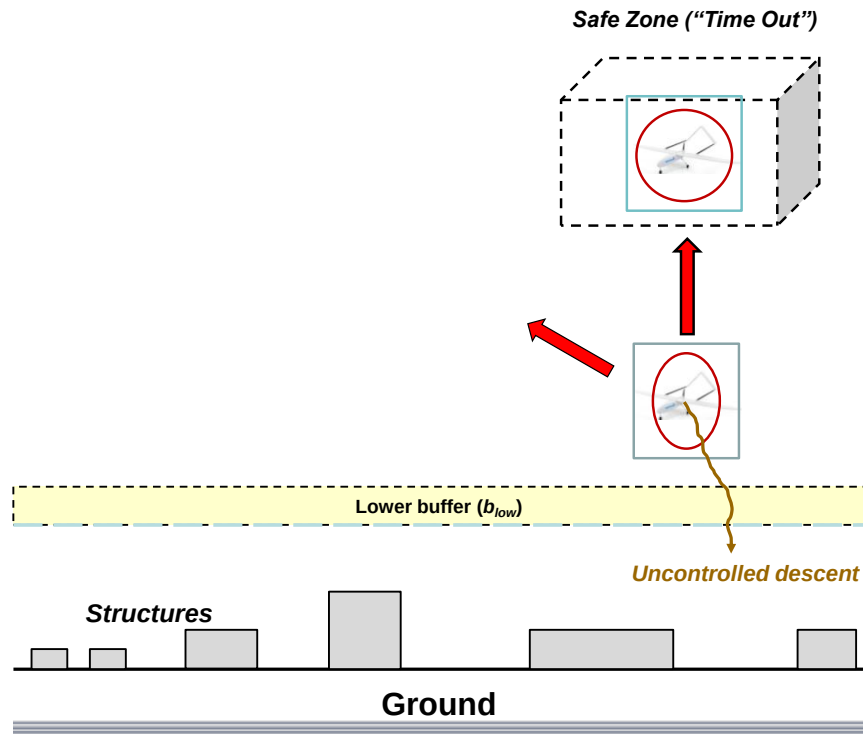


Figure 8: Example of Severe UAV Fault: Uncontrolled Descent

will eventually be returned to base and replaced with a working UAV.

A few foreseeable fault scenarios are almost immediately threatening and are thus more difficult to handle. One example is shown in Figure 8, where a UAV on station just above the lower altitude limit suffers a crippling failure causing sudden, uncontrolled descent toward the ground. If the GS notices this situation (because the navigation and return datalink functions on the UAV remain functional), it will immediately respond with a command to execute a "guided recovery" to a safe zone or to base. If GS intervention fails but the UAV's local guidance function still works, it will issue this command itself. If both interventions fail, or if the remaining UAV functionality is insufficient to boost the UAV back above the lower altitude limit, whatever guidance is functional attempts to cushion the descent and select a landing site that poses as little danger to people and property on the ground as possible.

In the case of total UAV failure, where the UAV "shuts down" and becomes completely unresponsive, no response will help – the UAV will fall down and impact the ground (or a building) at a location near where the UAV was hovering "on station." This creates a derived reliability requirement: the probability (per unit time) of the UAV entering this unrecoverable state must be well below the allowed probability of violating the lower

altitude limit. Pre-planning by the GS can also mitigate the consequences of this failure by selecting "on-station" positions over areas where UAV crashes would be less dangerous. For example, positioning small UAVs over large buildings with flat roofs likely minimizes the severity of an uncontrolled UAV crash into the ground compared to hitting the ground directly and possibly hitting people or their property.

As illustrated by the sudden-descent scenario in Figure 8, at the onset of an unexpected event, significant separation margin may be lost before the GS can react. The maneuver margin built into the ZoOs is the first line of defense. If it is insufficient, but GS reaction is feasible, the GS will attempt to move the smallest number of UAVs necessary to restore a situation where all ZoOs avoid intersecting (or "overlapping"). If this is not possible, or if the maneuvers required are beyond the computational or coordination capability of the GS, *the ZoOs are discarded* as a basis for emergency planning until it becomes possible to resume nominal operations. Instead, separation guidance is based on a set of *penalty functions* that reflect, in real time, the collision risk implied by the current UAV positions and those forecast to occur under one of several alternative guidance strategies. The development and refinement of these penalty functions is thus key to maintaining safety while allowing operations to proceed and recover to nominal as soon as possible.

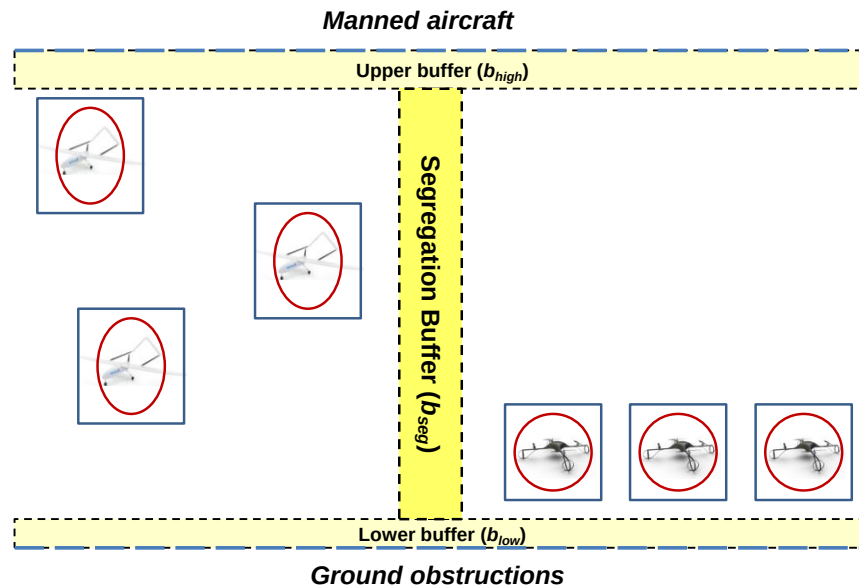


Figure 9: Airspace Segregated Among Different UAV Networks

The concept of "penalty functions" comes from the field of global optimization with "soft" constraints, meaning constraints that can be violated to some degree but at a cost to the objective function that is proportional to the degree of violation (for an introduction, see [5]). Here, the soft constraint is the concept that ZoIs must not overlap or intersect each other, which would imply that the separation standards are (at least temporarily) violated. Since the set of unexpected events that may befall networked UAVs cannot be bounded, it is not possible to ensure that this constraint is met under every conceivable scenario. In other words, as illustrated by the uncontrolled-crash scenario in Figure 8, it is impossible in practice to make the ZoI-non-overlap constraint a "hard" one. Instead, a penalty-function approach (e.g., using polynomials of 3rd to 5th order) properly motivates the GS to avoid violations of the ZoI separation constraint where possible without forcing it to find solutions that prevent all overlaps. Given the multiple operational parameters that need to be evaluated and traded off in real time, no ideal penalty function or set of functions exists. Instead, extensive simulation and (where feasible) testing of foreseeable anomalies and surprises is needed to refine the order and coefficients of each penalty function until the responses close to those that would be chosen by human controllers are achieved.

7.0 Multi-User Airspace Management

7.1 Other UAV Networks ("Out-of Network" UAVs)

If all UAVs operating in a given region are "in network," meaning that they are controlled and use differential corrections from the same GS, guidance and control are

much simpler than if UAVs operated by multiple, separate controllers are allowed to share the same airspace. Figure 9 shows the situation where this difficulty is resolved by assigning separate sub-spaces of the overall UAV airspace to different users at given times. In it, the right-hand section of the airspace is allocated to UAVs focused on zoomed-in observations of the ground (as in Figures 5-8), while the left-hand section is allocated to a separate network of UAVs spread out more to collect data of a different type. The vertical "segregation buffer" between the two sub-spaces is sized based on a generous (conservative) ZoO that bounds the ZoI for "out-of-network" UAVs relative to each other.

In order to fairly and efficiently sub-allocate the available airspace, external coordination would be required. A simple model would be reserving limited blocks of time in advance, much like tennis courts and golf tee times are assigned. If, for example, 10 different UAV users wanted to access the same airspace "cell" during a given day, an external, independent means would be developed to parcel out the hours of the day among these 10 users so as to maximize overall user utility and "fairness" over the set of users (e.g., minimizing or limiting the "disutility" suffered by the least-favored user). This approach thus gains the relative simplicity of single-user operations in each block of airspace against the restricted benefit that can be obtained if only one user can access a given block of airspace at a time.

Figure 10 shows the more-flexible alternative of sharing the same airspace among multiple UAV users and networks in real time. The short lines coming from each UAV indicate the presence of a new low-power, short-range datalink that allows UAVs to communicate with

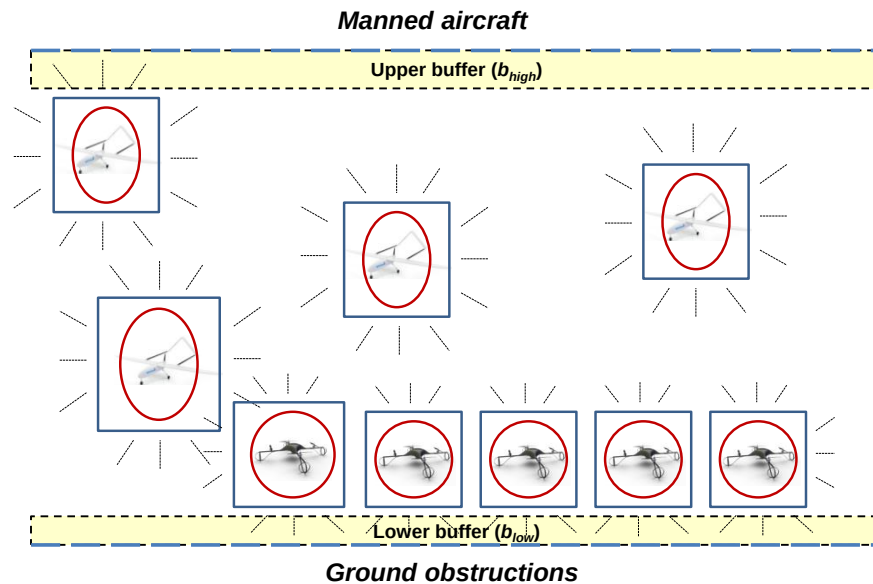


Figure 10: Airspace Shared Among Different UAV Networks

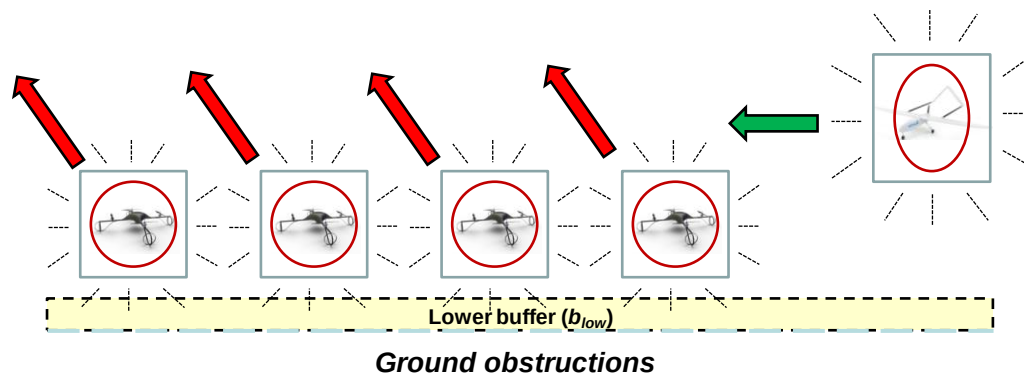


Figure 11: Potential Airspace "Takeover" by Non-Cooperating UAV

each other across networks to share information on position, velocity, and intent (i.e., "I intend to maintain my current velocity for T seconds and then halt."). Information conveyed by this datalink would be downlinked to each GS to allow coordination of UAV maneuvers within the same airspace. In Figure 10, the two networks sharing the airspace are performing different missions (as in Figure 9), which keeps most of their UAVs in separate regions of the airspace and minimizes potential conflicts. However, the lower-left corner of Figure 10 shows two different UAVs operating close to each other and constraining each other's actions. The leftmost UAV of "Type 1" (the type located just above the lower altitude limit) and the nearby UAV of "Type 2" have larger ZoIs and ZoOs than the others because these two UAVs have separation standards dictated by the nearby presence of the other (out-of-network) UAV.

The sharing of airspace shown in Figure 10 is far more desirable than having to operate separately in Figure 9,

but the level of coordination and cooperation required across UAV networks to predictably and fairly share airspace in real time is very challenging. Figure 11 shows an extreme scenario that illustrates the potential problems. In it, a single UAV approaching from the right properly uses the short-range datalink to alert a network of on-station UAVs of its entry into the airspace. Since overlapping ZoOs would result, a cooperative protocol is required to "balance the utilities" of the two UAV networks and thereby determine where the newly-arriving UAV can go (and if it can be allowed to require the pre-existing "on-station" UAVs to move). However, if the arriving UAV is "non-cooperating," it could proceed on its intended course regardless of the guidance determined by the cooperative protocol. The network of on-station UAVs following the protocol would presumably then be forced to vacate their positions to avoid unsafe loss of separation, allowing the arriving UAV to "clear the airspace" for its own use or perhaps to mask activities going on below. Pilots acting in such an unsafe manner would be punished by revocation of their license, but

future UAVs are likely to be more numerous and harder to track and police.

7.2 Sharing Airspace with Manned Aircraft

A great deal of research is needed to develop cooperative protocols that are operationally efficient, fair to all parties, and somehow robust to "bad actors" like the intruder in Figure 11. The difficulty of achieving these objectives among different UAV networks illustrates the further difficulty of sharing the same airspace among both UAVs and manned aircraft. Nevertheless, this is the clear goal of the U.S. Federal Aviation Administration (FAA) as it seeks to integrate UAVs into the U.S. National Airspace rather than provide separate or segregated airspace for UAVs [7].

In Figures 10 and 11, a datalink is proposed to allow adjacent out-of-network UAVs to share information. This is partially intended to duplicate the functions of Automatic Dependent Surveillance-B (ADS-B) in manned aircraft without requiring UAVs themselves to be equipped with ADS-B. However, UAVs that operate in the same airspace as manned aircraft will likely need to use ADS-B in some fashion to support the same conflict-avoidance function. The ADS-B equipment available today is too large, too power-hungry, and too expensive for small UAVs, but the gap has been shrinking. One supplier, SageTech, has developed ADS-B transponders intended for UAVs that only weight 100 grams and have been flight tested on an "Arcturus" UAV [8,9].

For the local-area UAV networks proposed in this paper, the preferred alternative to equipping each UAV with ADS-B would be equipping only the GS with ADS-B. Since the GS is the primary source of guidance, it is the most natural place to receive and decode ADS-B information from manned aircraft ("ADS-B In") and determine if any changes to UAV guidance are required. It can also provide "ADS-B-Out" broadcasts of location information for each UAV in the network. Making the GS the center of ADS-B information avoids the complication of individual UAVs having to transmit ADS-B information back to the GS and wait for a response (if warranted).

8.0 Summary and Ongoing Work

Based upon the concept proposed in [1,2], this paper describes an automated guidance methodology for local-area UAV networks controlled by a single ground station. It defines the mission requirements (in terms of continuous observation and real-time response capability) and safety requirements (in terms of maintaining safe separation from other vehicles and ground obstacles) and defines operational procedures to achieve them under nominal and anomalous conditions.

Central to this methodology are the maintenance and updating of zones of influence and zones of operation. Zones of influence (ZoIs) describe the regions around each UAV that must be kept clear to keep the risk of colliding with nearby vehicles and other objects acceptably small. Zones of operations (ZoOs) describe larger regions around each UAV that enclose all ZoIs of that UAV plus additional space that serves as maneuvering room as well as safety margin for failures or other unexpected events.

Under nominal conditions, most UAVs are "on station" making observations, and the GS maintains them with separated (non-overlapping ZoOs) with minimal effort. When anomalies or other unexpected events occur, the GS first attempts to maintain separated ZoOs through a series of procedures that include moving faulty UAVs to "safe zones" where off-nominal performance is temporarily tolerable. For scenarios where this is insufficient, ZoO maintenance is discarded in favor of penalty functions that strongly motivate the GS to keep ZoIs separated (and thus continue to meet separation standards) where possible but allow minor separation violations to occur if necessary. This methodology is illustrated under both nominal conditions and under anomalous conditions that require rapid GS response.

To be practical, this concept must support simultaneous usage by separate UAV networks with different controllers. Two different approaches have been proposed: one in which subsets of airspace are reserved for the use of a single network at a time, and one in which multiple networks use the same space and cooperate in real time to maintain safe operations. The latter is far more flexible but poses many challenges, including handling "non-cooperating" users that may attempt to exploit the safety protocols of the cooperating users to "take over" much of the airspace. Solving these problems for separate networks of UAVs would represent a major step forward to allowing safe sharing of airspace between UAVs and manned aircraft.

