

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

NEARMAP US, INC.,
Petitioner

v.

PICTOMETRY INTERNATIONAL CORP.,
Patent Owner

IPR2024-00729
Patent 9,182,657

**EXPERT DECLARATION OF JUNE ANN MUNFORD IN
SUPPORT OF PETITION FOR *INTER PARTES* REVIEW OF
U.S. PATENT NO. 9,182,657**

1. My name is June Ann Munford. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same. Unless otherwise indicated, I have personal knowledge of the facts set forth in this Declaration. All statements herein made of my own knowledge are true and all statements made on information and belief are believed to be true. If called upon to do so, I would testify competently thereto.
2. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Appendix CV.
3. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog search performance and creating lending agreements between libraries during my time as a Library

Director.

4. I am fully familiar with the catalog record creation process in the library sector. In preparing a material for public availability, a library catalog record describing that material would be created. These records are typically written in Machine Readable Catalog (herein referred to as “MARC”) code and contain information such as a physical description of the material, metadata from the material’s publisher, and date of library acquisition. In particular, the 008 field of the MARC record is reserved for denoting the date of creation of the library record itself. As this typically occurs during the process of preparing materials for public access, it is my experience that an item’s MARC record indicates the date of an item’s public availability.
5. Typically, in creating a MARC record, a librarian would gather various bits of metadata such as book title, publisher and subject headings among others and assign each value to a relevant numerical field. For example, a book’s physical description is tracked in field 300 while title/attribution is tracked in field 245. The 008 field of the MARC record is reserved for denoting the creation of the library record itself. As this is the only date reflecting the inclusion of said materials within the library’s collection, it is my experience that an item’s 008 field accurately indicates the date of an item’s public availability.
6. I have reviewed EX1011, “A Microcomputer-Based Camera Control System” by R.J. Hall and P. Hiscocks as published in *Photogrammetric Engineering &*

Remote Sensing, April 1990.

7. Attached hereto as Appendix HALL01 is a true and correct copy of the MARC record for *Photogrammetric Engineering & Remote Sensing* as held by the Penn State University library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix HALL01 accurately describes the title, author, publisher, and ISSN number of *Photogrammetric Engineering & Remote Sensing*. The 'Availability' field of this record visible on page 6 indicates this collection includes the April 1990 edition of *Photogrammetric Engineering & Remote Sensing* containing "A Microcomputer-Based Camera Control System".
8. Attached hereto as Appendix HALL02 is a true and correct copy of "A Microcomputer-Based Camera Control System" as published in *Photogrammetric Engineering & Remote Sensing* as held by the Penn State University library. I secured these scans myself from the library's collection. In comparing EX1011 to Appendix HALL02, it is my determination that EX1011 is a true and correct copy of "A Microcomputer-Based Camera Control System" by R.J. Hall and P. Hiscocks as published in *Photogrammetric Engineering & Remote Sensing* April 1990.
9. The 008 field of the MARC record in Appendix HALL01 indicates the date of record creation. The 008 field of Appendix HALL01 indicates the Penn State University library first subscribed to this journal starting in August 4, 1982

and continued that subscription until 2013. Considering this information, it is my determination that the April 1990 edition of *Photogrammetric Engineering & Remote Sensing*, and therefore “A Microcomputer-Based Camera Control System” was made available to the public, including by the Penn State University library, shortly after its initial release in April 1990. Additionally, this library’s subscription history, plus page 5 of Appendix HALL02, confirms that *Photogrammetric Engineering & Remote Sensing* is a regularly published journal, stating that “PE&RS (*Photogrammetric Engineering & Remote Sensing*) (ISSN 0099-1112) is published monthly by the American Society for Photogrammetry and Remote Sensing....”

10. The 650 fields of the MARC record in Appendix HALL01 indicate that interested persons would have been able to locate EX1011 by searching for terms such as “photographic surveying,” “photogrammetry,” “aerial photography,” and “remote sensing.” Other fields in the MARC record provide additional terms that would have been searchable by interested parties to locate EX1011.
11. I have reviewed Exhibit EX1012, “TIER II Plus Airborne EO Sensor LOS Control and Image Geolocation” by K. James Held & Brendan H. Robinson as published in *1997 IEEE Aerospace Conference Proceedings*.
12. Attached hereto as Appendix HELD01 is a true and correct copy of the MARC record for *1997 IEEE Aerospace Conference Proceedings* as held by the

University of Pittsburgh library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix HELD01 accurately describes the title, author, publisher, and ISBN number of 1997 *IEEE Aerospace Conference Proceedings*.

13. Attached hereto as Appendix HELD02 is a true and correct copy of "TIER II Plus Airborne EO Sensor LOS Control and Image Geolocation" as published in 1997 *IEEE Aerospace Conference Proceedings* as held by the University of Pittsburgh library. I secured these scans myself from the library's collection. In comparing EX1012 to Appendix HELD02, it is my determination that EX1012 is a true and correct copy of 1997 *IEEE Aerospace Conference Proceedings* by K. James Held & Brendan H. Robinson.
14. The 008 field of the MARC record in Appendix HELD01 indicates the date of record creation. The 008 field of Appendix HELD01 indicates the University of Pittsburgh library first acquired these proceedings as of March 25, 1997. Considering this information, it is my determination that 1997 *IEEE Aerospace Conference Proceedings* and therefore "TIER II Plus Airborne EO Sensor LOS Control and Image Geolocation" was made available to the public by the University of Pittsburgh library shortly after its initial acquisition as of March 1997. Additionally, I note that Appendix HELD02 shows that the 1997 *IEEE Aerospace Conference Proceedings* was published by the Institute of Electrical and Electronics Engineers, a well-known, reputable compiler and

publisher of scientific and technical publications.

15. I have reviewed EX1007, “Digital Image Georeferencing from a Multiple Camera System by GPS/INS” by Mohamed M.R. Mostafa and Klaus-Peter Schwarz as published in *ISPRS Journal of Photogrammetry & Remote Sensing*, June 2001.
16. Attached hereto as Appendix MOSTAFA01 is a true and correct copy of the MARC record for *ISPRS Journal of Photogrammetry & Remote Sensing* as held by the University of Pittsburgh library. I secured this record myself from the library’s public catalog. The MARC record contained within Appendix MOSTAFA01 accurately describes the title, author, publisher, and ISSN number of *ISPRS Journal of Photogrammetry & Remote Sensing*. The ‘Location Items’ field of this record visible on page 2 indicates this collection includes the June 2001 edition of *ISPRS Journal of Photogrammetry & Remote Sensing* containing “Digital Image Georeferencing from a Multiple Camera System by GPS/INS.”
17. Attached hereto as Appendix MOSTAFA02 is a true and correct copy of “Digital Image Georeferencing from a Multiple Camera System by GPS/INS” as published in *ISPRS Journal of Photogrammetry & Remote Sensing* as held by the University of Pittsburgh library. I secured these scans myself from the library’s collection. In comparing EX1007 to Appendix MOSTAFA02, it is my determination that EX1007 is a true and correct copy of “Digital Image

Georeferencing from a Multiple Camera System by GPS/INS” by Mohamed M.R. Mostafa and Klaus-Peter Schwarz as published in *ISPRS Journal of Photogrammetry & Remote Sensing* June 2001.

18. The 008 field of the MARC record in Appendix MOSTAFA01 indicates the date of record creation. The 008 field of Appendix MOSTAFA01 indicates the University of Pittsburgh library first subscribed to this journal starting in October 9, 1989 and continued that subscription until December 2001. Considering this information, it is my determination that *ISPRS Journal of Photogrammetry & Remote Sensing* June 2001 and therefore “Digital Image Georeferencing from a Multiple Camera System by GPS/INS” was made available to the public, including by the University of Pittsburgh library, shortly after its initial release in June 2001. Additionally, the library’s subscription history (from October 1989 through December 2001) and the volume information on the cover (“Volume 56 – issue 1 June 2001”) of Appendix MOSTAFA01 along with the statement that “For 2001 volume 56 is scheduled for publication” indicate that *ISPRS Journal of Photogrammetry & Remote Sensing* is a regularly published periodical.
19. The 650 fields of the MARC record in Appendix MOSTAFA01 indicate that interested persons would have been able to locate EX1007 by searching for terms such as “photographic surveying,” and “photogrammetry.” Other fields in the MARC record provide additional terms that would have been searchable

by interested parties to locate EX1007.

20. I have been retained on behalf of the Petitioner to provide assistance in the above-illustrated matter in establishing the authenticity and public availability of the documents discussed in this declaration. I am being compensated for my services in this matter at the rate of \$200.00 per hour plus reasonable expenses. My statements are objective, and my compensation does not depend on the outcome of this matter.

21. I have been warned that willful false statements and the like are punishable by fine or imprisonment, or both (18 U.S.C. 1001) and may jeopardize the validity of the patent at issue in this proceeding. I declare under penalty of perjury that the foregoing is true and correct.

Dated: 3/27/2024

A handwritten signature in black ink, appearing to read 'June Ann Munford', with a stylized flourish at the end.