The concepts developed here are new and need additional quantification and simulation-based evaluation to judge their practicality. As explained in [1], a key uncertainty is the navigation and path-following performance of different types of small, inexpensive UAVs likely to be used for commercial applications. UAV flight experiments with LADGNSS navigation are planned as a means to evaluate this and thereby improve our estimates of achievable ZoIs for UAVs. Meanwhile, numerical simulations of nominal and unexpected conditions will continue to refine the selection of ZoO sizes (relative to ZoIs) and the penalty function parameters that determine how large of a separation violation is acceptable under various anomaly scenarios. The existing numerical simulation tool will be gradually expanded as new

guidance strategies and complications (e.g., sharing airspace with out-of-network UAVs or manned aircraft) are considered.

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APPENDIX E

Using Outage History to Exclude High-Risk Satellites from GBAS Corrections

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ABSTRACT: *GNSS augmentation systems that provide integrity guarantees to users typically assume that all GNSS satellites have the same failure probability. The assumed failure probability is conservative such that variations among satellites in a given GNSS constellation are not expected to violate this assumption. A study of unscheduled GPS satellite outages from 1999 to 2011 shows that, as expected, older satellites are much more likely to fail than younger ones. In addition, satellites that have recently experienced unscheduled outages are more likely to suffer additional unscheduled outages. Combining these two factors suggests that it is possible for a subset of GPS satellites to violate the overall satellite failure probability assumption, although this has not yet been demonstrated. Potential rules for GPS satellite exclusion based upon satellite age and recent outages are investigated, and suggestions for including satellite geometry are explored. Copyright © 2012 Institute of Navigation.*

INTRODUCTION

GNSS applications with demanding requirements for real-time integrity verification must make a series of assumptions regarding the performance of the satellite constellation(s) that they are using. One key assumption is the probability of unexpected satellite outages or failures. Integrity monitors that operate directly on standalone (uncorrected) GNSS measurements, such as Receiver Autonomous Integrity Monitoring (RAIM), as well as systems that provide differential corrections such as Space Based and Ground Based Augmentation Systems (SBAS and GBAS, respectively), rely on this assumption to determine the false-alert and missed-detection probabilities that their integrity monitor algorithms must achieve.

Regarding satellite failures, two different probabilities are important. One is the probability of any unexpected satellite outage, which makes the affected satellite unusable and thus affects continuity. The other is the probability of events that pose a potential integrity risk to SBAS and GBAS users. These probabilities can be represented as rates (e.g., probability of outage per satellite per hour) or as state probabilities, meaning the long-term average probability that a given satellite is in an “outage” or “failed” state.

For the purposes of verifying that integrity and continuity requirements are met, the systems mentioned above assume that all satellites have the same

probability of outage or integrity failure. This assumption is made for simplicity, and the probabilities assumed are typically very conservative; thus little or no risk arises due to potential violations of this assumption. However, it is known from the history and planning of GPS satellite operations (and satellite operations in general) that older satellites are much more likely to fail than younger ones. This was captured earlier in the history of the GPS constellation by former GPS Joint Program Office director, Col. Gaylord Green (USAF, Ret.), who noted that “*GPS satellites are operated to failure.*” [1] By this, he meant that GPS satellites were not retired when they first began experiencing problems or were approaching the end of their expected useful life but instead when they failed in a manner that was not recoverable (or was recoverable but no longer maintainable). This means that older satellites, and those which have recently experienced outages, will generally keep being used despite their higher propensity for further failures.

This paper examines the degree to which unexpected GPS satellite outages and failures vary with satellite age and prior outage history. It uses the archive of GPS Non-Availability notices to NAVSTAR Users (NANUs) to compile a history of unexpected satellite outages from January 1999 to August 2011 [2, 3]. These outages are examined to identify the likelihood of outages as a function of satellite age and recent outage history. These results show that, as expected, older satellites are much more likely to experience outages than younger ones, as are satellites with a history of recent outages (in the last year or two).

While these results do not immediately suggest that the satellite-fault-probability assumptions made by GBAS and other systems are violated for specific satellites, they at least raise the possibility. To address this risk, two potential satellite-exclusion heuristics are examined in terms of their impact on GPS user satellite geometry quality. The need to select a subset of satellites from the full set that is in view is not new: it was a common need of four and six-channel GPS receivers in the early 1990's, when GPS rapidly expanded to a full constellation of 24 satellites by 1993. Since more than six satellites were commonly in view, some means was needed to down-select the 4 or 6 satellites that were most worth tracking. Various methods were applied to do this, including differentiation by satellite quality [4] and selection of the subset that gives the best satellite geometry in terms of dilution of precision (DOP) [5]. Computationally efficient methods for computing DOP and thus finding optimal satellite subsets are still important [6].

Past and present experience can be combined to infer two general cases where satellite sub-selection is desirable. In the *channel-limited scenario*, not all satellites can be used due to hardware limitations. This includes both receiver limitations and data bandwidth constraints for augmentation systems like GBAS, which can only send differential corrections and integrity information for a limited number of satellites. In the *channel-unlimited scenario*, hardware constraints do not apply, but satellites are down-selected to remove those with poor performance or other negative traits. The former scenario is primarily a concern to future systems that make use of GPS in combination with other GNSS constellations such as GLONASS, Galileo, Compass, and/or QZSS. This paper will mostly consider the latter scenario with the intent of excluding satellites whose fault likelihoods might violate the integrity assumptions made by GBAS or other high-integrity services.

This paper describes the expected GPS satellite fault probabilities and the more conservative numbers assumed by GBAS. It then provides the results of the unexpected satellite outage study, showing the degree to which satellite age and number of recent outages affect the likelihood of future outages. The paper uses this information to propose example satellite-exclusion heuristics and examine their impacts on GPS-only satellite geometries as measured by Vertical DOP at two U.S. user locations. It also explains how the multiple-hypothesis protection level approach utilized in Advanced RAIM (ARAIM) can be used to make real-time trade-offs between the integrity risk posed by a weak satellite and the satellite geometry benefit that it provides. The final section summarizes this paper and briefly examines the impact that the future use of multiple satellite constellations may have on satellite exclusion.

EXPECTED GPS SATELLITE FAULT PROBABILITIES

The primary open source of GPS satellite outage information is the latest (2008) *GPS Standard Positioning Service (SPS) Performance Standard* document [7], which gives both historical information on satellite outage rates and states the minimum performance requirements that the U.S. Government, the GPS Wing, and the 2nd Space Operations Squadron (2 SOPS) hold themselves to in managing and maintaining the system.

Section 3.5.1 of [7] expresses the SPS Signal-in-Space (SIS) Integrity Standard as a probability of 10^{-5} per hour or less that the SIS User Range Error (URE) exceeds ± 4.42 times the upper bound on User Range Accuracy (URA) corresponding to the URA integer broadcast by the satellite in question without a warning that prevents use of the affected measurement (this event is called a "major service failure"). Over a 32-satellite constellation, which is the maximum number of satellites that can be supported in the broadcast almanac, the above probability implies an average of three "major service failures" per year [7]. This is confirmed by doing the reverse calculation as follows:

$$\frac{3 \text{ events/yr}}{8766 \text{ hrs/yr}} \frac{1}{32 \text{ satellites}} = 1.07 \times 10^{-5} \text{ events/SV/hr} \quad (1)$$

When applying this number to a civil system such as GBAS, it is important to note that "major service failures" for SPS do not include all events that represent potential integrity threats to GBAS. GBAS separates potential integrity threats due to satellite faults into five classes [8]:

- Clock failures (excessive acceleration)
- Low signal power
- Code-carrier divergence (separate from that caused by the ionosphere)
- C/A-code signal deformation
- Navigation data failures (e.g., large ephemeris errors)

Because the "major service failure" definition does not cover these, and because the numbers cited in [7] cannot be taken as guaranteed, GBAS assumes a satellite integrity fault probability of 10^{-4} per satellite per hour instead of 10^{-5} . Furthermore, this probability is assumed for *each* of the above five failure classes instead of all five combined [8]. This is very conservative for fault classes that are known to have been observed once at most (e.g., signal deformation and code-carrier divergence). On the other hand, the same probability is assumed for all usable GPS satellites regardless of their age or current status.

Section 3.6.1 of [7] specifies a somewhat-different satellite outage probability related to continuity of service. This is stated as a probability of 0.9998 or greater over any hour of "... Not Losing the SIS SPS

Availability from a Slot Due to Unscheduled Interruption.” In other words, given that a satellite (occupying an orbit slot) is healthy and broadcasting usable signals at the start of a given hour-long period, the probability of losing usable signals from that slot (or satellite) is 0.0002 or less. This translates into a lower bound on the Mean Time Between Outages (MTBO) of 5000 hours, which is lower than the numbers assumed by GBAS based on the previously-assessed operational history of GPS satellites (e.g., 9740 hours in [9]). In general, the CAT I GBAS continuity sub-allocation to satellite failures is conservative because it allows for many more “critical satellites” than normally occur in available satellite geometries (a “critical satellite” is one whose sudden loss would lead to loss of continuity for the current operation – see [10]).

The probability given in Section 3.6.1 of [7] is directly related to the results in this paper because unexpected outages tabulated from NANUs archives cannot be separated into “outages affecting only continuity” and “outages that potentially threaten integrity” without more details. In almost all cases, the set of events that creates integrity risk is a subset of the events that cause outages. In the case of GPS, the Operational Control Segment (OCS) detects and excludes (flags as “unhealthy” or triggers a switch to an unusable PRN or to “non-standard C/A code”) practically all faults of significance within a few hours [7], although its response is not fast enough to meet the time-to-alert

for most applications. The fraction of unexpected outages that pose a potential integrity threat is hard to estimate. It is likely to be much less than 1.0, although a significant fraction of unexpected outages appear to occur from satellite clock anomalies, which can threaten civil user integrity if not quickly detected.

UNSCHEDULED OUTAGES OF GPS SATELLITES SINCE 1999

As noted above, the data source for this study of unscheduled (or unexpected) GPS satellite outages is the archive of NANUs that were issued at or near the time that the outages occurred. Most outages are “scheduled” for orbit and clock maintenance and are indicated by a forecast NANU (to alert users of the upcoming outage) followed by a report of the outage after it has been completed. Unscheduled outages, of course, are not preceded by any forecast. Two NANUs typically exist for them as well – one alerting that an unscheduled outage has begun and a report on its duration after it is over and the satellite has been returned to service or has been decommissioned. Although the NANU archives cannot be regarded as complete or definitive outage records, they are sufficient to explore the degree to which satellite outages are equally spread across the constellation.

Table 1 lists the 31 GPS satellites that were commissioned and healthy as of (approximately)

Table 1—Healthy GPS Satellites as of 20 Sept. 2011

SVN	PRN	Block	Launch Year	Launch J-Day	Orbit Slot (as of 9/20/11)	Age as of 9/20/11 (years)
23	32	IIA	1990	330	E5	20.81
24	24	IIA	1991	185	D5	20.21
26	26	IIA	1992	188	F5	19.20
39	09	IIA	1993	177	A1	18.23
35	30	IIA	1993	242	B5	18.05
34	04	IIA	1993	299	D4	17.90
36	06	IIA	1994	069	C6	17.53
33	03	IIA	1996	088	C2	15.48
40	10	IIA	1996	198	E6	15.18
43	13	IIR	1997	204	F3	14.16
38	08	IIA	1997	310	A3	13.87
46	11	IIR	1999	280	D2	11.95
51	20	IIR	2000	131	E1	11.36
44	28	IIR	2000	197	B3	11.18
41	14	IIR	2000	314	F1	10.86
54	18	IIR	2001	030	E4	10.64
56	16	IIR	2003	029	B1-A	8.64
45	21	IIR	2003	090	D3	8.47
47	22	IIR	2003	355	E2	7.75
59	19	IIR	2004	080	C3	7.50
60	23	IIR	2004	175	F4	7.24
61	02	IIR	2004	311	D1	6.87
53	17	IIR-M	2005	269	C4	5.98
52	31	IIR-M	2006	268	A2	4.98
58	12	IIR-M	2006	321	B4	4.84
55	15	IIR-M	2007	290	F2-A	3.92
57	29	IIR-M	2007	354	C1	3.75
48	07	IIR-M	2008	075	A6	3.51
50	05	IIR-M	2009	076	E3	2.51
62	25	IIF	2010	148	B2	1.31
63	01	IIF	2011	197	D2-A	0.18

20 September 2011. The rows are sorted by age, and the first two rows are highlighted to indicate that two satellites (Block IIA SVN 23 and 24) are now more than 20 years old. This is quite remarkable considering that the Block IIA satellites had a design life of only 7.5 years, and it illustrates the truth of Col. Green's claim in the Introduction. The two highlighted satellites (among others now retired) were not only "operated to failure," but they were brought back into active service after previously being decommissioned (and retired) due to end-of-life failures of other satellites.

Figure 1 plots the ages of the satellites in Table 1 from newest to oldest (in blue) and shows a linear fit to these points (in red). This plot shows that the current age distribution among the GPS satellites is close to uniform, meaning that older and newer satellites are present with approximately equal frequencies (this appears in the plot as roughly linear from newest to oldest). A roughly uniform distribution with age is expected from a "mature" constellation, and it suggests that outage frequencies should appear uniform as well if the underlying outage probabilities are roughly the same for all satellites. It should be noted, however, that the distribution of GPS satellites ages was not necessarily uniform over the entire period in which outages were tabulated (January 1999 – August 2011).

Figure 2 plots each of the 178 unscheduled outages found in the NANU archives by year of occurrence and age of the affected satellite at the time of the outage. This graph makes it clear that most outages occur on older satellites (for simplicity of wording, "outages" will often be used when referring specifically to "unscheduled outages"). It also shows that the definition of "older satellites" has changed since 1999 as the oldest satellites in the constellation continued to be usable well past their previously-predicted design

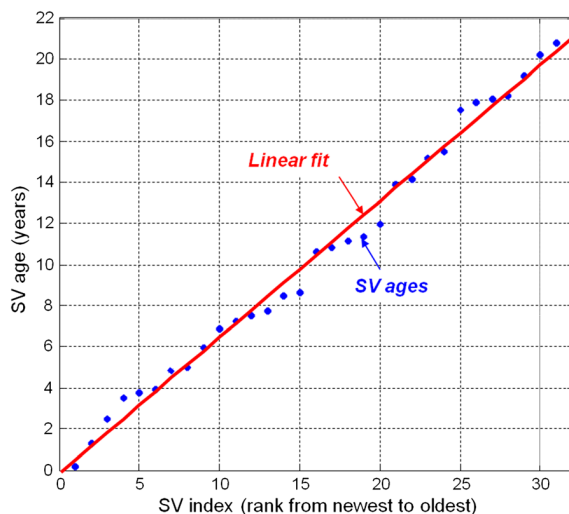


Fig. 1–Distribution of GPS Satellite Ages on 20 September 2011

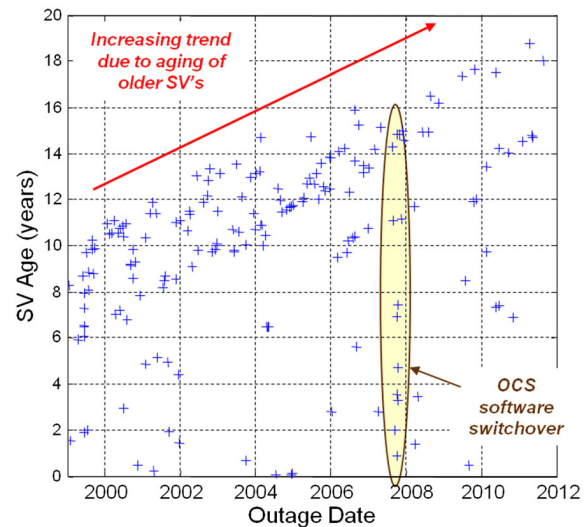


Fig. 2–Unscheduled Outages by Year and Satellite Age

lives. Except for a few "infant mortality" outages among new satellites and a brief period of outages across all satellite ages in late 2007, which are known to have been caused by the OCS software changeover that occurred at that time (see [11]), outages among newer satellites (less than the original Block IIA design life of 7.5 years old [7]) are relatively infrequent and are scattered randomly across the plot.

Figure 3 shows a histogram of outages by satellite age from 1 to 20 years (note that a given bin "x" represents all outages of satellite ages from $x - 1$ to x years). This histogram not only reinforces the relationship between satellite age and outage frequency but shows the variation of outage frequency with specific phases of satellite life. As expected, satellites newer than two years of age experience more outages than satellites in the "prime of life" due to unexpected design or manufacturing problems that

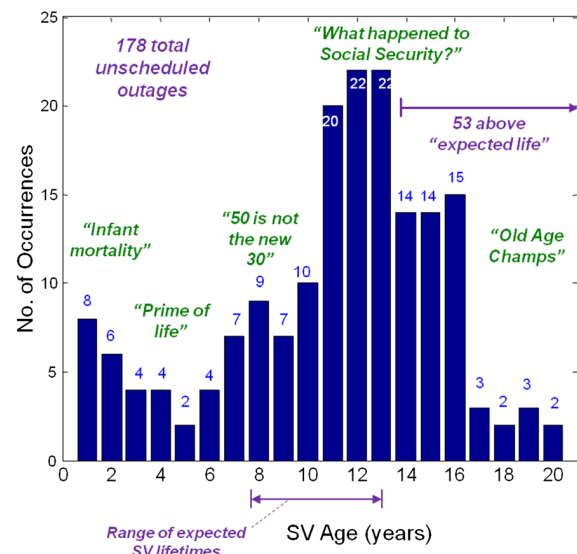


Fig. 3–Histogram of Outages by SV Age

were not discovered during testing. Outages increase in frequency as the expected satellite life-time (approximately 7.5 – 12.5 years, depending on satellite Block type) approaches and increases further as the expected lifetime is reached and passed.

The relative frequency of outages is highest for satellites that live beyond the 12.5-year expected lifetime of the most modern GPS satellites. Figure 3 does not make this clear because, as indicated in Figure 2, satellites aged 13 years or more are a relatively new component of the GPS constellation. Figure 4 emphasizes this point by re-plotting the outage histogram in Figure 3 while combining all satellites beyond 13 years of age into a single bin. This bin has 53 outages in it compared to the total of 64 outages for satellites from 10 to 13 years old, but the total prevalence of satellites over 13 years old during the data collection period is significantly lower than the prevalence of satellites from 10 to 13 years old. Figure 4 also clarifies that satellites newer than 10 years of age have significantly fewer outages than older satellites and can be treated as “nominal” relative to assumed satellite failure probabilities, even though significant outage variations within this class are visible in Figure 3.

Figure 5 changes the focus to individual satellites and shows the number of unscheduled outages experienced on each satellite observed during the data collection period. The x-axis is sorted by SVN instead of launch order, but these two sequences are highly correlated. What is most striking is the variability of outage frequency among the satellites. A few SVNs show zero outages because they expired before 1999 (e.g. SVNs 20 and 28), have not had any unscheduled outages yet (e.g., SVNs 48 and 52), or never entered service (e.g., SVN 42, which suffered a launch failure). Otherwise, some satellites of the

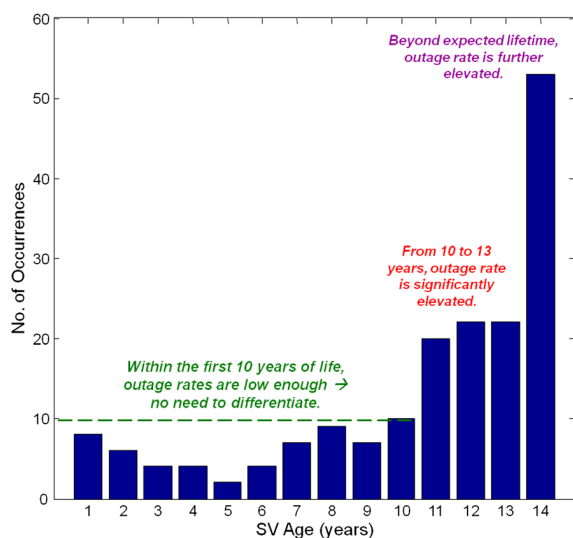


Fig. 4–Histogram of Outages by SV Age (Ages > 13 years combined into a single bin)

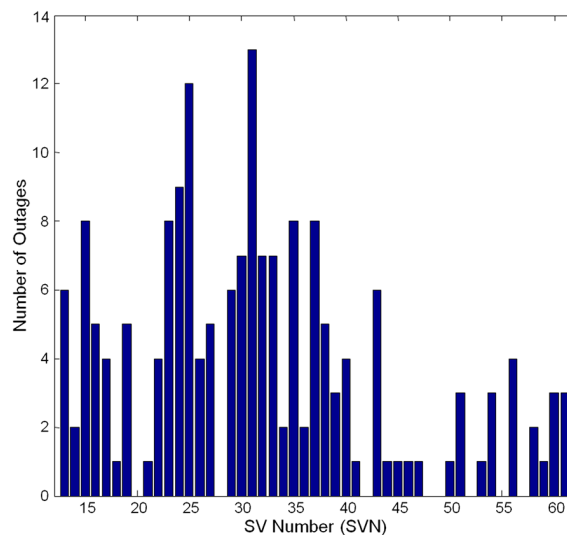


Fig. 5–Histogram of Outages by SV Number

same type, such as Block IIA SVNs 25 and 31, experienced many more outages (12 and 13, respectively) than did other Block IIA satellites. Long life is not the sole explanation, as SVN 31 was decommissioned “for good” after 12.57 years, while SVN 25 lasted 17.82 years. While some variation of outage frequency would be expected even if all satellites had equal failure probabilities, the degree of variation shown in Figure 5 strongly suggests that “all satellites are not made equal.”

Figure 6 shows the outages for each satellite in more detail by plotting each one as a function of satellite age. Satellites are again indexed by SVN on the x-axis, while the y-axis indicates the age of each satellite at the time an unscheduled outage began. Five different symbols are used to indicate the approximate duration of each outage, as indicated

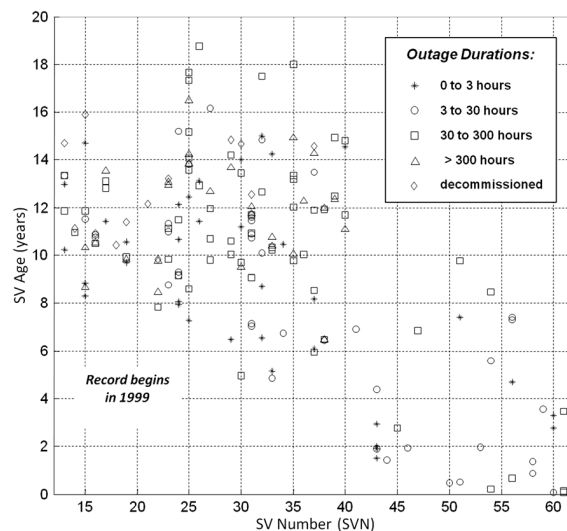


Fig. 6–Age and Duration of Outages on Each Satellite

in the plot legend. Because many outages occurred in close proximity to one another, they “overlap” on Figure 6 and are not clearly visible as distinct events. Also, the limits of the 1999–2011 data collection period affect this plot, as “young” outages for earlier GPS satellites are not apparent, nor are “old” outages for satellites launched in the last few years.

Of the 178 unscheduled outages observed during this period, 13 were not repaired, meaning that the satellite was instead decommissioned (five other satellites were also decommissioned during this period by OCS decision). Of the remaining 165 outages that were repaired, 36 lasted 3 hours or less, 41 lasted between 3 and 30 hours, 61 lasted between 30 and 300 hours, and 27 lasted longer than 300 hours (the longest lasted 4,638 hours, or just over 6 months). This wide range of outage durations corresponds to the many potential causes of anomalies that cause unscheduled outages. A frequent pattern involves a relatively rapid initial repair followed by one or more outages with longer durations, indicating that the original problem persisted or was incompletely assessed.

Figure 6 reiterates the fact that older satellites are more likely to have unscheduled outages, and it shows the history of outages and repairs on each satellite to help clarify what separates “well-behaved” and “troublesome” satellites. “Troublesome” satellites not only experience many outages, but these outages become more frequent as satellites age and pass their expected lifetimes. In particular, the appearance of one or two outages within one to two years on older satellites is a strong indication that more outages are coming.

Figure 7 highlights this tendency by “zooming in” on the unscheduled outage history of SVN 25, which as noted above experienced 12 unscheduled outages over a lifetime of almost 18 years before being

decommissioned (by OCS decision) in late 2009. The same data shown in Figure 6 is repeated in Figure 7 for SVN 25, but additional details are added in text form. Since outage durations are now provided by text, all outage start times are indicated by the same symbol (a square).

As shown in Figure 7, SVN 25 experienced two outages in 1999 and 2000 as it passed the original Block IIA design life of 7.5 years, and it experienced one more outage in 2004 after passing 12 years of age. Six months later, with the satellite now more than 13 years old, it experiences a series of 5 outages from February 2005 to May 2006. Two of these outages, on 23 and 25 December 2005, occurred so close to each other that they appear as one overlapping square in Figure 7. Note that the earlier of these two outages was resolved in about 8.5 hours, but the underlying problem remained and led to the second outage shortly thereafter. That second outage lasted about a month, but further outages followed, suggesting that the GPS OCS was fighting a persistent problem on this satellite. Four additional outages occurred on SVN 25 after the period of 5 outages ended in 2006, showing that the problems affecting SVN 25 were never completely resolved before it was decommissioned. Despite this, SVN 25 was continuously reactivated and kept in service until the level of maintenance and monitoring difficulty that it posed to OCS was no longer worthwhile.

The history of outages by individual satellites shown in Figures 6 and 7 suggests that recent outage history is at least as relevant as age in predicting future satellite outages. Since older satellites experience a significant majority of outages, the two effects are highly correlated, but considering prior outage history helps to separate older satellites with a particularly high risk of future outages from those whose risk is not high enough to require additional mitigation. The benefits of this will become apparent when example satellite-exclusion rules are examined in the following section.

Finally, what comparisons can be drawn between these results and the expected satellite failure and outage probabilities described previously? If the 178 outages observed in this study are divided by the number of hours covered by the data collection period (about 111,035 hours from January 1999 through August 2011, inclusive), an outage rate of 1.60×10^{-3} per hour is obtained. Dividing this result by 24 satellites (a conservative estimate of the number of satellites present in the constellation over this period) gives an outage rate of 6.67×10^{-5} per hour per satellite, which is well below the SPS Performance Standard of 2.0×10^{-4} per slot per hour for unscheduled outages. Furthermore, even if all of these outages represent potential integrity threats for GBAS, the observed outage rate is below the 10^{-4} per hour per satellite fault probability assumed by GBAS for each fault mode.

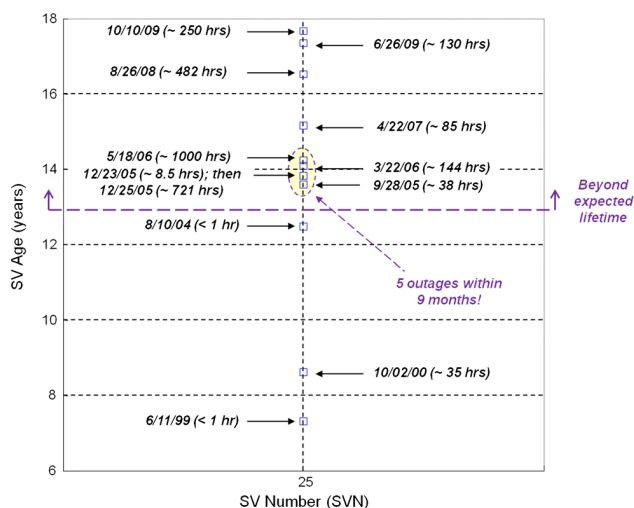


Fig. 7—Unscheduled Outage History of SVN 25

While these numbers suggest that the *average* outage and failure rates over the GPS constellation are sufficiently low, the focus of this study is the possibility that particular satellites might exceed what is assumed by GBAS or other systems. SVN 25, highlighted in Figure 7, is a good example. It experienced 12 outages over the period from January 1999 to its decommissioning in mid- December 2009 (a period of about 96,060 hours), giving an average outage rate over its lifespan of about 1.25×10^{-4} per hour. This is just under twice the overall outage rate for all satellites – it is elevated but not a major concern. However, if we focus on the period from the fourth outage (on 10 August 2004, when SVN 25 was about 12.5 years old) until decommissioning, nine outages occurred within a period of about 46,920 hours, giving an outage rate of 1.92×10^{-4} per hour. A more pessimistic number is obtained by focusing on the five outages that occurred between 24 February 2005 and 18 May 2006 (a period of about 10,750 hours). This gives an outage rate of 4.65×10^{-4} per hour, which exceeds the SPS outage rate and would exceed the SPS failure rate if the fraction of unscheduled outages that pose an integrity threat exceeds $10^{-5} / 4.65 \times 10^{-4}$, or about 2.15%. As noted above, the actual fraction of outages that pose integrity threats to GBAS or other civil systems is unknown but is almost certainly higher than this.

EXAMPLE SATELLITE-EXCLUSION HEURISTICS

The possibility that individual GNSS satellites might exceed the failure probabilities assumed by high-integrity civil systems motivates the consideration of satellite-exclusion heuristics, or rules that would prevent high-risk satellites from being used based on characteristics that are observable to these systems. Two example heuristics are proposed and evaluated in this section:

Heuristic 1: Exclude all GPS satellites greater than 13 years of age.

Heuristic 2: Exclude all GPS satellites greater than 10 years of age that have experienced one or more unscheduled outages within the last two (2) years.

Heuristic 1 is suggested as a conservative example only and is not intended to be practical when using only GPS for satellite navigation (i.e., without also using other GNSS satellites from GLONASS, Galileo, etc.). Recall from Figure 1 that the satellites in the current GPS constellation shown in Table 1 (as of 20 September 2011) are relatively uniformly distributed in age between 0 and 20 years. Therefore, excluding all satellites older than 13 years would eliminate a significant fraction of the constellation and would be impractical for most users. In particular, applying this heuristic to the GPS satellites in Table 1 would

eliminate the following 11 satellites (in descending order of age): SVNs 23, 24, 26, 39, 35, 34, 36, 33, 40, 43, and 38. Six of these 11 satellites are in “spare” orbit slots and thus contribute less to user geometry, but the other five remain in “primary” slots and are heavily relied upon.

Heuristic 2 is still very conservative for users of only GPS satellites, but it is less so than Heuristic 1 because it requires both advanced age (10 or more years instead of 13) and one or more unscheduled outages in the last two years. Table 1 shows that the 10-year age cutoff adds 5 more satellites (SVNs 46, 51, 44, 41, and 54) to the above list of those eligible to be excluded. However, the additional requirement of an outage within the last two years allows the majority of these satellites to be used despite their age. Only five satellites are excluded by Heuristic 2: SVNs 26, 35, 38, 40, and 51. Three of these five satellites are in “spare” orbit slots, and all but one (SVN 51) is included in the larger set of satellites excluded by Heuristic 1.

These two heuristics were evaluated using satellite geometry simulations at two locations in the U.S.: a mid-latitude site (Palo Alto, California, at 37.4° North latitude) and a high-latitude site (Fairbanks, Alaska, at 64.8° North latitude). One day of GPS satellite geometries was simulated at 5-minute intervals over 20 September 2011 (local time), and a satellite visibility elevation “mask angle” of 5° was used for both locations. Trimble’s freely-available “Setup Planning” software for Windows (Version 2.9) was used to perform this analysis [12].

The two plots in Figure 8 show the number of visible and usable GPS satellites on 20 September 2011 at both Palo Alto (left-hand plot) and Fairbanks (right-hand plot) under three scenarios. The first scenario, shown in solid line, includes all visible satellites without any exclusion rules. The second scenario, shown in dashed line, implements the satellite-exclusion rules of Heuristic 2, while the third scenario, shown in dotted line, implements the satellite-exclusion rules of Heuristic 1. The same pattern is followed in Figure 9, which plots Vertical Dilution of Precision (VDOP) at both locations. VDOP translates the quality of the usable satellite geometry into a measure of user error in the vertical dimension. Multiplying the current VDOP by the one-sigma accuracy of each ranging measurement provides an approximate one-sigma estimate of vertical position accuracy.

Figures 8 and 9 clearly show the disadvantages of implementing the proposed satellite-exclusion heuristics when only using GPS satellites for navigation. Heuristic 1, in particular, is clearly impractical. Although seven or more satellites are always visible at both locations, and nine or more satellites are visible at most times (10 or more at Fairbanks), the eliminations required by Heuristic 1 bring the number of usable satellites down to four to six at times.