June Ann Munford

APPENDIX HALL01

 **Catalog**

Bookmarks 0 Course Reserves My Account

Keyword Search... [Advanced search](#) [Start Over](#)

MARC View

LEADER 18400nas a22019931 4500
001 1295396
003 SIRSI
008 820804c19349999xx mu 0 0eng d
035 a| LIA51523141
010 a| 75643950
019 a| MARS
022 0 a| 0099-1112
050 0 0 a| TA593.A2 b| P5
245 0 0 a| Photogrammetric engineering and remote sensing.
246 1 0 a| PE&RS
246 1 0 a| P E & R S
246 1 3 a| PE & RS, f| Jan. 1986-
247 0 0 f| Sept. 1934-Sept. 1936, a| News notes of the American society of photogrammetry.
247 1 0 f| Oct. 1936-Dec. 1974, a| Photogrammetric engineering.
260 a| Washington, D.C. : b| American Society of Photogrammetry.
300 a| v. : b| ill. (part col., incl. ports.) plates, diagrs. ; c| 26-29 cm.
310 a| Quarterly. b| Jan. 1936-
362 0 a| v. 1- Sept. 1934-
500 a| Photolithographed.
500 a| Bimonthly, Sept. 1934-Dec. 1935.
500 a| Includes lists of members of the society.
504 a| Bibliography of photogrammetry: v. 2, no. 4 (Oct./Nov./Dec. 1936) v, 117 p.
525 a| Vol. 58, no. 8 (August 1992) accompanied by computer disk (Digital orthophoto : 5 1/4 in., HD). System requirements: IBM PC or compatible; VGA graphics; high-density disk drive.
525 a| Vol. 59, no. 3 (March 1993) accompanied by computer laser optical disk (ER Mapper 4.0 ; 4 3/4 in.). System requirements: SunSPARC; SunOS 4.1; Solaris 1.1.
555 a| v.1-45 (1935-1979). 1 v.
590 a| Computer disk with Aug. 1992 copied onto 3 1/2 in. HD disk.
650 0 a| Photographic surveying v| Periodicals.
650 0 a| Photogrammetry v| Periodicals.
650 0 a| Aerial photography v| Periodicals.
650 0 a| Remote sensing v| Periodicals.
710 2 a| American Society of Photogrammetry.
710 2 2 a| American Society of Photogrammetry. t| News notes.
949 a| TA593.A2P5 v.36 1970 w| LC PER c| 1 i| 000018886320 d| 6/4/2015 e| 5/28/2015 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 4/13/2001
949 a| TA593.A2P5 v.17-18 1951/52 w| LC PER c| 1 i| 000060018373 d| 2/25/2010 l| ACAD-BLDG m| UP-ANNEX q| 1 r| Y s| Y t| PERIODICAL u| 2/25/2010
949 a| TA593.A2P5 v.2-3 1936/37 w| LC PER c| 1 i| 000013470197 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.4-6 1938-1940 w| LC PER c| 1 i| 000068475468 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.7-8 1941/42 w| LC PER c| 1 i| 000068475475 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.9-11 1943-1945 w| LC PER c| 1 i| 000068475482 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.12 1946 w| LC PER c| 1 i| 000068475499 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.13 1947 w| LC PER c| 1 i| 000068475505 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.14 1948 w| LC PER c| 1 i| 000068475512 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.15-16 1949/50 & yrbk.1950 w| LC PER c| 1 i| 000068475529 d| 3/16/2017 l| ACAD-BLDG m| UP-ANNEX q| 1 r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.19-20 1953/54 w| LC PER c| 1 i| 000068475536 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.21-22 1955/56 w| LC PER c| 1 i| 000068475543 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.23 1957 w| LC PER c| 1 i| 000068475550 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.24 1958 w| LC PER c| 1 i| 24810803009 d| 8/7/2019 l| CATO-PARK m| UP-ANNEX q| 2 r| Y s| Y t| PERIODICAL u| 5/13/2010 x| C z| 2481 0| 0803 1| 009
949 a| TA593.A2P5 v.25 1959 w| LC PER c| 1 i| 000068475574 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010
949 a| TA593.A2P5 v.26 1960 w| LC PER c| 1 i| 000068475581 l| ACAD-BLDG m| UP-ANNEX r| Y s| Y t| PERIODICAL u| 5/13/2010

949	a	TA593.A2P5 v.27 1961 w	LCPER c	1 i	000068475598 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.28 1962 w	LCPER c	1 i	000068475604 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.29 1963 w	LCPER c	1 i	000068475611 d	3/21/2011 e	10/29/2010 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.30 1964 w	LCPER c	1 i	000068475628 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.31 1965 w	LCPER c	1 i	000068475635 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.32 1966 w	LCPER c	1 i	000068475642 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.33 1967 w	LCPER c	1 i	1295396-99001 d	7/2/2015 e	5/28/2015 I	BINDERY m	UP-ANNEX r	Y s	Y t
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.34 1968 w	LCPER c	1 i	000068475666 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.35 1969 w	LCPER c	1 i	000068475673 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.37 1971 w	LCPER c	1 i	000068475680 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.38 no.1-6 1972 w	LCPER c	1 i	000068475697 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.38 no.7-12 1972 w	LCPER c	1 i	000068475703 d	7/13/2010 I	ACAD-BLDG m	UP-ANNEX q	1 r	Y s	Y t
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.39 no.1-6 1973 w	LCPER c	1 i	000068475710 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.39 no.7-12 1973 w	LCPER c	1 i	000068475727 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.40 no.1-6 1974 w	LCPER c	1 i	000068475734 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.40 no.7-12 1974 w	LCPER c	1 i	000068475741 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.41 no.1-6 1975 w	LCPER c	1 i	000068475758 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.41 no.7-12 1975 w	LCPER c	1 i	000068475765 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.42 no.1-6 1976 w	LCPER c	1 i	000068475772 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.42 no.7-12 1976 w	LCPER c	1 i	000068475789 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.43 no.1-6 1977 w	LCPER c	1 i	000068475796 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.43 no.7-12 1977 w	LCPER c	1 i	000068475802 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.44 no.1-6 1978 w	LCPER c	1 i	000068475819 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.44 no.7-12 1978 w	LCPER c	1 i	000068475826 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.45 no.1-6 1979 w	LCPER c	1 i	000068475833 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.45 no.7-12 1979 w	LCPER c	1 i	000068475840 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.46 no.1-6 1980 w	LCPER c	1 i	000068475857 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.46 no.7-12 1980 w	LCPER c	1 i	000068475864 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.47 no.1-6 1981 w	LCPER c	1 i	000068475871 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.47 no.7-12 1981 w	LCPER c	1 i	000068475888 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.48 no.1-6 1982 w	LCPER c	1 i	000068475895 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.48 no.7-12 1982 w	LCPER c	1 i	000068475901 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.49 no.1-6 1983 w	LCPER c	1 i	000068475918 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.49 no.7-12 1983 w	LCPER c	1 i	000068475925 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 v.50 no.1-6 1984 w	LCPER c	1 i	000068475932 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.50 no.7-9 1984 w	LCPER c	1 i	000068475949 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
949	a	TA593.A2P5 v.50 no.10-12 1984 w	LCPER c	1 i	000068475956 I	ACAD-BLDG m	UP-ANNEX r	Y s	Y t	PERIODICAL u	5/13/2010
		PERIODICAL u									5/13/2010
949	a	TA593.A2P5 Index v.1-45 1934-79 w	LCPER c	1 i	000058568750 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	7/31/2006
		z									6324
949	a	TA593.A2P5 v.51 Jan-Apr 1985 w	LCPER c	1 i	000050124985 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	9/25/2002 z
		6324									6324
949	a	TA593.A2P5 v.51 May-Aug 1985 w	LCPER c	1 i	000050124992 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	9/25/2002 z
		6324									6324
949	a	TA593.A2P5 v.51 Sept-Dec 1985 w	LCPER c	1 i	000050125005 d	6/21/2005 I	CATO-2 m	UP-ANNEX q	1 r	Y s	Y t
		PERIODICAL u									9/25/2002 z
949	a	TA593.A2P5 v.52 Jan-June 1986 w	LCPER c	1 i	000050125012 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	9/25/2002 z
		6324									6324
949	a	TA593.A2P5 v.52 July-Dec 1986 w	LCPER c	1 i	000050125029 d	2/23/2007 I	CATO-2 m	UP-ANNEX q	1 r	Y s	Y t
		PERIODICAL u									9/25/2002 z
949	a	TA593.A2P5 v.53 Jan-May 1987 w	LCPER c	1 i	000050125036 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	9/25/2002 z
		6324									6324
949	a	TA593.A2P5 v.53 June-Aug 1987 w	LCPER c	1 i	000050125043 I	CATO-2 m	UP-ANNEX r	Y s	Y t	PERIODICAL u	9/25/2002 z
		6324									6324

949	a TA593.A2P5 v.53 Sept-Dec 1987 w LC PER c 1 i 000050125050 I CATO-2 m UP-ANNEX r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.54 Jan-Apr 1988 w LC PER c 1 i 000050125067 d 3/15/2017 I CATO-2 m UP-ANNEX q 1 r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.54 May-Aug 1988 w LC PER c 1 i 000050125074 I CATO-2 m UP-ANNEX r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.54 Sept-Dec 1988 w LC PER c 1 i 000050125081 d 6/22/2007 e 6/22/2007 I CATO-2 m UP-ANNEX n 1 q 1 r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.55 Jan-Apr 1989 w LC PER c 1 i 000050125098 I CATO-2 m UP-ANNEX r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.55 May-Aug 1989 w LC PER c 1 i 000050125104 I CATO-2 m UP-ANNEX r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.55 Sept-Dec 1989 w LC PER c 1 i 000050125111 d 12/8/2002 I CATO-2 m UP-ANNEX q 1 r Y s Y t PERIODICAL u 9/25/2002 z 6324
949	a TA593.A2P5 v.56 Jan-Apr 1990 w LC PER c 1 i 000050125128 d 12/8/2002 e 12/8/2002 I CATO-2 m UP-ANNEX n 1 r Y s Y t PERIODICAL u 9/25/2002 z 6324
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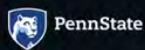
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Index Note:

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COVER PHOTO—Lake Nasser, Egypt, 29 September 1988. Handheld Hasselblad camera with 250 mm lens in a near vertical position, from the Space Shuttle Discovery. Geographic coordinates are 23.5° N and 33.0° E.

This photo shows the effect of sunglint (G) on the water of Lake Nasser, giving it a greyish-white appearance while the non-sunglint water is bluish in color. An airstrip (A) and the Aswan Dam (D) are clearly seen on this photo. The exposed lake bed (B) and receding shoreline is marked by silt deposition. The pronounced dry lake bed was not visible in 1981 Shuttle photos.