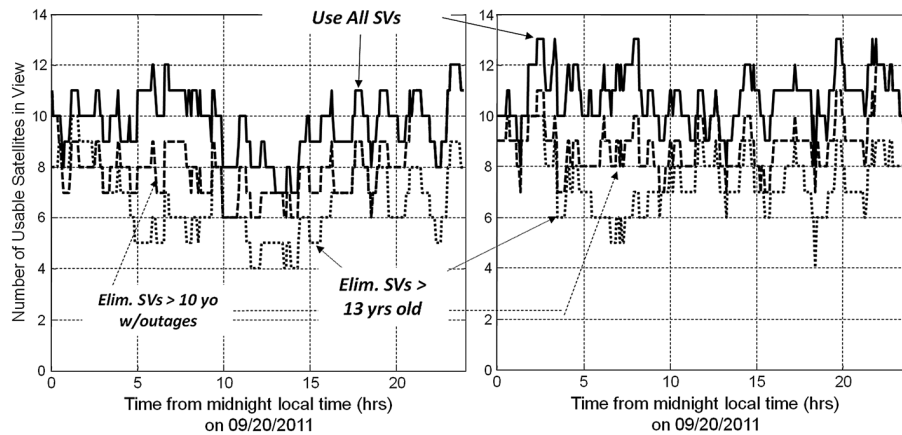


Fig. 8—Number of Usable Satellites at Palo Alto and Fairbanks

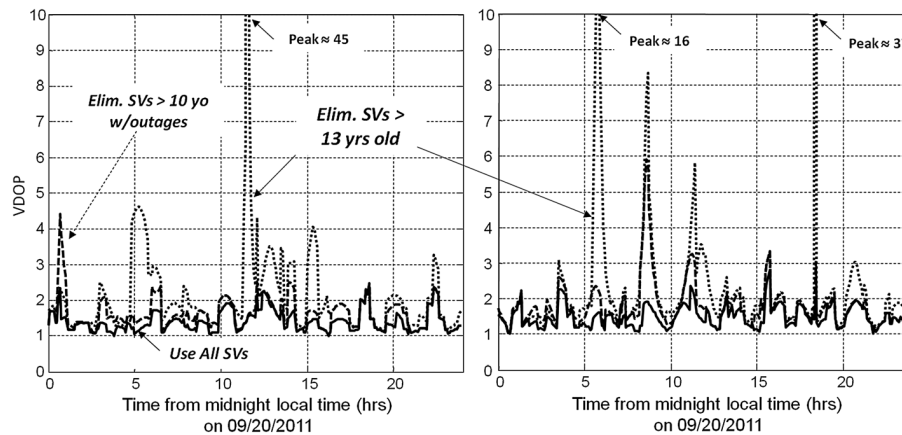


Fig. 9—Vertical DOP (VDOP) at Palo Alto and Fairbanks

The resulting penalty is most obvious in Figure 9, where the red curve representing Heuristic 1 has multiple undesirable “spikes” where VDOP grows to very high values, and a significant fraction of the day has VDOP above 3.0 for this case. In comparison, VDOP for Heuristic 2 (the green curve) stays much closer to the ideal VDOP for the no-SV-elimination case (the blue curve), although significant deviations are visible and will lead to lower availability if Heuristic 2 is implemented.

Figure 9 suggests that, while Heuristic 1 is too conservative, Heuristic 2 is a good starting point for refinement of the exclusion rules for GPS satellites. An improved heuristic likely needs to exclude fewer satellites to be optimal for users of GPS satellites only. On the other hand, if GPS were combined with another full or nearly-full satellite constellation of similar ranging accuracy in the future (e.g., potentially Galileo, COMPASS, and/or GLONASS), Heuristic 2 might be usable as is, as many more satellites would be available to make up for the excluded ones [13]. Use of GPS with other satellite constellations remains speculative, and the outage characteristics

of new GNSS satellites remain to be observed, but it is reasonable to expect that their behavior over time will follow patterns similar to those of GPS satellites.

Note that, while Fairbanks typically has more satellites in view (on average) than Palo Alto in Figure 8, VDOP at Fairbanks is worse than at Palo Alto in Figure 9. This is true for all three cases shown but is most visible for Heuristic 1, and it is due to the weakness of satellite geometries viewed from latitudes above the inclination angle of the GPS satellite constellation (55°). In general, locations with weaker satellite geometries under nominal conditions (e.g., due to local obstructions causing higher elevation mask angles) will make the loss of performance due to satellite exclusions that much worse, since “less margin” for these exclusions is present to begin with.

Another consideration regarding satellite-exclusion rules is how to implement them in civil systems in real time. The study used to develop these heuristics was based on access to archived NANUs via the Internet [2, 3]. Internet access is one straightforward means of obtaining NANUs, but some means external to GPS receiver hardware is needed because NANU

information is not broadcast in the GPS navigation data messages. Augmentation systems such as GBAS and SBAS, could obtain this information externally, but are not necessarily designed to do so. For example, the Honeywell SLS-4000 LAAS Ground Facility, which achieved CAT I System Design Approval in 2009 (but not yet airport site approval), mirrors the much older Instrument Landing System in allowing no external contact (beyond GPS and VDB signals) except for manual interaction with FAA maintenance personnel.

Without access to NANUs or other external information about satellite constellation health, even tracking satellite age is difficult because satellites do not broadcast their SV numbers – only their PR numbers, which can move from satellite to satellite (usually when a new satellite replaces an older one that has been decommissioned). Therefore, some external input is needed to update a maintenance file when a new GPS satellite is approved for use [14]. An opportunity for this exists for the SLS-4000 because manual input is required to approve the C/A-code signal quality of each new satellite.

However, as this paper establishes, tracking recent satellite outages is key to limiting the number of satellites that are excluded. Without regular NANU inputs, individual GBAS sites could observe satellites being flagged unhealthy when in view of that site, but they would miss the times when this occurs out of view, and more importantly, they could not easily distinguish between an unscheduled outage and a scheduled outage for maintenance unless that satellite was maneuvered. Ideally, augmentation systems (and ARAIM, which will rely on external integrity messages to some degree [13]) will expand their access to NANU information as they mature, but for now, its absence significantly limits our ability to implement satellite-exclusion rules.

REAL-TIME EXCLUSION METHOD THAT INCORPORATES SATELLITE GEOMETRY

The satellite-exclusion rules proposed in the previous section are simple “open-loop” rules that would be applied regardless of the usefulness of each satellite to a user’s position solution. This makes sense if the intent is to remove satellites whose potential harm to user integrity is large and exceeds the assumptions made by user integrity algorithms to an unknowable extent. While this could be the case, the results in this paper suggest that any such violations of existing assumptions will be a matter of degree rather than an immediate threat. If this is the case, and the degree of violation can be estimated and/or bounded, the methods currently used to verify integrity in civil-aviation navigation systems can be adapted to determine in real time (or near-real-time) when the value of a given satellite

to the user’s positioning geometry outweighs its failure risk. This approach would blend the risk-sensitive heuristics proposed above with the common means of channel-limited satellite selection described in the introductory section, which selects the satellite subset that minimizes the position DOP of interest. Minimizing DOP may be sufficient when all satellites have similar failure risks, but a generalized approach would handle the GPS satellite history shown earlier in this paper, where this is not the case.

The concept that makes this possible is known as the “multiple-hypothesis” (MH) approach to estimating integrity risk, which was first developed in [15] and has been used more recently as the basis for computing real-time user protection levels in ARAIM [16]. ARAIM computes protection levels by evaluating the probabilistic impacts of nominal conditions and each faulted or anomalous threat mode whose probability is significant relative to the overall loss-of-integrity probability that the system aims to protect (e.g., 10^{-7} per operation for the most demanding flight modes to be supported by ARAIM). Threats due to satellite faults are weighted by the assumed prior probability of that fault. Protection levels are output at each epoch that bound the maximum position errors at the required loss-of-integrity probability (or “PHMI”) based upon the current measurements and a prior allocation of that probability to each fault and to the fault-free case [16]. While this approach is used directly by ARAIM, the theory behind it underlies the calculation of protection levels for all civil-aviation applications and is thus widely applicable [17].

An addition to the ARAIM multiple-hypothesis method could handle potential satellite exclusions by treating them as potential “failures” whose risk could be *accepted* by including the satellites in question or *rejected* by excluding them. First, a list of “satellites of concern” with higher-than-normal failure probabilities would be built using a refinement of Heuristic 2, for example. The nominal protection-level calculation would exclude all of these “troubled” satellites, meaning that it would enforce the exclusion heuristic as an “in or out” rule. Next, each satellite excluded by the heuristic is re-included in a separate protection level calculation in which failures of the re-included satellite are evaluated with a higher probability based on the GPS satellite history reported earlier. If the resulting protection levels are meaningfully lower than for the nominal case (with all “troubled” satellites excluded), then that satellite should be included in the position solution because its improvement to user geometry outweighs the additional failure risk that it brings with it. To the degree that computational resources permit, this would be repeated for all satellites excluded by the heuristic being used.

The advantage of using heuristics as “in or out” rules is that there is no need to assess how much higher the probability should be for “satellites of concern” relative to the assumed probability for all satellites. However, the multiple-hypothesis approach requires a numerical assessment to support the quantitative trade-off that it performs. The GPS satellite outage results shown earlier suggest that assuming an integrity failure rate for “satellites of concern” that is two orders of magnitude greater than the number given by the SPS Performance Standard (i.e., about 10^{-3} per “troubled” SV per hour) would be sufficiently conservative for almost all of these satellites (note that the ARAIM multiple-hypothesis method does not require that the same failure probability be used for each satellite).

One concern of using a probability this high for “troubled” satellites is that independent, simultaneous failures of two “troubled” satellites would have a probability of roughly 10^{-6} per satellite per hour, and independent, simultaneous failures of one troubled satellite and one nominal satellite (using 10^{-4} per satellite per hour as conservative for nominal satellites) would have a probability of roughly 10^{-7} per satellite per hour. These probabilities are significant compared to the 10^{-7} PHMI requirement for many civil operations, which means that the multiple-hypothesis risk calculation might not be able to neglect dual-satellite failure scenarios for “troubled” satellites that it might have neglected previously because their probabilities were low enough to neglect. This is not a problem for the algorithm, but it points out one reason why the additional risk of using “troubled” satellites might not be worth the benefit.

SUMMARY AND FUTURE STEPS

This paper has examined the history of unscheduled GPS satellite outages from January 1999 to August 2011 (based upon NANU archives) and isolated two factors that can be used to identify satellites with much higher than average risk of future failures. As expected, satellite age is the primary observable factor. GPS satellites routinely outlive their predicted design lives by many years, but as they do so, they become much more susceptible to failures that require them to be declared unhealthy and repaired by the GPS OCS. In addition, certain “problem” satellites have a much greater propensity for recurring unscheduled outages than others. Therefore, once one or two recent outages have been observed on an older satellite, the probability of further outages increases significantly.

Since satellite age and number of outages are observable to GPS users (at least those who have access to NANUs or who independently monitor the constellation on a semi-worldwide basis), they can be used in heuristics that pre-emptively exclude “troubled”

satellites from use to avoid the potential integrity risk that they might pose. Doing this with today’s GPS satellite constellation is painful in terms of the number of satellites that would be excluded and the resulting degradation in positioning geometry, but this may change in the future as GPS is combined with other satellite constellations such as Galileo, GLONASS, Compass, or regional satellites such as SBAS GEOs or QZSS. In addition, a modification of the existing multiple-hypothesis protection level algorithm used in ARAIM would allow the positioning benefit of using troubled satellites to be traded against the increased failure risk that they add.

Much work remains to refine the satellite-exclusion heuristics proposed in this paper and to develop the multiple-hypothesis (MH) exclusion method into a practical algorithm. Computational workload is a concern for the MH method because the current proposal requires that a separate set of MH protection levels be computed for each satellite that is a candidate for exclusion. The performance benefit of the MH approach relative to using heuristics alone (meaning exclusion of all “troubled” satellites) should be evaluated for both the GPS-satellites-only case and one or more GPS + GNSS-satellites cases. Simulations of GNSS satellites in addition to GPS are complicated by the fact that most potentially usable non-GPS satellites are very new and have limited outage histories; thus the exclusion rules that should apply to them must be extrapolated from those that have been derived for GPS satellites.

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APPENDIX F



Ionospheric Threat Mitigation by Geometry Screening in Ground-Based Augmentation Systems

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Large spatial variations in ionospheric delay of Global Navigation Satellite System signals observed during severe ionospheric storms pose potential threats to the integrity of the Ground-Based Augmentation System, which supports aircraft precision approaches and landing. Range-domain monitoring within the Ground-Based Augmentation System ground facility cannot completely eliminate all possible ionospheric threats, because ionospheric gradients are not observable to the ground monitor if they impact the satellite-to-ground lines of sight with the worst-possible geometry and velocity. This paper proposes an algorithm called *position-domain geometry screening* to remove potentially hazardous satellite geometries under worst-case ionospheric conditions. This is done by inflating one or more integrity parameters broadcast by the ground facility. Hence, the integrity of the system can be guaranteed without any modification of existing avionics. This paper develops an algorithm that allows the ground station to conservatively estimate the worst-case ionospheric errors for Ground-Based Augmentation System users. The results of this algorithm determine which potential aircraft satellite geometries are safe and which are unsafe, and inflation of the broadcast σ_{vig} parameter is used to make all unsafe geometries unusable for the Ground-Based Augmentation System. Although the elimination of unsafe geometries reduces system availability, this paper shows that acceptable availability for category I precision approaches is attainable at Memphis International Airport and Newark Liberty International Airport while guaranteeing system integrity under anomalous ionospheric gradients.

I. Introduction

THE Ground-Based Augmentation System (GBAS) (known as the Local Area Augmentation System, or LAAS, in the United States [1]) is designed to augment Global Navigation Satellite Systems (GNSS) (e.g., the Global Positioning System, or GPS, in the United States and Galileo in Europe [2,3]) to enable GNSS-based aircraft landing guidance. A GBAS ground facility is fielded within the property of a particular airport as illustrated in Fig. 1. It measures and monitors GNSS signals and broadcasts pseudorange differential corrections and integrity information for satellites via a very-high-frequency (VHF) data broadcast transmitter. This information allows GBAS-equipped receivers on aircraft near the airport to compute the error bounds of its position solution with extremely high confidence and thus verify the safety of approach and landing operations in real time.

Almost all anomalies that could pose a threat to GBAS-supported approach and landing can be detected by monitoring of pseudorange measurements (in short, range-domain monitoring) performed by the GBAS ground facility. However, extremely large spatial gradients of GNSS signal delay due to anomalous ionospheric conditions pose a potential threat to the integrity of the guidance system. Since GBAS

reference receivers provide range-domain corrections for GNSS satellite measurements to airborne receivers within 45 km, significant ionospheric delay variation over short separations can cause nonnegligible user errors. For reasons that will be explained later, this threat cannot be completely mitigated by range-domain monitoring alone.

Datta-Barua et al. [4] first investigated anomalous ionospheric gradients discovered in 2000 by the new Wide Area Augmentation System (WAAS) [5] network of GPS reference receivers and discovered gradients as large as hundreds of mm/km (or hundreds of parts per million), which is far larger than typical ionospheric gradients of 1–5 mm/km. Even larger gradients were observed during the very powerful ionospheric storms of October and November 2003 [6,7]. Although gradients of hundreds of mm/km are very rare, the magnitude of potential GBAS user errors due to them exceeds what can be practically detected or bounded in range-domain.

To parameterize the potential threat due to ionospheric anomalies, extensive data analysis including all available ionospheric storm data in the conterminous U.S. (CONUS) was performed [6,7]. Based on the parameterized threat space, a novel position-domain mitigation technique has been developed. This method was designed to support the airborne receiver standards for category I precision-approach operations that had already been developed [8]. Subsequently, Mayer et al. [9] developed a less-threatening ionosphere threat space for Germany based on data collected there, but the CONUS threat model is used exclusively in this paper.

This paper describes a position-domain verification methodology known as geometry screening that was originally developed by the authors [10] and has been implemented by the Honeywell SLS-4000 category I LAAS ground facility to mitigate ionospheric threats in CONUS [11]. (Refer to [12] for a position-domain monitor for detecting mismodeling of GBAS tail error distributions, which is different from the geometry screening proposed in this paper for mitigating ionospheric threats.) Integrity information broadcast from the ground facility is adjusted by the mitigation algorithm so that potentially hazardous satellite geometries under ionospheric anomalies cannot be used by GBAS avionics. More recently, a simpler method of geometry screening within GBAS avionics has been

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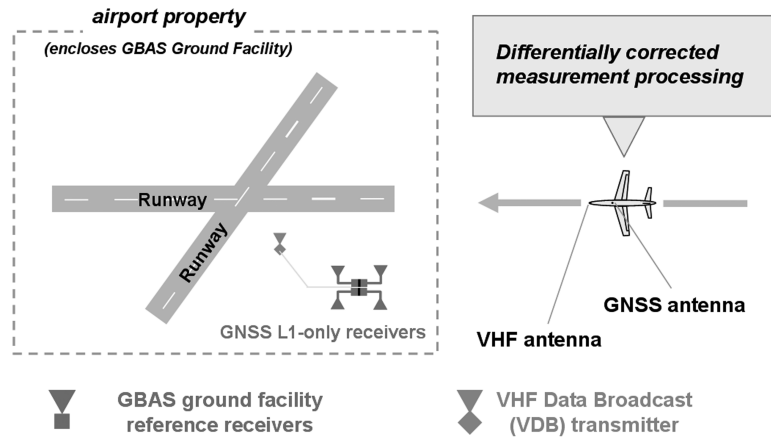


Fig. 1 Illustration of a typical GBAS configuration.

proposed for the GAST-D version of GBAS that will support categories II and III approaches for properly equipped users [13]. A major advantage of screening at the aircraft is that the actual satellite geometry is known, whereas the ground-based method described in this paper requires the evaluation of many possible airborne satellite geometries. However, applying geometry screening only at the aircraft requires additional ionospheric monitoring in both the ground station and aircraft that has not yet been fully validated.