Photo submitted by Kamlesh Lulla, Space Shuttle Earth Observations Office (SSEOO), NASA/Johnson Space Center, Houston, Texas; Mike Helfert, Chuck Wood, and SSEOO Staff contributed to this interpretation.

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PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING is the official journal of the American Society for Photogrammetry and Remote Sensing. It is devoted to the exchange of ideas and information about the applications of photogrammetry, remote sensing, and geographic information systems.

ASPRS has adopted the following definition: Photogrammetry and Remote Sensing are "the art, science, and technology of obtaining reliable information about physical objects and the environment, through the process of recording, measuring, and interpreting imagery and digital representations of energy patterns derived from noncontact sensor systems."

Conventional photogrammetry includes the compilation of topographic maps and surveys, complete with contour lines, based on measurements and information obtained from aerial and space photographs with optical analog instruments and/or analytic instruments/computations. Similar topographic principles of precision measurement are applied in close-range photogrammetry, to map (measure) objects that are difficult to study in other ways, such as the shape of an astronomic radio reflector subject to environmental deformations, for synoptically recording measurable deformations in engineering models, for the medical study (in situ) of live specimens, etc.

Remote sensing uses imagery acquired with a sensor other than (or in addition to) a conventional camera, such as by electronic scanning, or using electromagnetic radiations outside the normal visual range of the film and camera — microwave, radar, thermal infrared, and ultraviolet, as well as multispectral. Special techniques are applied to process and interpret remote-sensing imagery for the purpose of producing conventional maps, thematic maps, resource maps, digital data files for GIS, surveys, etc., applications in the fields of agriculture, archaeology, forestry, geography, environmental sciences, geology, and others.

Geographic information systems are the computer hardware/software used to input, store/retrieve, manipulate/analyze, display, and plot/print spatially referenced digital data (e.g. digitized maps, remote sensor, tabular data, etc.). Thus a GIS is comprised of three essential subcomponents: computer hardware, computer software, and various types of digital data.

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A Microcomputer-Based Camera Control System

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ABSTRACT: It is economical and preferable to use helicopters for the acquisition of small format, large-scale aerial photographs in northern Canada due to the large land area and small number of airports. To facilitate air photo procurement, a computer-based control system was designed and packaged for rapid installation into unmodified helicopters, to operate from its own source of battery power, and to work in conjunction with an external, removable camera pod. This paper describes the requirements, design, and performance characteristics of the camera control system that was developed.

INTRODUCTION

THE USE OF HELICOPTERS IN PHOTO ACQUISITION

There are few airports and runways in northern Canada. As a result, long ferry flights are required to move conventional fixed-wing aircraft to the site of an air photo mission. Helicopters, however, are often located and available in small communities. Though their rental cost is higher than fixed wing aircraft, this is justified by shorter ferry distances and their capability to land in small clearings. The slower forward flying speed and lower flying height capabilities of helicopters are also preferable when photo scales of 1:200 to 1:2000 are required. For example, a typical photo scale for sampling regeneration stocking is 1:500 (Hall, 1984); and a typical scale for sampling timber volumes is 1:1000 (Aldred and Lowe, 1978).

HISTORY OF THE PROJECT

The Northern Forestry Centre (NoFC) in Edmonton, Alberta, has previously been involved in research to develop and refine methods of obtaining and applying small format, large-scale aerial photographs for forest inventory surveys (Kirby and van Eck, 1974; Kirby, 1980; Hall, 1984, Spencer and Hall, 1988).

In 1974, a mechanical camera control system (van Eck and Bihuniak, 1978) was developed for aerial photo operations. In 1981, the requirement arose for a more functional system that would be simpler to use, and yet provide for more rigorous control of photogrammetric parameters such as overlap and image motion.

An advanced control system for 70- and 35-mm cameras at that time was in operation at the Ontario Centre for Remote Sensing (Roberts and Hiscocks, 1981). This system included a Commodore PET computer * and is capable of controlling up to four cameras of three different types (Vinten, Hasselblad, Nikon). A joint redesign effort was undertaken to adapt that system for helicopter use, reduce the size and weight of the system by using newer electronic technology, convert the system to battery power, and interface and connect the system to the cameras and radar or laser altimeter that were in a self-contained helicopter camera pod. The system software was completely rewritten to improve the operator interface, and the control system was redesigned to mount into an aeronautically approved instrument rack, which attaches to the seat rails of the Bell 206B Jet Ranger helicopter.

*The mention of trade names does not imply endorsement by the authors.

Since then, operational use has resulted in a number of technical refinements, the building of a second system for the Yukon Northern Affairs Program, and the manufacture of an additional system for private industry. The purpose of this paper is to describe the components, functionality, and performance characteristics of the camera control system.

THE CAMERA CONTROL SYSTEM

THE CAMERA MOUNT

In the past, both internal and external camera mounts have been used on helicopters. Internal camera mounts allow access to the cameras for film changes, leveling, and drift adjustment, but they require modified aircraft (Benson *et al.*, 1984). External camera mounts have the advantage of not requiring modifications to the aircraft, but they require preflight leveling and the aircraft must land to change film magazines. The NoFC system uses an external camera pod (Figure 1). A photograph and brief description of its features in relation to other systems is given in Spencer and Hall (1988).

The camera pod mounts to the underside of the helicopter and contains two 70-mm Vinten aerial cameras, a radar or laser altimeter and annotation display unit, and a monochrome video camera. Cables link the electronics in the pod to the camera control system rack inside the helicopter.

CONTROL SYSTEM HARDWARE

The camera control system instrument rack inside the helicopter contains a Commodore 64 computer, a Commodore 1541 disk



FIG. 1. Illustration of camera pod and instrument rack installed on helicopter.

drive, an electronics subrack, the power management unit, 117-volt alternating current (AC) inverter, the control unit for the laser altimeter (or altitude indicator for the radar altimeter), and a consolidated battery power pack (Figure 2).

The Commodore 64 computer is responsible for executing the control functions, timing the cameras, and acquiring data from a radar or laser altimeter. The disk drive stores the operational programs for the system and the height data from the flight mission.

The center of the electronics subrack contains the video display screen, which shows computer data readouts and status indicators, menus for software operation, the video camera ground image, the moving grid that is synchronized to the speed of the ground image for determining cycling intervals, drift lines, and displays of the field of view of the two photo cameras. The left side of the electronics subrack contains power supply and plug-in cards for the camera relay interface and radar or laser interface. Empty card slots are available for future expansion of the system.

The power management unit serves a number of miscellaneous functions. Its principal purpose is to act as a connection point for the 17 cables to the pod electronics and to organize and distribute the system electrical power. It also contains a digital voltmeter to monitor system voltages, power on and off switches, 117-volt AC outlets, and control functions for the Vinten cameras. The camera control functions consist of two single-shot relay interfaces, electromechanical frame counters, camera heater switches, 8 picture per second (PPS) and 4 PPS selector switches, film wind indicators to confirm that film is moving through the camera, switches for selection of continuous or single-shot camera operation, and selector switches for the motor-driven lens apertures. Noise filters in the power management unit isolate

the 40-millisecond, 20-amp noise pulses generated by the Vinten camera from the rest of the electronic circuitry.

The inverter (Flite-tronics PC -16) converts the direct current of the battery to 117-volt, 60-Hertz alternating current (sine wave) for operation of the disk drive, the computer, the electronics subrack, and any ancillary test equipment. The provision of AC line voltage simplifies maintenance, allows any unmodified disk drive or computer to be used in the system, and makes it possible to operate the system from AC line power when located in a hangar.

The system was designed to operate from a battery pack because some helicopters are not equipped with an auxiliary power connector. The battery pack supplies 12-, 24-, and 30-volts direct current (DC) from a series and parallel arrangement of 6- and 12- volt gel cells. Each output has a capacity of approximately 40 amp-hours, and the battery will operate the system for about 3.5 hours. The battery pack weighs 39 kg and has circuit breakers and Mil connectors for the system and battery charger. During flight operation, two identical battery packs are alternated. While one is in use a second identical battery unit is charged on the ground. Although ni-cad and lead-acid cells are physically smaller and weigh less than gel cells, gel cells were used because they are completely sealed, they do not vent hydrogen or spill electrolyte, and they could be certified for aircraft use. To take advantage of helicopters situated at various locations, heavy duty shipping cases were built for the pod, the rack, and each of the two battery units.

CAMERA TIMING

A major portion of the system software is a Commodore BASIC program that operates the computer displays and accepts operator data. It uses two small machine code programs: a screen editor and a camera timing routine. The screen editor simplifies the operator data entry process, provides rudimentary editing facilities, and locks out some errors that would otherwise abort a BASIC program. Using this routine, the operator enters the values for the camera film size, focal length, and desired overlap. The focal length of the video camera is usually fixed and is therefore given a variable name in the BASIC program. This variable is simply changed with the screen editor, however, if a video camera lens of a different focal length is employed.

Camera timing begins with a measurement of grid speed. Using a front panel control, the camera operator adjusts the rate of the moving grid (or grid speed) to the speed of the moving video image. Using the previously entered camera parameters, grid speed, and the intervalometer formula (Roberts and Hiscocks, 1981), the required firing intervals for the two cameras are calculated to obtain the desired forward overlap between photographs. The firing interval information is then passed to the machine-code timing-routine for the actual triggering of the cameras.

Grid speed may vary over a wide range and so the computer uses an adaptive measurement scheme that maximizes accuracy and minimizes the time between speed updates. At low grid speeds, a small movement of the grid across the screen is sufficient to obtain an accurate measurement. At high grid speeds, movement across the entire screen is used. In either case, the computer establishes a suitable distance for the grid to move and then measures the time (to a resolution of 1/60 second) for the grid to move that distance.

Sixty times per second, the Commodore 64 is interrupted from its operation of the main BASIC program to scan the keyboard, check the position of the grid, and check the camera trigger routine to determine if a camera should be fired. If a camera is to be fired, the electronic rack relay interface is actuated, which then triggers the Vinten Controller circuit.

The Vinten camera is a simple mechanism, consisting essentially of a motor-driven belt (shutter blind) with a slit shutter.

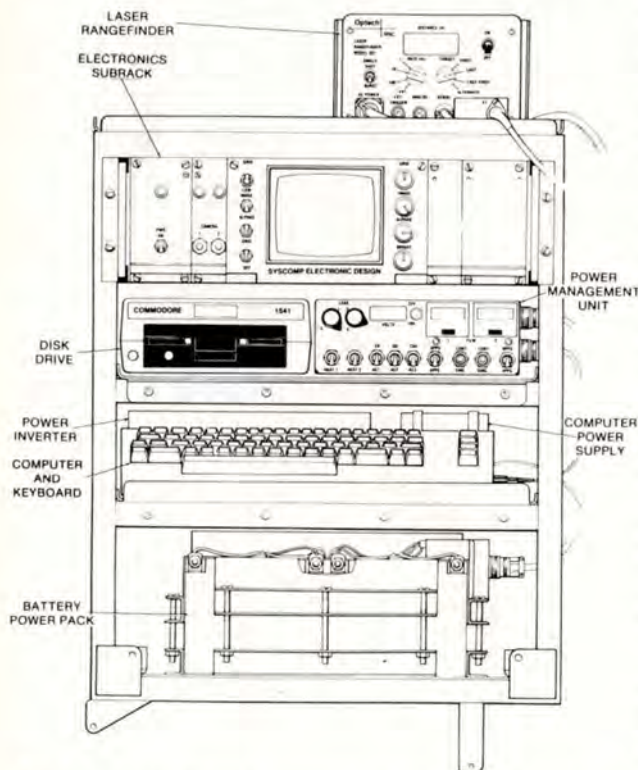


Fig. 2. Camera control system components mounted on the instrument rack.

A cam switch closes at the beginning of a shutter cycle and opens at the end of a cycle. The Vinten controller circuit is required to apply full voltage to the camera motor at the beginning of a camera cycle and to short circuit the motor to dynamically brake it when the cam switch opens. In this system, the application and removal of voltages is accomplished by a combination of electronics and relays.

The speed of the shutter blind is controlled by a centrifugal switch inside the Vinten camera, which can be set to 4 or 8 PPS. In the 4 PPS position, the width of the slit gives an exposure of 1/1000 second; in the 8 PPS position, the belt speed is doubled and the exposure is halved. The shutter blind can be changed to obtain different slit widths.

CAMERA TIMING MODES

The hardware controls and the software timing routines can be combined to operate the cameras in a number of different modes (Figures 3).

Continuous Framing. Under continuous framing, a steady DC voltage is applied to the camera belt motor and the camera will frame continuously at either 4 or 8 PPS. Continuous framing is intended for rare instances when photography from a high-speed, low-altitude aircraft is necessary. In this system, continuous framing is primarily used to check that a camera is working properly.

Single-Shot Framing. Most aerial photography is acquired in this mode. In single-shot mode, the cameras can be triggered manually by push-buttons or automatically by the computer. The computer can automatically calculate the timing interval between frames from the grid speed and the camera parameters (grid mode), or it can cycle the cameras on the basis of a manually entered timing interval between frames (manual mode). Manual mode is useful when flying conditions are too unstable to use the video grid mode. The operator calculates the timing intervals between frames using a separate NoFC flight planning computer program, based on aircraft altitude and speed, camera focal length, film size and overlap, and cycling rate and shutter speed. The operator then manually enters the calculated interval.

Burst Mode. A camera in burst mode fires a burst of frames and waits for a specified interval before firing another burst. Burst mode is often used for sampling when 100 percent coverage of a flight line is not required. The operator specifies which camera is to be in burst mode, the number of frames per burst, and the waiting time, in seconds, between bursts. The timing interval between frames during the burst may be automatically calculated by the computer from the speed of the video grid to give the desired overlap, or it may be entered manually.

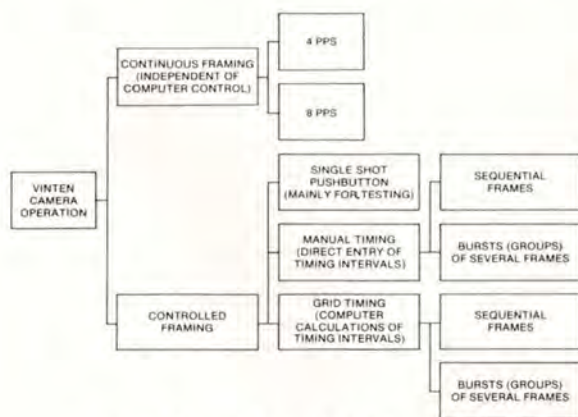


FIG. 3. Operating modes for the Vinten camera.

HEIGHT MEASUREMENT SYSTEM

Both a radar altimeter (Honeywell APN194-V) and a laser altimeter (Optech 501) have been interfaced to the camera control system. The radar altimeter outputs height data in binary format, 12 bits of information, corresponding to a resolution of one foot in a maximum range of 4095 feet. This information is delivered from the radar in a serial stream, which is then formatted and displayed on the video screen (as either feet or metres). The laser outputs metric data in four parallel, binary-coded decimal digits, corresponding to a resolution of 1/10 metre over a maximum range of 500 metres. This information is converted to a serial stream, input to the computer, and again displayed in feet or metres. Either altimeter is read at a 60-Hz rate as part of the interrupt routine of the Commodore 64 computer.

FLIGHT REPORTING

When flight reporting is toggled on, a flight record entry is made every time either of the two cameras is fired. Each data entry consists of the film frame counts for the two cameras and a height reading from the radar or laser altimeter. The flight record is stored in the shadow Random Access Memory (RAM) underneath the BASIC Read Only Memory (ROM) in the Commodore 64, where there is sufficient room for 1000 entries, corresponding to two rolls of camera film. The flight records contained in shadow RAM are then written out to a file on floppy disk when flight reporting is toggled off. A separate BASIC program is used at the conclusion of the flight to print out the flight record disk file.

The laser altimeter has an RS-232 serial output that is connected to a height display film annotation unit on Vinten camera #1. The annotation unit is synchronized to the Vinten relay controller so that the height reading is frozen when the camera shutter is in motion to allow the height reading to be recorded on the film frame.

THE VIDEO SYSTEM

There are three video sources in this system: the video camera display of the ground image, the computer alphanumeric video, and the moving grid signal. The ground image signal (from a 12-volt DC monochrome television camera, RCA type TC2055) and the moving grid signal (generated by a special purpose digital circuit) are synchronized to the Commodore 64 alphanumeric video and then added together to generate the combined video screen image. Any combination of these sources can be displayed, and two rear panel connectors supply the camera image signal and the display screen image signal. Either can be recorded by a videotape recorder to obtain a video record of the mission.

A rectangle can be drawn on the video display to represent the field of view of the photo cameras because the aerial camera and video camera focal length information are employed in computer calculations. This is particularly useful when a ground feature must be centered in the photo camera frame. (The field of view of the video camera must be greater than that of the photo cameras.)

SUMMARY OPERATIONAL EXPERIENCE

Many features of the system have worked particularly well:

- There is independent overlap control for cycling both cameras using either aircraft ground speed from video tracking, or direct entry of previously calculated camera timing intervals.
- Flight recording information, which includes the camera frames fired and their associated flying heights above ground, has been employed in post flight film annotation and documentation.
- Operation from AC line power as well as battery power has been valuable in system training, testing, and software development.

- System monitors such as the film advance indicators and digital voltmeter have provided warning of potential faults as they have occurred.
- The system endurance on battery operation (3.5 hours with cameras firing) is satisfactory.

On the other hand, there are some limitations, which will be addressed through future development:

- The battery packs are heavy, and recharging in remote areas requires carrying a portable AC generator and fuel. Some helicopters are equipped with a connector to the 28-volt aircraft power bus and, where this is available, it should be used.
- The system currently uses 17 military connectors to connect to the pod electronics, all of which have to be connected with each system installation. This setup is time-consuming, and some form of quick disconnection would be preferable.
- Film exposure is currently set using a sun angle computer program, film step wedges, average gradients, and a Kodak aerial exposure computer. A light metering system and an aircraft attitude indicator, integrated into the camera control system, would provide optimal results. The differential light metering system by Fent and Polzin (1986) has been adapted for low altitude applications, but has not been integrated into the overall LSP camera system.
- The flight planning program is invaluable for preflight planning and calculations of camera timing, image motion, film consumption, and other parameters. The current NoFC program runs on a Hewlett Packard 9816 or 9825 computer and will be rewritten for the Commodore 64 and IBM PC. The latter is because of its more common platform and the program will be made available for public use.

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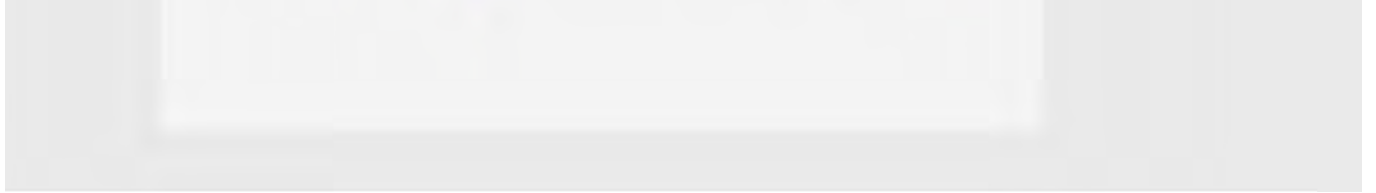
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TIER II Plus Airborne EO Sensor LOS Control and Image Geolocation

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Abstract - TIER II Plus is a high altitude unmanned reconnaissance aircraft carrying a synthetic aperture radar (SAR) and electro-optical / infrared (EOIR) sensor that will provide all-weather, day and night, high resolution imagery of ground targets for joint armed forces users. Its high area coverage rate is achieved in near real-time by transmitting the collected imagery while the vehicle is airborne and relaying that imagery via satellite to ground stations for processing and dissemination. A typical TIER II Plus mission is to fly 3000 nautical miles to a designated station in 9 hours to provide high resolution area reconnaissance over a 24 hour period, and return to base.