After describing the threat posed by the anomalous gradient and developing an ionospheric threat model for CONUS in Sec. II, we provide a detailed study of GBAS errors induced by ionospheric anomalies in the range and position domains in Sec. III. Section IV develops the position-domain geometry-screening method that mitigates this threat. Further, a new mathematical expression to calculate ionosphere-induced vertical position errors is suggested. Although geometry screening involves increasing position bounds and therefore lowering availability, the simulation results in Sec. IV demonstrate that this method provides acceptable availability for category I GBAS operations at Memphis International Airport and Newark Liberty International Airport. Section V describes how geometry screening is implemented in real time in GBAS ground stations. Our conclusions are given in Sec. VI.

II. Ionospheric Gradient and Threat Model

A. Nominal and Anomalous Ionospheric Gradients

Among the various GNSS error sources, error introduced by the ionosphere is one of the largest and most variable for single-frequency GNSS users. The ionosphere is an ionized plasma region located in the Earth's upper atmosphere from about 50–2000 km in altitude. Because of the free electrons and ions produced by solar radiation, radio signals are refracted as they propagate through this region. The main effect of this refraction is a delay in the code-phase measurement of GNSS signals and an advance in the carrier-phase measurement by an equal amount. This divergence of code and carrier measurements, usually called code-carrier divergence (CCD), is one method that is used to detect anomalous ionospheric behavior (details will be provided in Sec. III.A).

Under nominal conditions (without ionospheric storms), ionospheric delays on GPS pseudorange measurements are very highly correlated over the short separations between a GBAS ground facility and approaching airplanes. Thus, differential GBAS user errors caused by typical ionospheric delays are very small and do not measurably affect system performance. However, unusual solar events such as coronal mass ejections can cause the ionosphere to behave very differently. Extremely large ionospheric gradients observed during past severe ionospheric storms produced spatial gradients that were two orders of magnitude higher than the standard broadcast 1σ value of 4 mm/km, which was chosen as a conservative bound on nominal zenith ionospheric spatial gradients [14]. Gradients this large, if undetected, could generate vertical position errors signifi-

cantly exceeding the tolerable error limit, which will be explained with details in Sec. III.B.

As mentioned earlier, Datta-Barua et al. [4] first analyzed WAAS [5] data during the 6–7 April 2000 ionospheric storms and observed gradients as large as 320 mm/km in slant (along the actual path between a satellite and a receiver). The discovery of gradients of this magnitude was a major surprise to the GBAS community because they could not be bounded by the broadcast ionospheric σ . Before investigating possible mitigation techniques, the ionospheric threat caused by large spatial gradients needed to be better-understood and parameterized based on previous observations. The ionospheric threat model in CONUS, which has been developed from several years' effort of multiple researchers, is introduced in the next section.

B. Ionospheric Threat Model for CONUS

The simplified ionospheric front geometry shown in Fig. 2 was used to develop the CONUS ionospheric threat model [6]. This model assumes a linear, semi-infinite ionospheric front that moves with constant speed relative to the ground. The threat model is parameterized by the spatial gradient (or slope) in slant ionospheric delay, the width of the zone where the gradient is present (i.e., the distance between low and high-delay regions), and the propagation speed of an ionospheric front. Note that the product of width and gradient yields a total difference in slant ionospheric delay. Each of these parameters is bounded in the ionospheric anomaly threat space summarized in Table 1. The upper bound on the gradient is given as a

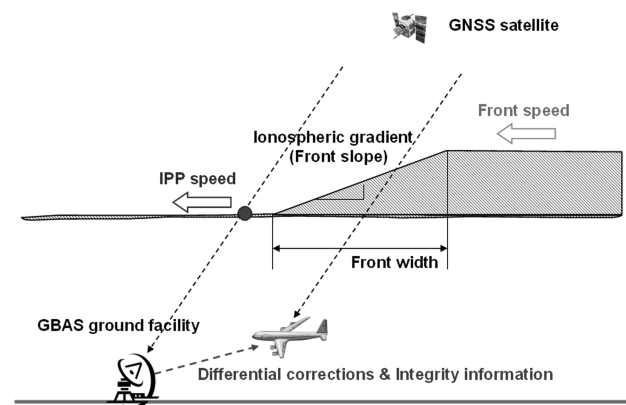


Fig. 2 Illustration of ionospheric front model. The range delay suffered at the ground facility is significantly different from the delay suffered by the aircraft in this scenario. If the front speed matches or lines up with the IPP speed, the large ionospheric gradient is not observable to the ground monitor. This undetected postcorrection range error is potentially hazardous.

Table 1 Ionospheric gradient threat space

Parameter	Value
Max. front slope, mm/km	
Low elevation ($<15^\circ$)	375
Medium elevation ($15^\circ < \text{El} < 65^\circ$)	$375 + 50(\text{El} - 15)/50$
High elevation ($>65^\circ$)	425
Front width, km	25–200
Front speed, m/s	0–750
Max. differential delay, m	50

function of satellite elevation angle: 375 mm/km at low elevation (below 15°), increasing linearly to 425 mm/km at high elevation (above 65°). These bounds slightly exceed the largest gradient validated from the CONUS data analysis due to margin added to account for measurement and estimation errors. In addition to the maximum gradient bounds, bounds were established on ionospheric front speed with respect to the ground (up to 750 m/s), ionospheric front width (between 25 and 200 km), and total differential delay (up to 50 m) [6,7]. The limit on the total delay difference acts as a constraint on the allowed combinations of width and gradient. For example, 350 mm/km and 200 km both fall within the limits for gradient and width, respectively, but their product is an implied total differential delay of 70 m, which exceeds the 50 m limit. Therefore, this combination of gradient and width falls outside the threat model.

Note that this threat model only describes potential ionospheric behavior and thus does not include other parameters that are necessary for analyzing anomalous-ionosphere-induced errors on GBAS avionics. These additional factors include the orientation of an ionospheric front with respect to an approaching airplane and a runway, the horizontal-approach speed of the aircraft, and the velocities of the ionospheric pierce points (IPPs), which represent the theoretical intersections between lines of sight to satellites and the ionosphere when modeled as a thin shell at a particular altitude above the Earth (typically 350–450 km). Figure 2 illustrates a possible configuration of an ionospheric front, airplane, runway, GBAS ground facility, and GNSS satellite. If the front velocity and the IPP velocity are the same (or very close) in direction and magnitude, the ionospheric delay observed by the ground facility does not change in time fast enough to be detected by the CCD monitor; hence, the anomalous gradient is not observable to a category I ground facility (a detailed explanation of the worst-case geometry with two impacted satellites is given in Sec. III.A). GAST-D ground facilities plan to add differential smoothed-code or carrier monitors over medium-to-long baselines to make large gradients observable directly, without requiring a significant change over time [15].

In Fig. 2, the ionospheric delay suffered at the ground facility is significantly different from the delay suffered by the aircraft. Hence, large range errors would remain even after the aircraft applies differential corrections to its range measurements. If these errors grow large enough before detection, they can cause an integrity risk to the affected aircraft.

III. Ionosphere-Induced Errors Because of Anomalous Ionospheric Gradients

This section describes in detail how anomalous ionospheric gradients can induce undetected errors in the range and position domain. Closed-form equations modeling the magnitude of range-domain errors are introduced. It is also explained that the protection level (the confidence bound on position solutions) calculated by airborne users with the nominal range-error bounds broadcast by the GBAS ground facility may not prevent integrity risk under severe ionospheric storm conditions. As noted above, this is because CCD monitors within the ground facility cannot detect anomalous ionospheric gradients with a specific geometry of satellites and ionospheric front movement.

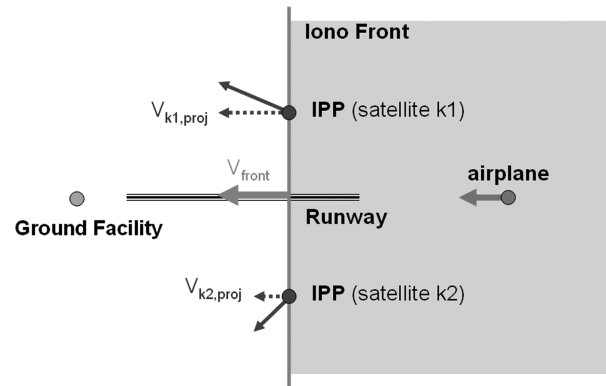


Fig. 3 An example worst-case geometry causing undetected range errors. If the projected velocity of satellite $k1$ matches with the velocity of the ionospheric front moving to the runway direction, the CCD monitor within the ground facility cannot detect the anomalous gradient impacting satellite $k1$.

A. Ionosphere-Induced Errors in the Range Domain

The CCD monitor within the GBAS ground facility is present to detect satellite-generated divergence but can also be used to detect anomalous ionospheric conditions [16]. Since the CCD monitor observes the time-variation of divergence between code and carrier measurements caused by dispersive media such as the ionosphere, its detection capability depends on the relative speed of an ionospheric front with respect to the lines of sight from the ground facility to satellites. Figure 3 illustrates an example worst-case scenario of ionospheric front movement, runway direction, and movement of ionospheric pierce points (IPPs) between the ground facility and two satellites. Under this scenario, the ionospheric front moves in the same direction as an aircraft performing a straight-in runway approach and impacts the IPPs of two satellites (satellites $k1$ and $k2$ in Fig. 3) simultaneously. At the same time, the velocity of one satellite projected onto the line perpendicular to the front ($V_{k1,proj}$) happens to be the same as the velocity of the ionospheric front (V_{front}).

As mentioned earlier, the detection capability of the CCD monitor depends on a relative speed, Δv , between the ionospheric front and the projected IPP velocity. Hence, if $V_{k1,proj}$ is the same as V_{front} as shown in Fig. 3, $\Delta v = |V_{k1,proj} - V_{front}| = 0$; the ionospheric gradient is not observable by the CCD monitor. Consequently, the remaining error on the airborne ranging measurement of satellite $k1$ can grow large without a timely alert, which implies an integrity risk. Therefore, the CCD monitor alone cannot prevent the potential integrity failure caused by ionospheric anomalies under specific worst-case combinations of geometries.

At a given epoch, the IPP velocities of the satellites in view are generally different. If the IPP of one satellite has zero Δv (as for the case of satellite $k1$ in Fig. 3), the IPP of the other satellite (i.e., satellite $k2$) at the same epoch generally has nonzero Δv (i.e., $\Delta v = |V_{k2,proj} - V_{front}| \neq 0$). Hence, there is a higher chance for an anomalous ionospheric gradient impacting the IPP of satellite $k2$ to be detected by the CCD monitor. Based on this concept and a mathematical model of the CCD monitor, Ramakrishnan et al. [17] presented closed-form expressions for ionosphere-induced range errors as functions of the relative speed Δv , based on the model originally suggested by P. Enge.** These expressions have been updated and used in [18,19] and can be summarized as follows (the derivation of these models is beyond the scope of this paper).

When Δv is small, a category I ground station that is reliant on the CCD monitor cannot detect anomalous ionospheric gradients, as explained above. Hence, to guarantee aviation integrity with a minimum reliance on assumptions, it is assumed that an undetected anomalous gradient always exists in this case. If the undetected anomalous gradient occurs with the worst-case geometry, ionosphere-induced range errors increase as the effective separation between the

**Private communication, P. Enge, May 2007.

GBAS ground facility and an approaching airplane increases, and this increase happens within the region of the linear change in slant ionospheric delay defined with the front width in Fig. 2. The effective separation includes a physical separation, x_{aircraft} , between ground facility and airplane and a synthetic separation, $2\tau v_{\text{aircraft}}$, due to the memory of the single-frequency carrier-smoothing filter in both ground and airborne GBAS measurement processing [16]. The maximum ionospheric gradient g is obtained from the CONUS ionospheric threat model [6] as a function of satellite elevation. Since the maximum differential slant delay is 50 m from the threat model, a gradient g greater than $50/w$ is not valid under the threat model and is discarded from ionosphere-induced range-error calculations (w is the ionospheric front width as defined in Fig. 2). As a result, the closed-form approximation of the ionosphere-induced differential range error ε for small Δv is expressed as follows:

$$\varepsilon = \min\left(\frac{50}{w}, g\right) \times (x_{\text{aircraft}} + 2\tau v_{\text{aircraft}}) \quad (1)$$

$$\text{if } \Delta v < \frac{0.0229}{\min(\frac{50}{w}, g)} \quad \text{and} \quad \Delta v < 0.11$$

where ε is the ionosphere-induced differential range error (meters); w is the ionospheric front width (kilometers) (refer to Fig. 2); g is the ionospheric gradient (m/km) (refer to Fig. 2); x_{aircraft} is the physical separation between the GBAS ground facility and an approaching airplane (kilometers); τ is the time constant of the single-frequency GBAS carrier-smoothing filter, 100 s for category I GBAS; v_{aircraft} is the velocity of an approaching airplane (km/s) (this paper assumes a constant velocity of 0.07 km/s); Δv is the relative speed between the ionospheric front velocity and the projected velocity of an IPP (km/s) (refer to Fig. 3). The constants 0.0229 and 0.11, specifying the boundary of a small Δv , are obtained from the CONUS threat model [6] and a conservative mathematical model of the minimum detectable error of the ground-station CCD monitor [16,19].

When Δv is moderate, the CCD monitor can detect some anomalous gradients before the maximum differential error occurs. Under the CONUS threat model, ionosphere-induced differential range errors grow no greater than 4 m in this case [17]. Hence, the closed-form model of the ionosphere-induced differential range error ε for a moderate Δv is

$$\varepsilon = 4, \quad \text{if } \frac{0.0229}{\min(\frac{50}{w}, g)} < \Delta v < 0.11 \quad (2)$$

When Δv is large, the anomalous gradients are detected by the CCD monitor with a very small probability of missed detection. Under the CONUS threat model, ionosphere-induced differential range errors grow no greater than 2.5 m in this case [17]. Hence, the closed-form model is

$$\varepsilon = 2.5, \quad \text{if } \Delta v > 0.11 \quad (3)$$

Once the satellite geometry at a particular GBAS location is known from an almanac, we can hypothesize the worst-case geometry of Fig. 3 for each individual satellite and pair of satellites with known IPP velocities at each epoch. The paired-satellite scenario always assumes that the velocity of one satellite (satellite $k1$ in Fig. 3) projected onto the line perpendicular to the ionospheric front is the same as the velocity of the front (this is the same assumption that would be made for the case where satellite $k1$ is the only satellite impacted). Thus, Δv of the other satellite (satellite $k2$) in the paired case is obtainable from the satellite geometry alone; Δv of satellite $k2$ is the same as the relative projected velocity of satellite $k2$ with respect to the projected velocity of satellite $k1$. Therefore, an almanac and the ionospheric threat model (i.e., the range of possible front widths, gradients, and velocities) provide enough information to study ionosphere-induced differential range errors using Eqs. (1–3).

For this model, the worst-case ionosphere-induced error in both the range and position domains is given by the worst pair of satellites. It is theoretically possible for three or more satellites to be simultaneously impacted by the same ionospheric front, but such scenarios

are both very improbable and are generally no more threatening to precision-approach operations than the worst two-satellite case. This is because as more satellites are impacted by the ionospheric front, a significant fraction of the induced error becomes common mode, and this component of the error only affects the GBAS clock solution.

B. Ionosphere-Induced Errors in the Position Domain

The closed-form expressions of ionosphere-induced differential range errors under the CONUS ionospheric threat model were introduced in Sec. III.A. Using these range-error models, ionosphere-induced errors in the position domain are examined in this section. Specifically, we are interested in the largest possible vertical position errors resulting from the range errors of the worst-case geometries at each epoch, as this is directly related to the integrity of GBAS systems (undetected errors exceeding a safe error limit are threatening to the users). Figure 3 shows an example worst-case geometry that results in ionosphere-induced errors without being detected by the CCD monitor. Because the CCD monitor may not alert such errors, this worst-case situation must always be assumed in order to guarantee aviation integrity without relying on the rarity of the underlying event. The ionosphere-induced vertical position error (denoted as ionosphere-induced error in vertical, or IEV) for a satellite pair ($k1, k2$) can be obtained from Eq. (4):

$$\text{IEV}_{k1,k2} = |S_{\text{vert},k1} \varepsilon_{k1}| + |S_{\text{vert},k2} \varepsilon_{k2}|$$

$$S \equiv (G^T W G)^{-1} G^T W$$

$$G_i = [-\cos \text{El}_i \cos \text{Az}_i \quad -\cos \text{El}_i \sin \text{Az}_i \quad -\sin \text{El}_i \quad 1]$$

$$W^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \dots & 0 \\ 0 & \sigma_1^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_N^2 \end{bmatrix} \quad (4)$$

where $S_{\text{vert},ki}$ is the vertical position component of the weighted-least-squares projection matrix S for satellite ki (refer to Sec. 2.3.10.2 in [8]), $S_{\text{vert},ki}$ is dependent on the satellite geometry (the number and geometric distribution of satellites in view) at each epoch, ε_{ki} is the ionosphere-induced range error for satellite ki , G_i is the i th row of the observation matrix G , corresponding to the i th satellite in view (satellite i , for simplicity); El_i is the elevation of satellite i ; Az_i is the azimuth of satellite i ; W^{-1} is the inverse of the least squares weighting matrix; and σ_i^2 is the variance of a normal distribution that overbounds the true postcorrection range-domain error distribution for satellite i under the fault-free hypothesis.

The range errors ε in Eqs. (1–3) are absolute values of actual range errors. Theoretically, the range errors of the two satellites in Fig. 3 can have any combination of positive or negative signs. The absolute value of each term is taken in Eq. (4), which results in the largest possible bounding IEV for any possible combination of signs of range errors on two impacted satellites. (Note that $S_{\text{vert},ki}$ can also be positive or negative, but it is determined by the satellite geometry regardless of ionospheric front configuration.)

For a given satellite pair, the ionospheric front velocity is always assumed to match the projected velocity of one satellite (i.e., either $V_{\text{front}} = V_{k1,\text{proj}}$, as in Fig. 3, or $V_{\text{front}} = V_{k2,\text{proj}}$). After calculating IEVs for both cases, the greater IEV value is selected because we are interested in the worst-possible vertical position error at each epoch. Note that any satellite pair from all satellites in view can be potentially impacted by the ionospheric front. Hence, the IEVs of every satellite pair from an approved satellite geometry that can be used by an approaching airplane should be calculated and compared in order to obtain the maximum IEV (MIEV) for that particular geometry. If there are k satellites in view, for example, the IEVs of

$$\binom{k}{2}$$

possible satellite pairs are calculated and compared in order to obtain MIEV.

For various reasons, satellites that are visible to the GBAS ground facility may not be included in the positioning solution of an approaching airplane. To represent this possibility, it is assumed that up to two satellites from the all-in-view satellite set at the ground facility are not used by airborne GBAS avionics during the final-approach segment. Hence, if there are N satellites visible to the GBAS ground facility, there are

$$\sum_{k=N-2}^N \binom{N}{k}$$

subset satellite geometries (subsets of the set of satellites visible to the GBAS ground facility), which can be possibly used by the airplane. Note that each subset geometry has its own MIEV; thus the maximum over all possible subsets (including the all-in-view geometry) for a particular epoch can be thought of as the maximum MIEV for that epoch. However, the maximum MIEV has little practical significance, as *every* MIEV that exceeds the tolerable limit must be mitigated, not just the worst one.

Figure 4 shows an example of MIEV values for a particular epoch. Since there are seven satellites in view at this epoch, the total number of subset geometries to consider is

$$\sum_{k=5}^7 \binom{7}{k}$$

Each of these subset geometries is represented with an index number (in no particular order) on the x axis of Fig. 4, and the MIEV of each subset geometry is plotted on the y axis. The MIEVs of 11 geometries are greater than the category I tolerable error limit (TEL) in the vertical direction (28.78 m at the minimum decision height of 200 ft) derived from the obstacle clearance surface for precision approach [20]. The geometries with indices of 4 and 25 have MIEVs greater than 50 m. These (hypothetical) large vertical position errors exceeding TEL are not acceptable for GNSS-based aircraft landing systems. Although some of the potentially hazardous geometries with MIEVs exceeding TEL are excluded by the nominal operation of airborne GBAS avionics, which will be explained in the next subsection, all must be excluded to mitigate the potential integrity risk.

C. Range-Domain Error Bounds and Protection Levels

An airborne GBAS receiver calculates the confidence bound of its position solution (usually called its *protection level*) at each epoch

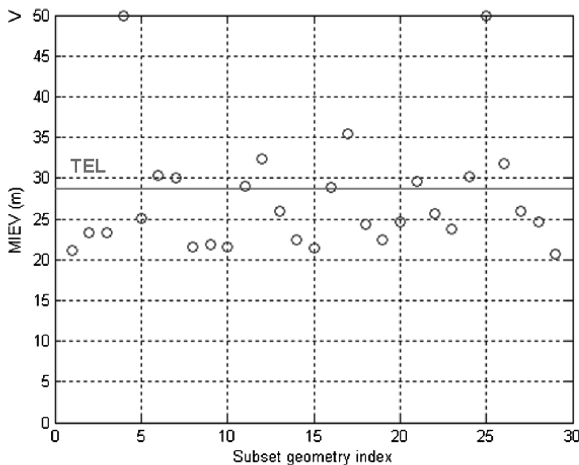


Fig. 4 MIEV of each subset geometry. Given seven satellites in view at this epoch, 29 possible subset geometries can be used by an approaching airplane. The 11 subset geometries with MIEVs exceeding the TEL are potentially hazardous for aircraft landing guidance.

based on the satellite geometry and the broadcast range-domain σ (standard deviations of zero-mean Gaussian distributions that overbound the true signal-in-space error distributions) from the ground facility. The vertical protection levels (VPLs) are calculated at each epoch using Eqs. (5) and (6) (see Secs. 2.3.11.5.2.1.4 and 2.3.11.5.2.1.5 in [8]; note that VPL_{H1} is not shown here because it is not relevant to ionospheric geometry screening):

$$VPL_{H0} = K_{\text{ffmd}} \sqrt{\sum_{i=1}^N S_{\text{vert},i}^2 \sigma_i^2} \quad (5)$$

$$VPL_{\text{eph}} = \max_k (VPL_{\text{eph},k})$$

$$VPL_{\text{eph},k} = |S_{\text{vert},k}| x_{\text{aircraft}} P_k + K_{\text{md_eph}} \sqrt{\sum_{i=1}^N S_{\text{vert},i}^2 \sigma_i^2 \Delta} \quad (6)$$

where VPL_{H0} is the vertical protection level (bound on vertical position error) under the fault-free hypothesis, K_{ffmd} is the multiplier (unitless), which determines the probability of fault-free missed detection, $K_{\text{ffmd}} = 5.847$ for four ground subsystem reference antennas to provide the required probability of 10^{-7} (refer to Sec. 2.3.11.5.2.1.4 in [8]), $S_{\text{vert},i}$ is the vertical position component of the weighted-least-squares projection matrix for satellite i , σ_i^2 is the variance of a zero-mean Gaussian distribution that overbounds the true range-domain postcorrection error distribution for satellite i under the fault-free hypothesis, $VPL_{\text{eph},k}$ is the vertical protection level under a single-satellite (satellite k) ephemeris fault, x_{aircraft} is the physical separation between the GBAS ground facility and the approaching airplane, P_k is the ephemeris error decorrelation parameter for satellite k [$P_k = 0.00018$ is used in this paper (refer to [18,19])], and $K_{\text{md_eph}}$ is the multiplier (unitless) derived from the probability of missed detection given that there is an ephemeris error in a GPS satellite [$K_{\text{md_eph}} = 5.085$ is used in this work (refer to [18,19])].

Figure 5 shows an example of calculated VPLs at the same epoch as Fig. 4. The VPL in Fig. 5 for each subset geometry is obtained as the larger value between two vertical position bounds, VPL_{H0} in Eq. (5) and VPL_{eph} in Eq. (6). If the VPL of a certain geometry exceeds the 10 m vertical alert limit (VAL) for category I precision approach, the geometry is not approved for use. Hence, the geometries with indices 4, 17, and 25 in Fig. 5 are not approved and will not be used by an airplane. If an airplane views one of these unapproved geometries with VPLs exceeding VAL at this epoch, onboard

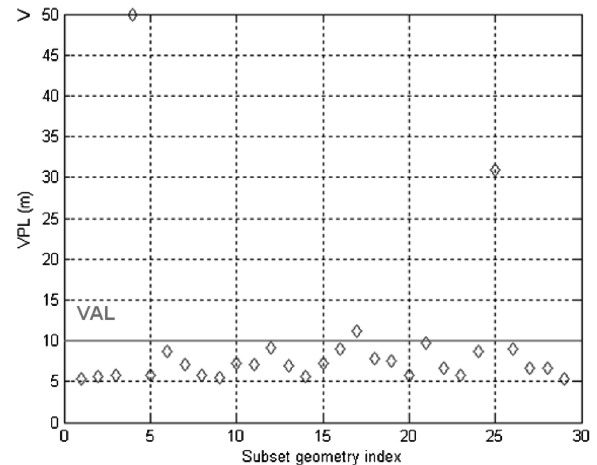


Fig. 5 VPLs with nominal range-domain error bounds at the same epoch as Fig. 4. The subset geometries with VPLs exceeding the VAL are not approved for positioning. Hence, they cannot cause an integrity failure even though their MIEVs are greater than the tolerable error limit in Fig. 4.

avionics raise a flag and hence a pilot receives a timely alert. Thus, geometries 4, 17, and 25 are potentially hazardous because their MIEVs are greater than TEL in Fig. 4, but they do not cause any integrity failure because those geometries are screened out by this VPL calculation and VAL comparison. However, if the airplane uses one of the other potentially hazardous geometries with indices 6, 7, 11, 12, 16, 21, and 26 with MIEVs exceeding TEL (Fig. 4) but whose VPLs are smaller than VAL (Fig. 5), those geometries will not be removed by the VPL calculation based on the nominal broadcast σ . If an airplane uses one of these geometries and, at the same time, the IPPs of the worst two satellites are impacted by an undetected large ionospheric gradient with the worst-case geometry as shown in Fig. 3, the position output of onboard avionics has unacceptable error but the pilot does not receive a timely alert. This would result in an integrity failure.

As explained in Sec. III.A, range-domain monitoring that relies upon the CCD monitor cannot meet the integrity requirement because ionospheric fronts are not observable to ionospheric-rate-based monitors under specific combinations of geometries (Fig. 3). Although some hazardous geometries are screened out by the nominal VPL calculation and VAL comparison, others will pass this test. Therefore, an additional defense is needed to protect against this possible integrity risk. The next section proposes a position-domain verification method to guarantee system integrity in the presence of ionospheric anomalies.

IV. Mitigating Ionospheric Threats by Position-Domain Geometry Screening

This section develops a position-domain geometry-screening method as a means to mitigate ionospheric threats. Because this method protects user integrity by indirectly removing or screening out potential user satellite geometries that would not be safe under the worst-case ionospheric anomaly, GBAS system availability is reduced. However, the results demonstrate that this method meets the integrity requirement with an acceptable loss of availability, especially when the realistic IEV equation defined here is applied to the position-domain screening algorithm.

A. Position-Domain Geometry Screening as a Means to Mitigate Ionospheric Threats

The key to screening out potentially hazardous satellite geometries is to selectively increase the integrity-related parameters broadcast by the ground facility. Among these parameters are the 1σ error bounds that contribute to the total user range-error variance σ_i^2 in Eqs. (5) and (6), which is decomposed as shown in Eqs. (7–9) (see Secs. 2.3.9.1, 2.3.12.1, and 2.3.12.3 in [8]):

$$\sigma_i^2 = \sigma_{\text{pr_gnd},i}^2 + \sigma_{\text{tropo},i}^2 + \sigma_{\text{pr_air},i}^2 + \sigma_{\text{iono},i}^2 \quad (7)$$

$$\sigma_{\text{pr_air},i}^2 = \sigma_{\text{multipath},i}^2 + \sigma_{\text{noise},i}^2 \quad (8)$$

$$\sigma_{\text{iono},i} = F_i \sigma_{\text{vig}} (x_{\text{aircraft}} + 2\tau v_{\text{aircraft}}) \quad (9)$$

where σ_i^2 is the variance of a normal distribution that overbounds the true postcorrection range-domain error distribution for satellite i under the fault-free hypothesis, $\sigma_{\text{pr_gnd},i}$ is the total fault-free 1σ ground error term associated with the corresponding differential correction error for satellite i , $\sigma_{\text{tropo},i}$ is the 1σ ground error term associated with residual tropospheric uncertainty for satellite i , $\sigma_{\text{pr_air},i}$ is the 1σ error term that bounds fault-free airborne receiver measurement error for satellite i , $\sigma_{\text{multipath},i}$ is the fault-free 1σ airborne error term associated with multipath error for satellite i , $\sigma_{\text{noise},i}$ is the fault-free 1σ airborne error term associated with receiver noise for satellite i , $\sigma_{\text{iono},i}$ is the 1σ ground error term associated with residual ionospheric uncertainty for satellite i , F_i is the vertical-to-slant ionospheric thin-shell-model obliquity factor (unitless) for satellite i , σ_{vig} is the standard deviation of a normal distribution associated with residual ionospheric uncertainty due to nominal

spatial decorrelation (vig stands for vertical ionospheric gradient), x_{aircraft} is the horizontal separation between the GBAS ground facility and airplane, τ is the time constant of the single-frequency carrier-smoothing filter in the GBAS avionics, 100 s (same as that used in the ground facility), and v_{aircraft} is the horizontal-approach velocity of the airplane in the direction of the GBAS-equipped airport.

Recall that, as demonstrated in Figs. 4 and 5, the airborne VPL calculation in Eqs. (5) and (6) does not remove all potentially hazardous geometries if nominal σ are broadcast. However, if the GBAS ground facility increases the broadcast σ values or, in other words, inflates them above the nominal values, the airborne VPL increases as well. Once sufficient σ inflation is implemented, all hazardous geometries would be screened out because their individual VPLs would all exceed VAL. Of course, many geometries that are not hazardous will be screened out as well, leading to an unavoidable loss of availability.

A key design decision for geometry screening is to select the most effective parameter(s) to inflate among the broadcast σ . We selected σ_{vig} as the most effective parameter because increasing σ_{vig} naturally increases σ_i^2 in Eq. (7) as a function of the ground-to-aircraft separation x_{aircraft} [see Eq. (9)]. The inflated value of σ_{vig} (or, equivalently, the σ_{vig} inflation factor) should be just large enough to increase the VPL of all potentially hazardous geometries (recall that this means geometries with MIEVs exceeding TEL, as shown in Fig. 4) over VAL so that they cannot be used by airborne receivers. If the inflation factor is increased further, additional safe geometries will be screened out unnecessarily.

To obtain the minimum acceptable inflation factor, the ground facility calculates the MIEVs of all credible airborne subset geometries at a given epoch and then computes VPL for each of these geometries using the nominal $\sigma_{\text{vig}} = 4.0$ mm/km suggested in [14] and an initial (default) inflation factor $I_{\text{vig}} = 1$. In this paper, a more-conservative number, $\sigma_{\text{vig}} = 6.4$ mm/km, is used as the nominal value to include additional margin for anomalous tropospheric errors (this is in accordance with [19]). In general, VPLs for the all-in-view geometry and each credible airborne subset geometry are calculated using the inflated $\sigma_{\text{vig}} = 6.4 I_{\text{vig}}$ mm/km. If the VPLs computed using the initial (or current) value of σ_{vig} are not large enough to remove all potentially hazardous geometries, the ground facility increases the inflation factor I_{vig} by a small amount (we used a step size of 0.01) and performs the VPL calculations again using the updated inflation factor until all hazardous geometries are properly removed. After obtaining the minimum inflation factor that eliminates all hazardous geometries, the ground facility calculates and broadcasts the inflated σ_{vig} based on this inflation factor. Since the ground-facility processing involves position-domain calculation and verification (i.e., MIEV and VPL are calculated in the position domain and are compared with TEL and VAL, respectively), this method is called *position-domain geometry screening*. Note that, except for this procedure, the ground facility only implements range-domain (CCD) monitoring on a satellite-by-satellite basis. Although almost all other anomalies can be detected by the range-domain monitoring included in the category I GBAS ground facility, the worst-case ionospheric anomaly requires this additional mitigation technique.

Figure 6 illustrates geometry screening by σ_{vig} inflation using the same example satellite geometry shown in Figs. 4 and 5. After applying the inflated σ_{vig} values, the VPLs of the potentially hazardous geometries with MIEVs exceeding TEL (i.e., geometries 6, 7, 11, 12, 16, 21, 24, and 26) are now greater than VAL. Hence, all hazardous geometries are properly removed. The geometries 4, 17, and 25 are not displayed here because those geometries are already screened out without σ_{vig} inflation, as shown in Fig. 5. Unfortunately, the inflated σ_{vig} eliminates some safe geometries as well. For example, geometries 10, 15, 18, and 19 in Fig. 6 are safe to use because their MIEVs are smaller than TEL, but they are also removed from the approved set of geometries. This inevitable removal of safe geometries by σ_{vig} inflation reduces the availability of the GBAS system. The next section discusses the expected availability of GBAS-supported category I precision approach when the position-domain geometry-screening method is applied.