Mounted near the nose section of the Teledyne/Ryan built high altitude aircraft, the electro-optical sensor assembly consists of a mid-wave infra-red (MWIR) staring array built by Hughes Aircraft Company and a CCD visible staring array from Kodak that share common reflective optics. The telescope/sensor subassembly is mounted on the inner gimbal of a two axis gimbal set that directs the sensor line-of-sight (LOS) to designated earth-fixed locations. An on-gimbal inertial rate sensor provides the 2-degree-of-freedom (2DOF) inertial reference to stabilize the sensor LOS. An off-gimbal GPS-aided inertial navigation system (INS)

provides aircraft navigation data to the control system for inertial position stabilization and for determining the target image geolocation.

The high resolution field-of-view (FOV) along with the high coverage rate and staring array, requires that the sensor assembly be stabilized to a high accuracy and its LOS be step/stared at a 30 hertz rate. The fine stabilization and step/stare requirement is jointly achieved with two-axis image motion compensation (IMC) mirror mechanisms mounted internally in the telescope optical train. The IMC mirror removes high frequency vibrations to stabilize the LOS and performs the backscan function that cancels the gimbal scan motion to meet staring requirements during video integration. This backscan operation allows for efficient wide area coverage by continuously scanning the gimbals, thus reducing frame-to-frame settling times and extending gimbal hardware life.

This paper describes the salient features of the TIER II Plus control system design with emphasis on the algorithms used for LOS control, command generation, and target image geolocation. Computer simulation results will be presented to support the design.

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- 2.0 LOS CONTROL
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1.0 INTRODUCTION

The technical challenge for the TIER II Plus system is to point and stabilize the line-of-sight (LOS) of a visible and infrared (IR) sensor that is mounted on the underside of a high altitude unmanned reconnaissance aircraft to provide all-weather high resolution imagery of ground targets. The sensors are mounted side-by-side on the inner gimbal of a two axis gimbal set that is controlled to microradian stabilization accuracies to achieve typical target recognition ranges of 28.8 kilometers. Because the sensors are staring arrays, the control system must step/stare the sensor line of sight (LOS) at a 30Hz video frame rate to achieve wide area earth coverage. The TIER II Plus design accomplishes this task by assigning these high frequency commands to a low torque, low inertia mirror assembly with travel limits of less than ± 1 degree that is located in the sensor optical train. This reduces power requirements and hardware component stress, and minimizes reaction torques to the gimbal and aircraft structures; hence reducing structural vibrations that can compromise LOS stability.

Further control challenges involve developing algorithms to command the sensor LOS with respect to a 'quiet' local level reference frame that is decoupled from aircraft angular motion. LOS scan commands require special consideration to ensure that the sensor LOS earth projections result in gap-free coverage. Also, the location of the sensor field-of-view (FOV) projection on the earth's surface (geolocation) requires an accuracy of 20 meters circular error probability (CEP). This requirement is met without calibrating the gimbal or performing aircraft maneuvers that would interrupt the mission plan [1].

The purpose of this paper is to highlight the unique aspects of the TIER II Plus control system. The control design is significant for its low flyaway cost solution to challenging LOS stabilization and 30Hz video frame rate step/stare reposition requirements. It meets both stabilization and repositioning requirements by enhancing the two axis gimbal with two 2-axis image motion compensation (IMC) mirrors. For stabilization, the IMC mirrors replace mechanical isolators which complicate the mechanical design. An all digital control system implementation allows for maximum flexibility in closing 12 distinct servo loops, generating servo commands to operate in several modes, and computing geolocation parameters for each video frame.

Severe temperature operating conditions place extreme accuracy requirements on the IMC mirror mechanism. Inaccuracies in the backscan IMC mirror position knowledge result in LOS angular velocity errors. Variations in the IMC mirror position sensor scale factor compromise the earth fixed LOS rate, which results in image smear. This condition requires an in flight calibration of the IMC mirror scale factor prior to sensor operation, but after the IMC mirror assembly has reached a steady state temperature.

This paper first addresses the TIER II Plus operational modes. This is followed by a description of the EO receiver unit which consists of the visible and infrared video sensors that are mounted side-by-side along with the shared optics on the inner gimbal of a precision two axis gimbal subassembly. A discussion of the control system design philosophy is followed by a detailed description of the control system which encompasses

- (1) servo loop design
- (2) servo command generation algorithms
- (3) LOS geolocation algorithms

Computer simulation analyses will be presented to verify the design functionality and provide an added insight to its philosophy.

1.1 TIER II Plus Operational Modes

The primary operating mode of the TIER II Plus system is to fly a prescribed straight-and-level trajectory over a designated target region to record gapless imagery of potential ground targets. With the electro-optical (EO) sensors mounted on the underside of the forward fuselage section, the sensor LOS is scanned about the roll gimbal axis (in scan) which is aligned with the aircraft's longitudinal or roll axis. The in scan angular rates enable wide area gapless frame coverage by methodically step/staring the LOS one FOV over the frame period of 1/30 second. During video integration, the IMC backscan mirror mounted in the telescope's optical train, is scanned in the direction opposite to the in scan roll gimbal to cancel LOS roll motion. The orthogonal pitch/yaw gimbal axis (cross scan) is used predominantly to cancel angular rates induced by the aircraft's linear motion. The scan bar is terminated when the aircraft's induced cross scan angular motion equals one FOV frame, at which time the cross scan gimbal steps one FOV and the in scan gimbal reverses its scan to reposition the sensor LOS for scanning a subsequent scan bar in the opposite direction. This Wide Area Search (WAS) mode is illustrated in Figure 1.1.1.

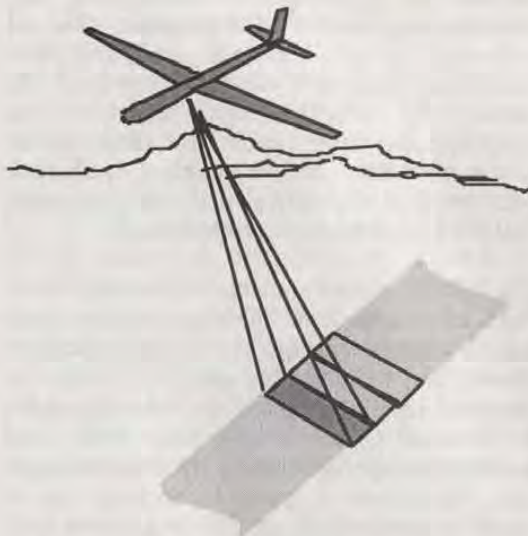


Figure 1.1.1 Wide Area Search Mode

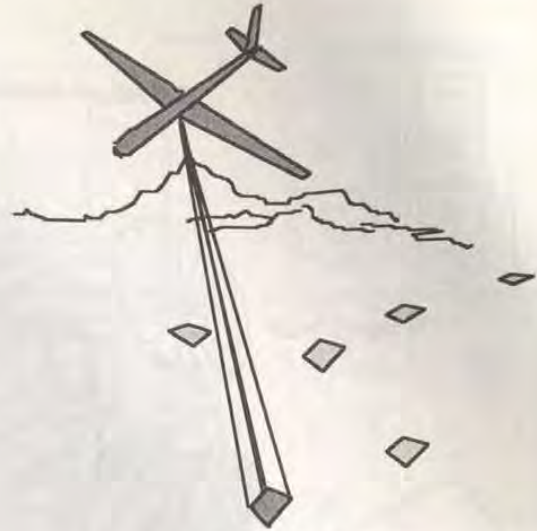


Figure 1.1.2 Spot Mode

The Spot mode is a variation of the WAS mode in which the gimbal is scanning a predetermined pattern independent of aircraft velocity. During WAS mode, the aircraft has a nominal straight and level flight path with cross track video coverage dictated by the aircraft's ground speed. For the Spot mode, the aircraft trajectory is less restricted, allowing it to perform coordinated turn maneuvers that enable the user to concentrate imagery on areas of high target probability, as depicted in Figure 1.1.2.

The EF (Earth-Fixed) Point mode is a stabilized sensor stare mode that reduces the imaging region to a single video frame on the earth's surface. This mode allows the user to perform various calibrations and to view a specified latitude/longitude coordinate with moderate LOS stabilization ('moderate' defined in Section 2.0)

The Base Reference mode is a utility mode that is used to control the sensor gimbal position during stow, unstow, idle, IMC calibration, and laboratory testing. In this mode, gimbal control is referenced to the aircraft gimbal base without closing any inertial stabilization loops.