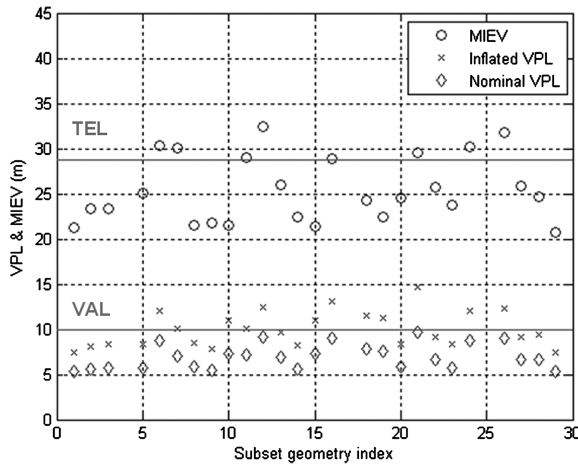


Fig. 6 Position-domain geometry screening by σ_{vig} inflation. (The inflation factor I_{vig} is 2.58 in this case.) The subset geometries with inflated VPLs exceeding VAL are not approved by airborne receivers. Hence, all hazardous geometries with MIEVs exceeding TEL are excluded after σ_{vig} inflation. The downside is that several safe geometries with MIEVs less than TEL are screened out as well. (An approaching airplane is assumed to be at 6 km from the ground facility in this simulation.)

B. Availability Analysis with Position-Domain Geometry Screening

Figure 6 illustrated an example result of position-domain geometry screening at a single epoch and a single distance from the ground facility that is at or near the maximum practical separation for existing airports. After applying the inflation factor to the VPL calculation, all potentially hazardous geometries at the given epoch and distance are screened out. To analyze the resulting system availability over a 24 h period of repeatable GPS satellite geometries, we calculate an inflation factor at every minute over 24 h (i.e., a total of 1440 epochs). In Fig. 6, we exclusively considered a distance of 6 km from the ground facility to an airplane that just reaches the 200 ft decision height (DH) of category I precision approaches (for simplicity, we notate this as DH = 6 km). However, DH can vary depending on the station and runway configuration. To cover all possible DHs, DH = 1 through 6 km (every 1 km) are considered in the simulation that generates inflation factors. In addition to the actual six DH distances, the simulation includes a hypothetical DH at 7 km to provide additional margin against granularity while protecting real DHs as far out as 6 km. The granularity problem comes from running simulations only for a limited number of discrete distances. As an example, the inflation factor required to protect a DH at 5.5 km could be larger than those driven by DH = 5 and 6 km. These small irregularities mean that the availability curve is not perfectly monotonic, but the curve as a whole decreases with increasing DH separation. Thus, a DH at 7 km generally requires more inflation than at 6 km, and adding it to the simulation provides margin against irregularities at shorter DH separations that are not sampled.

In addition to simulating a range of DH separations, an approaching airplane from DH + 7 km to the DH (checking every 1 km along this path) is simulated because the system must guarantee its integrity in this whole region. Consequently, a total of 56 cases (seven DHs and eight distances from a given DH) are considered at each epoch, and the largest inflation factor over all cases is chosen to obtain the new broadcast σ_{vig} of the epoch. The TELs [20] and VALs [8] at different distances from the DH location are shown in Fig. 7. Note that both TEL and VAL increase linearly beyond the DH because the distance from the nominal airplane path to potential obstacles grows.

For the availability analyses in this section, the standard RTCA 24-satellite GPS constellation (Table B-1 in [21]) is used, and the GBAS ground facility is assumed to be located at Newark airport (EWR) in New Jersey. The ground and airborne error models used in this study are plotted in Fig. 8. For the airborne error model, $\sigma_{\text{pr-air}}$ in Eq. (8), the

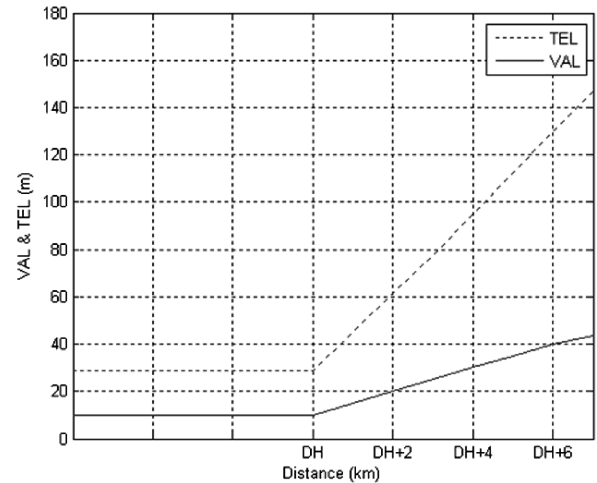


Fig. 7 TEL and VAL for category I precision approaches. Each runway has its own DH (distance from the ground facility to an airplane when the airplane reaches the minimum decision height of 200 ft).

more-severe airborne error model is used for MIEV calculation (i.e., airborne noise model, σ_{noise} , with airborne accuracy designator A [8]), and the minimum error model (i.e., $\sigma_{\text{noise}} = 0$ or $\sigma_{\text{pr-air}} = \sigma_{\text{multipath}}$) is used for VPL_{H0} and VPL_{eph} in Eqs. (5) and (6). This combination is a conservative choice because it maximizes MIEV while minimizing VPL. Thus, it considers more subset geometries as being potentially hazardous, and by increasing the gap between VPL and VAL, it increases the inflation factors required to remove potentially hazardous geometries. Separately, to determine the availability of the resulting VPL_{H0} and VPL_{eph} using inflated σ_{vig} (i.e., $I_{\text{vig}}\sigma_{\text{vig}}$), the less-severe error model (i.e., airborne noise model σ_{noise} , with airborne accuracy designator B [8]) is used to represent a more common state of airborne equipment.

With these settings, the required inflation factor I_{vig} at each epoch is calculated and shown in Fig. 9. It is notable that a significant fraction of epochs require no inflation; i.e., $I_{\text{vig}} = 1$ is sufficient. This tends to occur when the all-in-view geometry is very good such that all two-satellites-removed subsets are good enough to adequately resist the worst-case ionospheric anomaly. However, a substantial majority of epochs require inflation, and the amount of inflation often exceeds a factor of 2 and sometimes a factor of 3. This degree of σ_{vig} inflation may affect airborne user availability on some of these epochs. Note that an upper bound on I_{vig} exists because the maximum value of σ_{vig} that can be broadcast by GBAS is 25.5 mm/km [22].

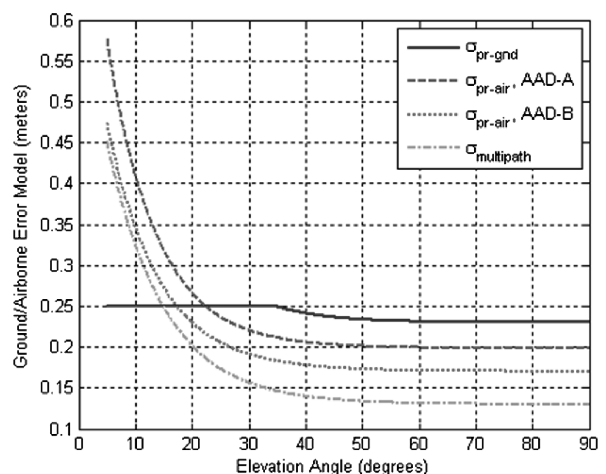


Fig. 8 Ground/airborne error models used in this paper; $\sigma_{\text{pr-grd}}$ (refer to [18,19]), $\sigma_{\text{pr-air}}$ with airborne accuracy designator A (AAD-A), $\sigma_{\text{pr-air}}$ with airborne accuracy designator B (AAD-B), and $\sigma_{\text{multipath}}$.

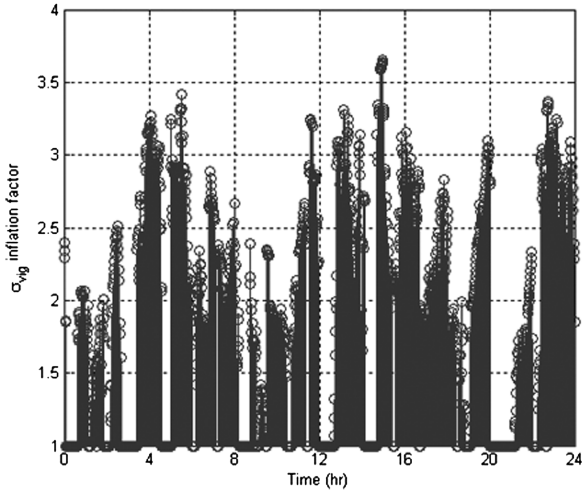


Fig. 9 The σ_{vig} inflation factors. The inflation factor at each epoch is the largest value among the inflation factors obtained at DH separations of 1 to 7 km (every 1 km) and aircraft distances from the DH of 0 to 7 km (every 1 km). The broadcast σ_{vig} is the nominal σ_{vig} of 6.4 mm/km times these inflation factors.

Given the nominal value of 6.4 mm/km used here, the maximum value of I_{vig} is $25.5/6.4 = 3.984$, or just under 4.0. The inflation factors for Newark in Fig. 9 stay within this constraint, but several epochs exceed 3.5 and thus come relatively close to it. If an inflation factor larger than this limit were ever required to protect integrity, the simplest option would be to discontinue the broadcast of differential corrections until the required inflation factor fell below the limit. Such a drastic step would not be needed if another broadcast parameter (such as $\sigma_{\text{pr_gnd}}$) could be inflated as well to exclude the potentially unsafe geometries that could not be removed by σ_{vig} at its maximum value.

By applying inflation factors to σ_{vig} , all potentially hazardous geometries (and many more acceptable geometries) are eliminated from the approved set of geometries. Hence, system integrity is guaranteed but with reduced system availability. We can estimate system availability at Newark for an aircraft at a DH 6 km from the ground facility using all satellites in view based on the VPL results in Fig. 10. In Fig. 10, nominal VPLs without inflation are always below the 10 m VAL at the DH. If VPL is lower than VAL at a particular epoch, the landing guidance service is available at the epoch (assuming that the aircraft uses all satellites in view, which it normally will). Hence, the availability during the 24 h period would have been 100% if the ionospheric anomaly threat did not exist or was less severe. Under the ionospheric threat model described earlier, the need for inflation of the broadcast σ_{vig} values results in VPLs that are also inflated, and there are several cases of VPLs exceeding VAL as shown in Fig. 10. The resulting availability impact is significant (97.5% availability instead of 100%), and the margin between VPL and VAL is reduced by inflation.

The degree of inflation required here is driven by the size of MIEV and the degree to which credible satellite subsets have MIEVs exceeding TEL. IEV for these results was determined by Eq. (4). This equation generates a conservative bound, but as will be explained shortly, it is too conservative to represent the threat model developed for CONUS. In the following section, we propose a modified equation for IEV to reduce the required inflation and improve availability without sacrificing integrity.

C. Availability Benefit from a More Realistic IEV Calculation

Equation (4) represents a very conservative expression to calculate IEV. As previously explained, this conservatism comes from considering all possible combinations of positive and negative differential range errors of two impacted satellites. If an anomalous gradient hits two satellites, as in Fig. 3, the pseudorange correction errors of both satellites induced by the same ionospheric gradient

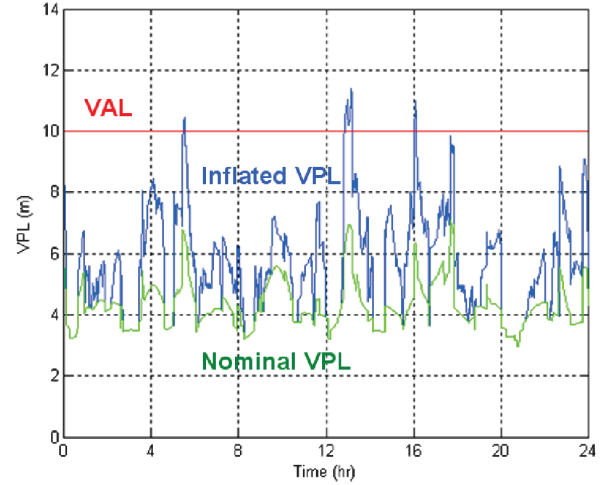


Fig. 10 Nominal VPL without inflation and inflated VPL (after applying the inflated σ_{vig}) at Newark airport. VPL at each epoch is the larger of VPL_{H0} in Eq. (5) and VPL_{eph} in Eq. (6). Availability during the 24 h period is 97.5% for a DH at 6 km and an aircraft using all satellites in view. The margin between VPL and VAL is significantly reduced after σ_{vig} inflation.

should have the same sign. It is not expected that the same ionospheric gradient causes a differential range delay for one satellite and a differential range advance on the other satellite. However, the carrier-smoothing filter [23] of GBAS avionics adds complexity to this picture. It is well known that the effects on code and carrier measurements due to dispersive media such as the ionosphere have the same magnitude but opposite signs, which means, for example, that positive code errors are accompanied by negative carrier errors. In GBAS, the carrier-smoothing filter smooths code measurements with less-noisy carrier measurements using a 100 s time constant. Since carrier measurements dominate in the smoothing filter outputs shortly after the impact of an ionospheric gradient, the error of smoothed code during this initial response grows in the opposite direction with respect to the error from a converged filter [24]. Figure 11 illustrates this behavior. During the early phase of smoothing, the smoothed range error has a negative sign, but its magnitude, $c \cdot \varepsilon$ ($0 < c < 1$), is much smaller than the positive magnitude of the maximum range error, ε ($0 < \varepsilon$), of a converged filter (recall that ε can be obtained from Eqs. (1–3) depending on Δv of the corresponding satellite). For this reason, a positive range error of one satellite can be accompanied by a negative, but relatively small, range error of the other satellite when two satellites are impacted almost simultaneously by the same ionospheric gradient front.

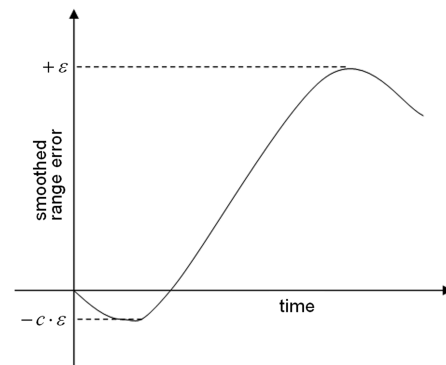


Fig. 11 Illustration of smoothed differential range error on a satellite after the impact of an ionospheric gradient. During the early phase of smoothing, the smoothed range error has a negative sign, although the smoothed range error from a converged filter has a positive sign in this example. Note that the magnitude of the maximum negative error, $c \cdot \varepsilon$, is much smaller than the magnitude of the maximum positive error, ε .

Although Eq. (4), which has been used in [18,19], covers the worst case of any possible combination of signs of differential range errors, it is a very conservative expression because it does not consider the characteristics of the carrier-smoothing filter described here and shown in Fig. 11. To represent the large magnitude difference between differential range errors with opposite signs of two impacted satellites, we suggest a more realistic expression to calculate IEV in Eq. (10):

$$\text{IEV}_{k1,k2} = \max\{|S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}|, |S_{\text{vert},k1}\varepsilon_{k1} - c \cdot S_{\text{vert},k2}\varepsilon_{k2}|, |S_{\text{vert},k2}\varepsilon_{k2} - c \cdot S_{\text{vert},k1}\varepsilon_{k1}|\} \quad (10)$$

The first term, $|S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}|$, represents the larger vertical error between a positive-positive range-error combination of two impacted satellites (i.e., $S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}$) and a negative-negative range-error combination (i.e., $-S_{\text{vert},k1}\varepsilon_{k1} - S_{\text{vert},k2}\varepsilon_{k2}$) because

$$\max\{S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}, -S_{\text{vert},k1}\varepsilon_{k1} - S_{\text{vert},k2}\varepsilon_{k2}\} = |S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}| \quad (11)$$

Similarly, the second and the third terms of Eq. (10) consider positive-negative range-error combinations. To represent the constraint shown above, once one satellite has a range error of ε_{k1} , the other satellite can only have a range error of $-c \cdot \varepsilon_{k2}$, which cannot be greater than $-\varepsilon_{k2}$ in magnitude. The maximum of these three terms in Eq. (10) is the largest possible IEV under any combination of signs of range errors between two satellites impacted by the same ionospheric gradient, as in Fig. 3.

If the c factor in Fig. 11 and Eq. (10) is assumed to be 1, the realistic IEV equation in Eq. (10) becomes the same as the conservative IEV equation in Eq. (4) (see the Appendix for proof). Therefore, Eq. (4) is merely the most conservative case of Eq. (10) when we consider the unrealistic situation of equally large positive and negative range errors (i.e., ε_{k1} and $-\varepsilon_{k2}$) on two impacted satellites. It is emphasized again that combinations of ε_{k1} and ε_{k2} or $-\varepsilon_{k1}$ and $-\varepsilon_{k2}$, or two impacted satellites are realistic, but combinations of ε_{k1} and $-\varepsilon_{k2}$, or $-\varepsilon_{k1}$ and ε_{k2} are not realistic. Only ε_{k1} and $-c \cdot \varepsilon_{k2}$, or $-c \cdot \varepsilon_{k1}$ and ε_{k2} with $0 < c < 1$ are realistic if the range errors of two satellites have opposite signs. Luo et al. [24] showed that the magnitude of differential range errors during the early phase of smoothing is less than 20% of the magnitude of differential range errors from a converged filter. Hence, $c = 0.2$ provides a reasonable bound on the differential range errors with opposite signs when two satellites are impacted by the same ionospheric gradient.