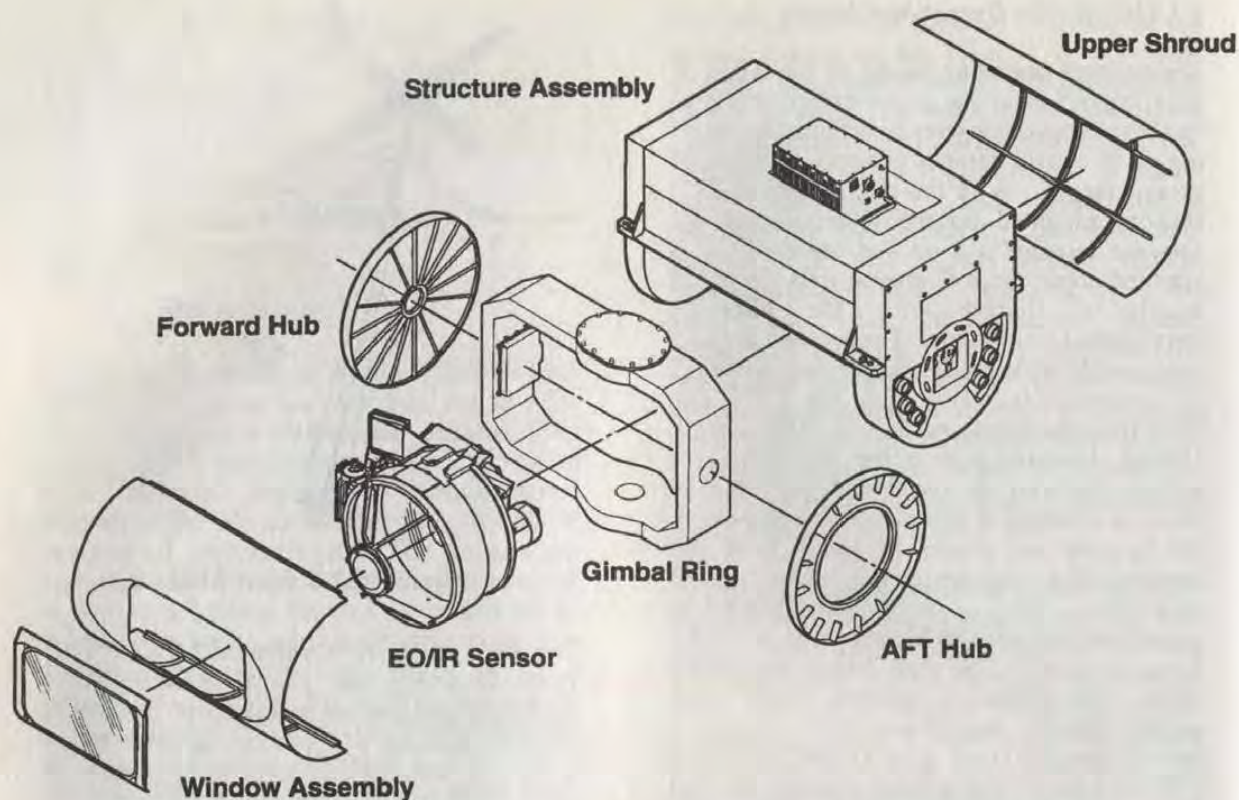


Figure 1.2.1 EO Receiver Unit Exploded View

1.2 EO/IR Receiver Unit (ERU)

The EO/IR Receiver Unit (Figure 1.2.1) consists of an EO/IR sensor system mounted in a shrouded two axis gimbal assembly that provides precision LOS pointing and stabilization. The EO receiver unit has an outer roll gimbal axis that is aligned with the aircraft longitudinal or roll axis. The inner pitch/yaw gimbal supports the sensor optical bench which is comprised of the multi-spectral telescope, midwave infrared (MWIR) and visible detector focal plane arrays (FPAs), cryogenic cooler, Fiber Optic gyros, and two image motion compensation mirror mechanisms. Each of the gimbal axes are driven by direct drive DC torquers and utilize multi-speed inductosyns to readout gimbal angle position. An outermost shroud gimbal is slaved to the roll gimbal to isolate the sensor from aerodynamic disturbances. On the base of the EO receiver unit is an Inertial

Navigation System (INS) that provides an inertial reference of the aircraft position and attitude for reporting LOS geolocation and commanding inertial LOS position. The all reflective afocal telescope and reflective imager are shared by both IR and visible sensors to minimize optic costs. The telescope and imager each have three optical surfaces while the remaining reflective surfaces fold the optical path for packaging and for image motion compensation.

The MWIR sensor consists of a staring array with small detectors allowing a short focal length telescope design to meet the specified resolution. The staring array capability to integrate for up to 16 milliseconds increases the detector signal-to-noise ratio (SNR) and reduces the aperture size. Due to its small size, the sensor is easier to package into a small volume which results in a lower cost and smaller optical system.

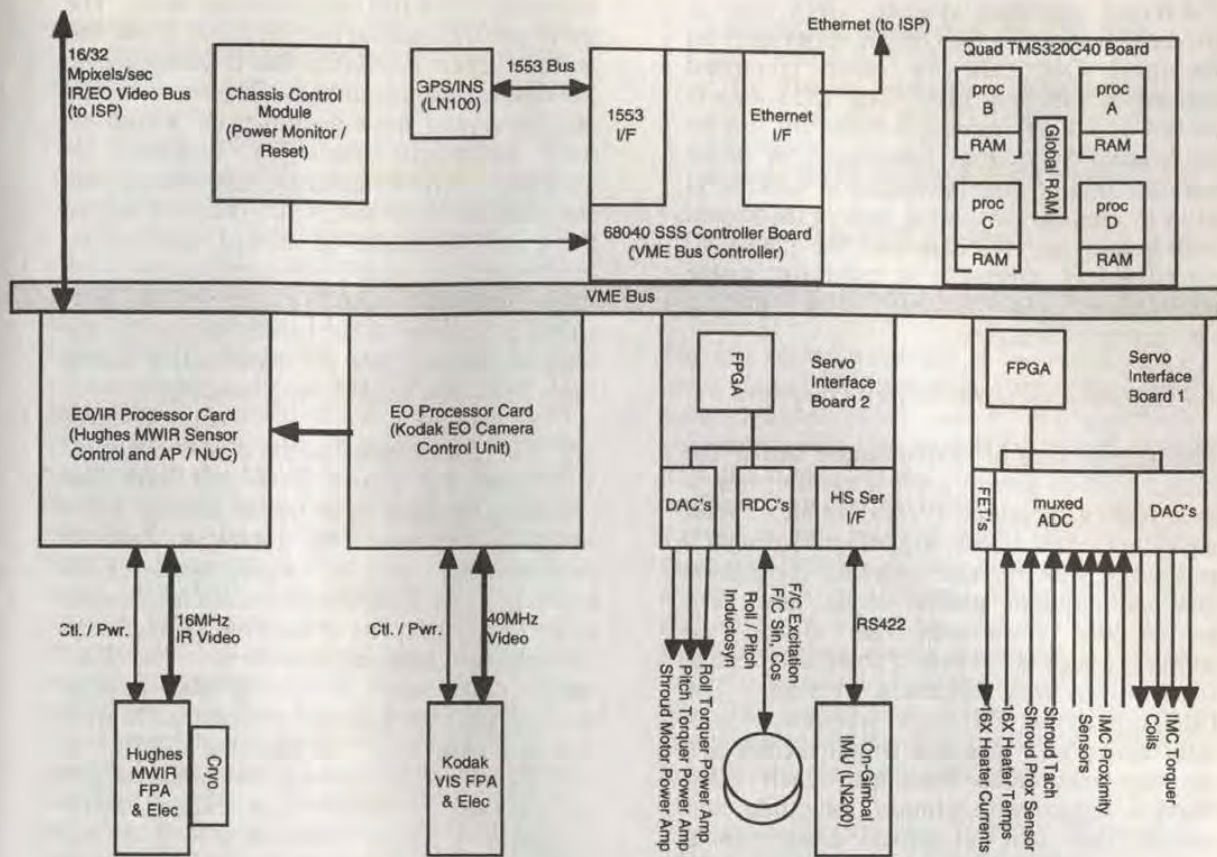


Figure 1.3.1. Sensor Electronics Unit Functional Block Diagram

1.3 Sensor Electronics Unit (SEU)

The Sensor Electronics Unit (SEU) (Figure 1.3.1) consists of a flight ready VME chassis containing a mixture of commercial "off-the-shelf" and Hughes-built interface and processor cards. The EO sensor is controlled by a Kodak camera control unit (CCU) and the IR sensor is controlled by a Hughes EO/IR processor card. Video from both cards is conditioned by the Hughes card and sent to the Integrated Signal Processor (ISP), where the bulk of the image processing takes place. The ISP is also responsible for top-level commands to the sensor control subsystem, which is the focus of this paper.

The control subsystem electronics consists primarily of two Hughes-built interface cards, a quad TMS320C40 DSP card, and a

68000-based 1553 and Ethernet interface card. Interfaces to the transducers and actuators used for closing all of the LOS control loops (Section 2.0) are handled by the Hughes-built interface cards. The on-gimbal inertial measurement unit (IMU) communication is a high-speed RS422 link, and the Inductosyn readouts for each axis are generated by resolver to digital converters (RDC's). Other transducer readouts are primarily muxed ADC's. The 12 servo loops correspond to 7 physical axes of control, which are commanded using DAC's and DC torquers. All of the control subsystem software resides on and is executed by the quad C40 card which has VME access to the servo interface cards.

The GPS/INS (LN100G) uses a 1553 bus for communication directly with the Ethernet / 1553 interface card, which runs under the

VXWorks operating system. INS data is used extensively by the control subsystem on the quad C40 card for servo command generation (Section 3.0). The 1553 data is placed into VME accessible RAM for use by the control subsystem software. A rather intricate timing and interpolation scheme is used to remove the timing delays associated with getting the INS data into the quad C40 global RAM, where it is used for image geolocation and recorded for ground processing of imagery.

1.4 Control Subsystem Design Overview

The sensor control system must direct the sensor LOS to ensure gapless earth coverage in a wide area search (WAS) mode. With navigation data consisting of the aircraft's position, velocity, and attitude, algorithms generate required gimbal angle and LOS inertial rate commands that ensure the sensor's image will cover a designated earth-fixed region with minimum overlap. The IMC's provide the high frequency LOS stabilization and backscan which mechanizes the step-stare video framing. Each video frame is tagged with latitude, longitude, and altitude data that is derived from gimbal readout data, INS data, and a WGS-84 earth model.

The control subsystem is an all digital design consisting of 12 servo loops. Six primary loops are needed to point and stabilize the sensor LOS in 2 degrees-of-freedom while the remaining six loops perform secondary functions (Section 2.0). The primary servo loops consist of

- (1) low bandwidth (2 to 3 hz) roll and pitch/yaw gimbal inertial position loops
- (2) medium bandwidth (30 hz) roll and pitch/yaw LOS rate stabilization loops
- (3) high bandwidth (200 to 300 hz) roll and pitch/yaw IMC loops

LOS stabilization is predominantly accomplished with the rate stabilization and IMC loops. Fiber Optic Gyros (FOG's) are mounted on the inner gimbal adjacent to the sensor with the gyro sensitive axes aligned to

the sensor LOS roll and pitch/yaw axes. The gyros provide inertial rate feedback of the roll and pitch/yaw LOS axes that is compared to the desired rate commands. The servo rejects any unwanted base disturbances within its loop bandwidth limits by torquing the gimbals. Any disturbances that exceed the stabilization loop bandwidth (but fall within the gyro bandwidth of around 500Hz) are fedforward as open loop corrections to the high bandwidth IMC loops. The IMC mirrors remove these disturbances in the telescope optical path for disturbances within the ~200 - 300 hz IMC loop bandwidth.

The IMC roll mirror has the dual function of stabilizing the sensor LOS roll axis and canceling gimbal scan rates during video imaging. Because the backscan task is implemented as a feedforward LOS correction, the IMC position scale factor error is a critical parameter in meeting the backscan velocity-matching requirements. The IMC mirror must cancel the gimbal scan velocity during video integration to within 0.3% over extreme operating temperatures (-25°C to +35°C) and IMC angular travel limits of ± 10 milliradians. This tight scale factor requirement led to extensive testing of the IMC over its operational temperature and travel limits. The lab testing concluded that the scale factor must be calibrated in flight to meet LOS velocity-matching requirements.

Only the rate stabilization and IMC loops are closed during video integration to maximize image stabilization. The outer inertial position loops are closed around these loops only when it is necessary to point or slew the gimbal to a designated position while maintaining a *moderately* stable LOS. For example, a slew maneuver is initiated to reposition the sensor LOS from its present position to the first frame position of a new WAS region, for which interval, moderate LOS stability is acceptable. The LOS position is also controlled during a turnaround maneuver, when the gimbal must reverse its scan direction and reposition in LOS coordinates for the next swath formation. The on-gimbal IMU rate errors will cause the LOS position to drift during intervals when the inertial position loops are not closed. By closing the position loops, these errors are

removed by the drift-free inductosyns and more accurate (and relatively drift-free) GPS-aided INS.

The inertial position loops control the pointing position of the sensor with respect to a local level frame. The sensor is directed to a designated earth-fixed location by referencing that command to aircraft coordinates such that any aircraft motion is decoupled from the LOS. The position commands to the inertial position loops are referenced to a local level frame that is subsequently transformed to aircraft coordinates such that the aircraft motion embedded in the command, cancels the same aircraft motion sensed by the gimbal angle transducers (multi-speed inductosyns). However, to minimize jitter caused by timing errors, the INS data used to derive the position commands must be synchronized (extrapolated up to current time) with the inductosyn readouts used to compute the gimbal angles. This approach eliminates the added expense and complexity of generating inertial LOS position quantities as servo feedback signals. These signals would be generated by integrating the on-gimbal gyros (using strapdown equations) and referencing their output to the base-mounted INS axes via transfer alignment techniques. The control subsystem primary functions are comprised of

- (1) LOS Control filters that compensate 12 independent digital servo loops (Section 2.0) to reject aircraft disturbances, attenuate unwanted structural modes, and modify the phase characteristics of the IMC mirror commands and control the pointing direction of the sensor LOS.

- (2) Command Generation algorithms that generate gimbal angle and inertial line-of-sight (LOS) rate commands based on aircraft and target positions, and, aircraft velocity and attitude data. The commands predominantly consist of stare, slew, or scan commands that are comprised of gimbal angle commands to the inertial position loops, and inertial rate and

acceleration commands to the rate stabilization and IMC loops.

- (3) Target Image Geolocation algorithms that locate sensor image projections on the earth's surface using a WGS-84 reference ellipsoid.

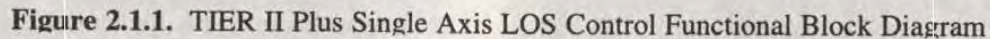
2.0 LOS CONTROL

2.1 Gimbal Angle And Inertial Rate Control

The EO sensor assembly is mounted on the inner gimbal of a two axis gimbal set. The outer gimbal (roll axis) is nominally coincident with the aircraft body roll axis, and the inner gimbal (pitch/yaw axis) is oriented between the aircraft body pitch or yaw (heading) axis depending on the outer gimbal roll angle. At zero gimbal angles, the sensor LOS is directed down along the aircraft body yaw axis and the on-gimbal IMU coordinate frame (assumed coincident with the sensor LOS frame) is parallel with the INS coordinate frame. Scans are conducted about the sensor roll axis, which at zero-zero, is the outer gimbal axis.

The controller provides 2 degree-of-freedom control of the sensor LOS about the LOS roll and pitch/yaw axes, respectively. Consequently, there is no control of the image about the sensor LOS axis. In the presence of aircraft angular base motion which results in disturbances about the LOS axis, the earth-fixed images exhibit random rotations from frame to frame. This effect is most noticeable for aircraft pitch motion at large roll angles and for aircraft heading motion at small roll angles. The random frame to frame rotations cause overlap errors of the projected earth images. Also, when scanning the sensor at non-zero pitch/yaw angles, the sensor LOS rotates about its roll and LOS axes. This LOS rotation does not introduce frame-to-frame gaps because the image rotation between frames is correlated due to the constant pitch/yaw angle. This geometry is covered in more detail in the Image Geolocation section.

In order to meet stabilization requirements during imaging (scanning), the control system step/stares the LOS by closing only



The low bandwidth (3Hz) inertial position loops are closed about multi-speed inductosyns during LOS position transfers and scan turnarounds. This position control removes LOS position biases due to gyro drift errors and accumulated position errors which build up during each scan bar.

inertial rate, inertial position, and IMC position loops. Table 2.1.1 summarizes some of the salient features of the LOS control loops referred to in Figure 2.1.1.

Fine image stabilization is achieved with two axis image motion compensation (IMC) mirrors which operate in the collimated space of the telescope. The telescope magnification of 12 adjusted by the $1/2$ angle mirror relationship results in a 6-to-1 gain of mirror motion to LOS motion. The sensor roll and pitch/yaw inertial rate loop errors are integrated to provide an open loop LOS correction to the IMC for frequencies up to 300 Hz. Each of the IMC mirrors is actually a two axis mirror. The passive axis of each mirror is caged at zero or a constant bias position to correct for misalignments in the optical system.

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Table 2.1.1. Summary Of Digital EO/IR Sensor LOS Control Loops

Loop	Qty.	Band width (Hz)	Sample Rate (Hz)	Type	Feedforward Signals	Feedback Transducer	Function
Sensor Inertial Rate	2	30	2000	III	Inertial acceleration command	LN200 IMU	Controls LOS inertial rate
Low Bandwidth Inertial Position	2	3	500	II	none	Inductosyn	Controls LOS EF position
IMC Active Axis Position	2	300	6000	II	IMC acceleration command, Spring cancellation (internal)	Kaman proximity sensor	Controls IMC position wrto sensor
IMC Passive Axis Position	2	300	6000	II	none	Kaman proximity sensor	Cages IMC wrto sensor.
Med Bandwidth Base Reference	2	30	2000	III	Gimbal acceleration command	Inductosyn	Controls gimbal angles during Base Reference Mode
Shroud Rate	1	20	500	I	Imbalance torque (gravity) Acceleration Friction Gimbal rate estimate	Tachometer	Controls shroud rate wrt base
Shroud Position	1	10	500	I	Imbalance torque estimation Roll acceleration command	Proximity sensor	Controls shroud position with respect to roll gimbal

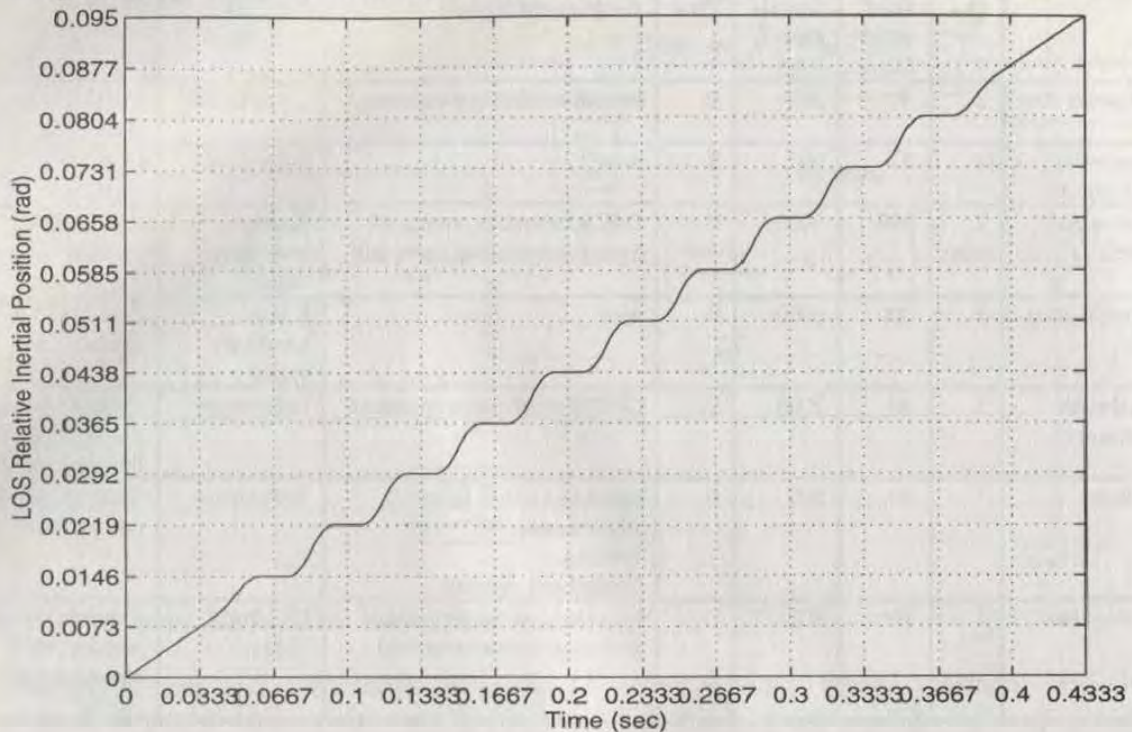
also has the capacity to attenuate any gyro or IMC loop dynamics through transfer function cancellation techniques.