Note that the discussion thus far pertains to two satellites impacted by the same ionospheric gradient. However, the filament structure of enhanced ionospheric delay observed in CONUS on 20 November 2003 (as shown in Fig. 12) indicates a possible exception. In this situation, it is possible for one affected satellite to observe a positive change in delay from the increasing-delay gradient that forms the leading edge of the filament, while another satellite simultaneously observes a negative change in delay from the decreasing-delay gradient that forms the trailing edge. In other words, under very rare circumstances, two satellites can be impacted by two different ionospheric gradients having opposite signs. However, the worst-case gradient would not be present on both edges at the same time. All of the near-maximum-gradient observations made from this event (for both high- and low-elevation satellites) came from the trailing edge at the time when the sharp downward change was observed in Ohio (just after 21:00 UT on 20 November 2003). The gradient on the leading edge ranged from roughly 30 to 120 mm/km, which is much lower than the (up to) 425 mm/km seen at the worst place and time on the trailing edge (Fig. 10 of [6]). Therefore, even this case better fits the proposed realistic IEV equation than the conservative IEV equation. The only change would be that the c factor in Eq. (10) might have to be increased from 0.2. If we take the ratio of 120/425 as a guideline, c would increase to about 0.28, and $c = 0.5$ would be a very conservative bound on this dual-front scenario.

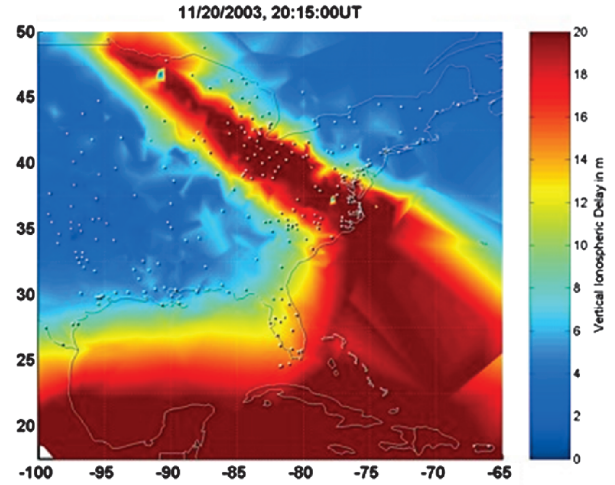


Fig. 12 Map of vertical ionospheric delay over eastern United States on 20 November 2003 at 20:15 UT (reproduction of Fig. 2 of [6]).

The benefit of the realistic IEV equation in Eq. (10) is clearly shown in Fig. 13. Comparing with Fig. 6, The MIEVs of the subset geometries are significantly reduced by the realistic IEV equation with $c = 0.5$. As a result, only one geometry (i.e., geometry 12) with MIEV exceeding TEL but VPL lower than VAL is potentially hazardous. (Remember that eight geometries are potentially hazardous in Fig. 6 applying the conservative IEV equation.) Thus, small inflation with $I_{\text{vig}} = 1.47$ is enough to screen the potentially hazardous geometry. By this inflation, two safe geometries (i.e., geometries 16 and 21) are also screened, but the number of approved geometries in Fig. 13 is 23, which is significantly better than the 14 approved geometries after the geometry screening in Fig. 6. The reduced inflation of VPL is directly related to availability benefit.

Using the realistic IEV equation proposed in Eq. (10), the availability analysis of the position-domain geometry-screening method is performed again. For this analysis, the cases of $c = 0.2$ and 0.5 are evaluated and compared. As shown in Fig. 14, the inflated VPLs with the realistic IEV calculation are not much greater than the nominal VPLs without σ_{vig} inflation, and 100% availability for aircraft using all satellites in view is achievable in these cases at Newark airport. More important, the new IEV equation provides significant margin between the inflated VPLs and VAL for both $c = 0.2$ and 0.5 , which is a major improvement compared with Fig. 10. Very similar results were obtained for Memphis airport (MEM), as shown in Fig. 15. Therefore, the position-domain

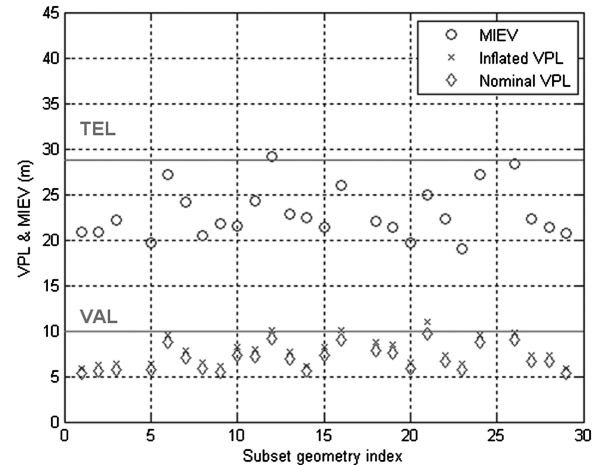


Fig. 13 Reduced MIEVs due to the realistic IEV equation with $c = 0.5$. (Except for the IEV equation, all other settings are the same as Fig. 6.) Comparing with Fig. 6, the inflation factor I_{vig} is significantly reduced from 2.58 to 1.47.

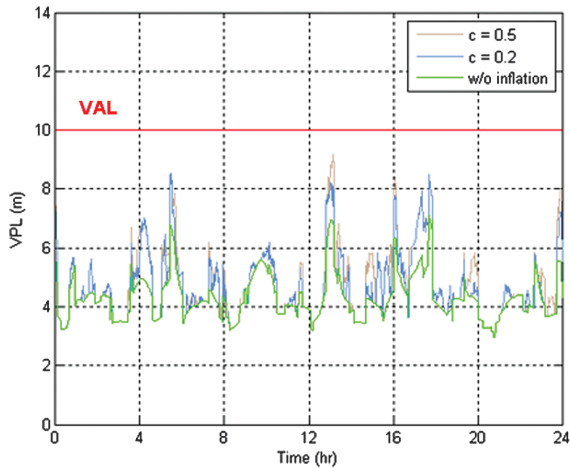


Fig. 14 Inflated VPLs calculated using the realistic IEV equation with $c = 0.2$ and $c = 0.5$ at Newark airport. $c = 0.2$ is a conservative value for two satellites impacted by a single ionospheric gradient, while $c = 0.5$ is a very conservative value that bounds all observed anomalous ionospheric conditions in CONUS, including a case where two gradients were caused by the same anomaly. For both cases, the gap between the inflated VPL and VAL is much larger than in Fig. 10.

geometry-screening method proposed in this paper can mitigate the worst-case ionospheric anomalies with a tolerable sacrifice of availability, especially when the newly proposed IEV equation is applied.

V. Real-Time Implementation of Geometry Screening

To be useful for ionospheric threat mitigation, the algorithms described in this paper must operate in real time within GBAS ground stations. It is theoretically possible to determine a worst-case inflation factor for a particular location via offline simulation, but it would be difficult to bound the set of possible variations of the GPS satellite constellation. Any reasonable allowance for significant constellation variation would likely create cases where the inflation factor exceeds the maximum allowed broadcast value of 3.984 derived in Sec. IV.B. Even if the maximum inflation factor in Fig. 9 (about 3.7) were accepted as the maximum possible value and were used all the time, the resulting category I approach availability would be unacceptably poor.

Because the simulation of all possible subset geometries to determine MIEV and the resulting inflation-factor search cannot be performed at the same rate that type I GBAS messages are updated

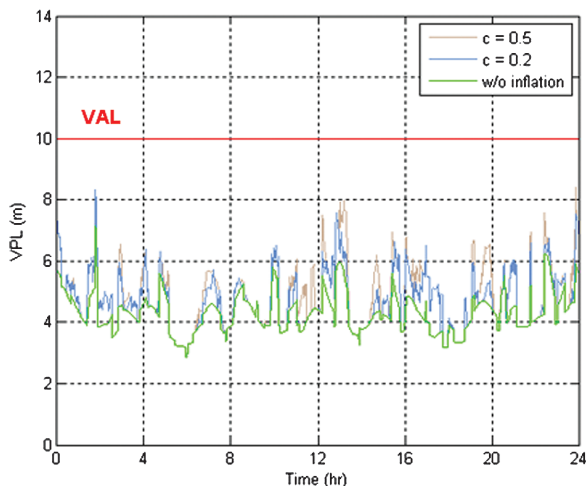


Fig. 15 Inflated VPLs calculated using the realistic IEV equation with $c = 0.2$ and 0.5 at Memphis airport. This result is very similar to the case of Newark in Fig. 14.

(twice per second), a slower update rate that corresponds to the rate of change of GPS satellite geometries must be selected. After some investigation, an inflation-factor update interval of 1 min (60 s, or 120 epochs at 2 Hz) has proven to be workable. Note that, if 1 min updates are used, a new inflation factor must be valid for the 60 s interval going forward until it is updated. In other words, when the geometry-screening algorithm determines a new inflation factor to be broadcast from time t_1 , that inflation factor must be valid over the interval $[t_1, t_1 + 60 \text{ s}]$. Therefore, separate inflation factors must be computed in advance for t_1 and $(t_1 + 60 \text{ s})$, and the larger of the two resulting inflation factors becomes the one that is broadcast over this interval.

Recall that the only thing that changes over time is the visible GPS satellite geometry. The procedure outlined above assumes that the 60 s update interval is short enough compared with the change in satellite geometry that the maximum of the t_1 and $(t_1 + 60 \text{ s})$ inflation factors is an acceptable bound on the entire interval. This assumption is clearly not perfect, but the error in it is acceptable as long as the interval between inflation-factor updates is reasonably short. Shorter intervals also have the effect of reducing the slight availability loss that comes from taking the maximum of two inflation factors over the update interval.

Regardless of the update interval chosen, a special procedure has to be added to handle sudden, unexpected losses of visible satellites in between normal inflation-factor updates. A sudden satellite loss can significantly increase the required inflation factor, but the ground-screening algorithms cannot be rerun to generate updated numbers instantly. Several strategies exist to handle this situation. The simplest is to delay updating as long as the ground-system time-to-alert allocation allows (3 s for category I precision approach). If a new inflation factor is not ready at that point, the maximum value of σ_{vig} (25.5 mm/km) can be broadcast until it is ready. This approach is nonoptimal in that it increases continuity risk more than is necessary. Alternatives that include precalculating inflation factors that would apply in case of satellite loss within the next update interval are preferable if computational resources allow this to be done within acceptably short update intervals.

Because GBAS ground stations do not interact with the outside world, they currently have no means of distinguishing anomalous ionospheric conditions beyond the monitors mentioned in this paper. The presence of potential ionospheric threats must be presumed at all times; therefore, geometry screening must be active at all times. This is very costly, as precision-approach availability is always sacrificed even though it is very rare for the ionosphere to be anomalous enough to potentially threaten GBAS. Furthermore, because geometry screening is not sufficient to support the GBAS Differentially Corrected Positioning Service (DCPS), DCPS has not yet been approved for use [19].

Several alternatives that would provide GBAS with sufficient knowledge to discontinue geometry screening and σ_{vig} inflation when the ionosphere is known to be nonthreatening have been proposed. One is to allow GBAS stations within good Satellite-Based Augmentation System (SBAS) coverage to use SBAS ionospheric corrections and error bounds as a means of determining when the ionosphere is nonthreatening [25]. This method is the easiest to integrate into GBAS since SBAS correction messages are broadcast as GPS L1 C/A-code signals. Whereas the benefits of SBAS information would be limited to regions with good SBAS coverage, SBAS is expected to expand to cover a large majority of the populated world over the next decade. Another approach that would require a new data channel into GBAS would be the use of improved space weather forecasts and to alert GBAS stations of the potential for ionospheric anomalies. A great deal of progress has been made in space weather forecasting and nowcasting over the past decade, but unlike SBAS, the current state of the art appears to fall short of the level of assurance needed for use in safety-critical systems.

VI. Conclusions

Anomalous ionospheric gradients that have been observed during severe ionospheric storms pose a potential integrity threat to

GNSS-based aircraft landing guidance systems. Under worst-case gradient configurations and aircraft approach geometries, anomalous gradients cannot be detected by the code-minus-carrier (CCD) range-domain monitor within a GBAS ground facility. Undetected gradients can cause unacceptable range errors for certain satellite geometries that can possibly be used by an approaching airplane. For category I precision-approach operations, it is not practical to modify airborne equipment that has already been certified. Instead, this paper proposes a method for position-domain threat evaluation and geometry screening performed by the GBAS ground facility. Once values of σ_{vig} inflated as needed by the position-domain screening process are broadcast, all potentially hazardous geometries with large undetected range errors are eliminated from the set of geometries that can be approved by the VPL calculation onboard the aircraft. This position-domain screening process requires significant software changes to the ground facility but does not require any modifications to airborne equipment or to the ground-to-airborne interface definition. However, the availability of the landing guidance system is reduced after the airborne VPL is inflated by the screening process.

To minimize the availability impact of geometry screening, this paper proposes a modified equation for worst-case ionospheric error impacts that removes unnecessary conservatism from previous calculations. Using this revised algorithm, availability analyses demonstrated that better than 99.9% availability for category I precision approach is attainable with margin at both Newark and Memphis airports without compromising system integrity.

The GAST-D upgrade to GBAS to support category II and III operations will make use of the lessons learned in developing geometry screening for category I ground systems. Monitoring will be added to both ground systems and avionics such that ground-based geometry screening is no longer necessary. Instead, each aircraft will perform its own screening based upon knowledge of its particular preapproach satellite geometry and its specific performance characteristics.

Appendix: Proof of IEV Equivalence When $c = 1$

This Appendix proves Eq. (A1), which states that Eq. (10) is the same as Eq. (4) when $c = 1$:

$$\begin{aligned} & \max\{|S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2}|, |S_{\text{vert},k1}\varepsilon_{k1} - S_{\text{vert},k2}\varepsilon_{k2}|\} \\ &= |S_{\text{vert},k1}\varepsilon_{k1}| + |S_{\text{vert},k2}\varepsilon_{k2}| \end{aligned} \quad (\text{A1})$$

Since the left-hand side and the right-hand side of Eq. (A1) are all positive, Eq. (A1) is equivalent to Eq. (A2):

$$\begin{aligned} & \max\{(S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2})^2, (S_{\text{vert},k1}\varepsilon_{k1} - S_{\text{vert},k2}\varepsilon_{k2})^2\} \\ &= (|S_{\text{vert},k1}\varepsilon_{k1}| + |S_{\text{vert},k2}\varepsilon_{k2}|)^2 \end{aligned} \quad (\text{A2})$$

The left-hand side of Eq. (A2) can be expanded as follows:

$$\begin{aligned} & \max\{(S_{\text{vert},k1}\varepsilon_{k1} + S_{\text{vert},k2}\varepsilon_{k2})^2, (S_{\text{vert},k1}\varepsilon_{k1} - S_{\text{vert},k2}\varepsilon_{k2})^2\} \\ &= \max\{S_{\text{vert},k1}^2\varepsilon_{k1}^2 + S_{\text{vert},k2}^2\varepsilon_{k2}^2 + 2 \\ &\quad \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}, S_{\text{vert},k1}^2\varepsilon_{k1}^2 + S_{\text{vert},k2}^2\varepsilon_{k2}^2 - 2 \\ &\quad \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}\} = S_{\text{vert},k1}^2\varepsilon_{k1}^2 + S_{\text{vert},k2}^2\varepsilon_{k2}^2 \\ &\quad + \max\{2 \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}, -2 \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}\} \end{aligned} \quad (\text{A3})$$

The right-hand side of Eq. (A2) can be similarly expanded as follows:

$$\begin{aligned} & (|S_{\text{vert},k1}\varepsilon_{k1}| + |S_{\text{vert},k2}\varepsilon_{k2}|)^2 = S_{\text{vert},k1}^2\varepsilon_{k1}^2 + S_{\text{vert},k2}^2\varepsilon_{k2}^2 \\ & \quad + 2|S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}| \end{aligned} \quad (\text{A4})$$

Since the first term in Eq. (A3) also appears in Eq. (A4), we only need prove Eq. (A5) to show that Eqs. (A3) and (A4) are the same:

$$\begin{aligned} & \max\{2 \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}, -2 \cdot S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}\} \\ &= 2|S_{\text{vert},k1}\varepsilon_{k1}S_{\text{vert},k2}\varepsilon_{k2}| \end{aligned} \quad (\text{A5})$$

Since $\max\{a, -a\} = |a|$ for any real number a , Eq. (A5) is true. Therefore, Eq. (A2) is proven; thus Eq. (A1) is also proven.

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