The digital loops which control the IMC's have a 6 kHz sample rate. The timing constraints on sensor readout reporting and the 300Hz target bandwidth require a high sample rate. The sample rate was chosen as high as possible without excessive processor computational loading. The IMC mirror which performs roll stabilization is also used as a backscan mirror. The sensor is a staring detector with an integration time between 5 and 10 ms. Thus, the sensor LOS must be earth-fixed during the integration interval to minimize image smearing. This is achieved by maintaining a constant earth-fixed rate of the sensor roll gimbal axis and backscanning the roll IMC mirror at the appropriate rate to exactly cancel the sensor earth-fixed motion. This continues throughout the video integration period, at which time the mirror is repositioned to the start location for the next backscan. This stare-retrace strategy requires that the commanded sensor inertial rate be

exactly equal to the IMC backscan rate in FOV space. Figure 2.2.1 shows a plot of the simulated LOS inertial angle as a function of time during imaging. The position command profile corresponding to the required 30Hz frame rate causes servo errors in the backscan IMC control loop which require settling time before the start of scene integration. This cuts into the available backscan time and increases mirror travel, requiring acceleration feedforward to minimize servo errors. Spring cancellation is also used to cancel the disturbance created by the mirror flexure mounts.

Proximity sensors are used to close the IMC loops. In the case of the roll backscan mirror, the scale factor error of this sensor is critical to the LOS control. Scale factor error directly affects image smear which must be limited to under 0.5 milliradians per second during video integration. Laboratory testing of the IMC mirror mechanism exhibited scale factor hysteresis when subjected to operating temperature variations. This disappointing result implied that the scale factor was not

Figure 2.2.1. Simulated LOS Inertial Position vs. Time For 10 Backscan Frames (30Hz)



repeatable with temperature thus requiring an in-flight calibration technique be employed when operating temperatures exceed prescribed limits. Another source of error in the backscan is the misalignment between the IMU and the roll mirror axis. This misalignment can be measured in the laboratory and removed by commanding the pitch mirror with the negative of the pitch component of the LOS motion caused by this misalignment. This pitch component is essentially proportional to the roll backscan command through a small gain.

The high sample rate (6kHz) of the IMC control loops is one of several factors driving the quad DSP solution. One of the four processors is dedicated exclusively to generating backscan commands for the active roll IMC axis, closing the four IMC loops, and maintaining the timing data used to interpolate the INS and gimbal angle data to the center of the image integration interval

3.0 COMMAND GENERATION

Command generation is mode dependent. The four modes discussed in Section 1.0 are Base Reference, Spot, WAS, and EF Point. Each of these modes uses a different command generation strategy. However, the design basically uses a set of command generation algorithms which are applied with different input sources and different output destinations depending upon the mode.

The four modes described in Section 1.0 require the following algorithm functional elements:

- (1) LOS Inertial Rate Generator;
- (2) Scan Generator,
- (3) Gimbal Angle Command Generator, and
- (4) Command Processor.

Most of the inputs required for command generation are provided by the LN100 GPS / INS. The following sections describe each of the functional elements (1 through 4) and

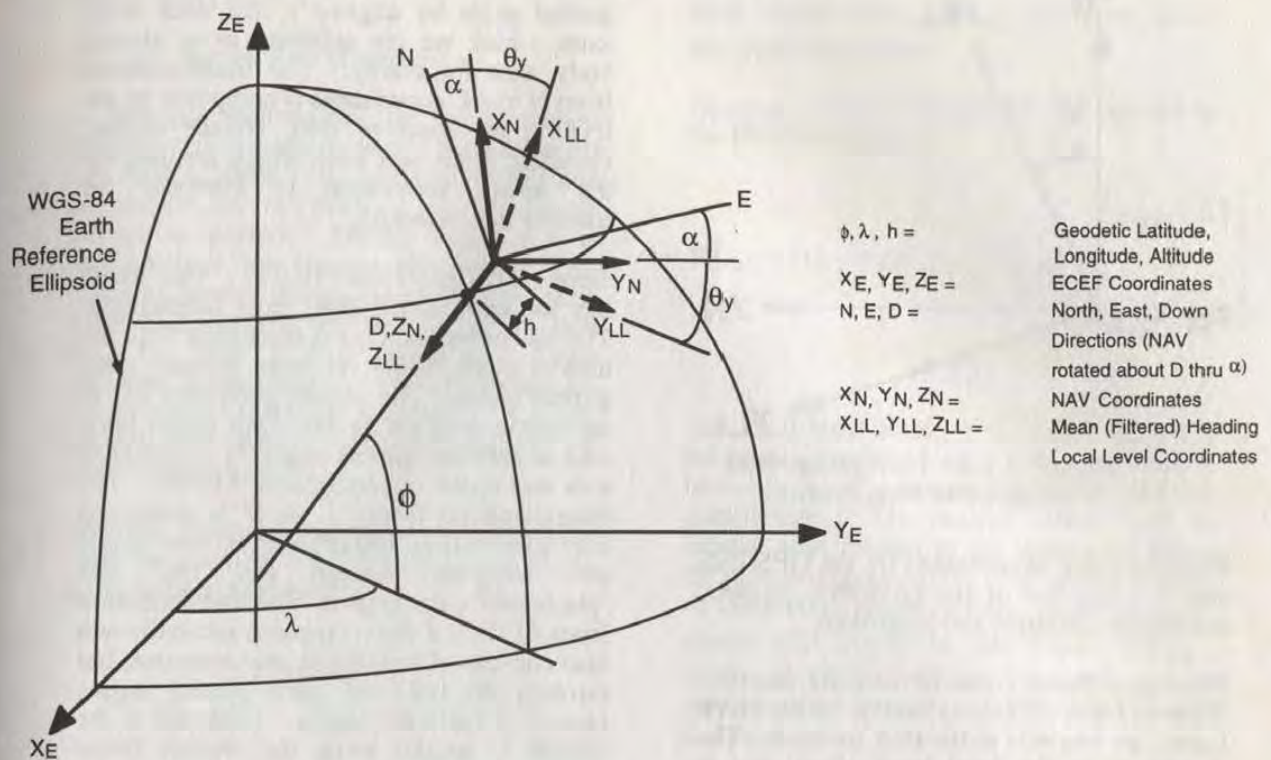


Figure 3.1.1. TIERII Plus Fundamental Coordinate Frames For Command Generation

list the GPS / INS inputs required for that functional element with a brief initial discussion of coordinate frames. Key elements of the command generation scheme are shown in Figure 3.4.1, which is a functional block diagram of the command generation.

3.1 Coordinate Frames

Five principal coordinate frames are used in the command generation. These are the earth centered earth fixed (ECEF) coordinate frame, the wander azimuth navigation frame (N), the local level frame (LL), aircraft body frame (AC), and the sensor LOS frame (S). Each frame (except aircraft body and sensor LOS) is shown in Figure 3.1.1. Figure 3.1.1 is the WGS-84 reference Earth ellipsoid with the above frames.

Earth Centered, Earth Fixed (ECEF) Frame - (Figure 3.1.1) This frame is defined in

WGS-84 and has its origin at the earth's geometric center. The X axis is in the equatorial plane at zero degrees longitude. Z points north through the polar axis, and Y forms an orthogonal right handed (RH) set.

Wander Azimuth Navigation (N) Frame - (Figure 3.1.1) The navigation coordinate frame is the reference in which the INS navigation computations are performed. The center for this frame is located at the INS location and is rotated at the earth's inertial rate plus the craft rate. (Craft rate is the angular rate of the local level and navigation frames with respect to the ECEF frame resulting from linear craft motion over the earth's surface). The Z_N axis lies along the local geodetic vertical and is positive down. X_N is normal to Z_N and is rotated from true north in the local horizontal plane by the wander azimuth angle α . Y_N completes the RH orthogonal set. The transformation from

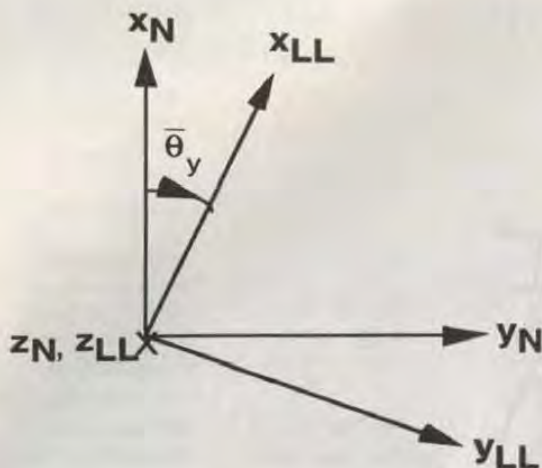


Figure 3.1.2. Navigation And Local Level Scan Frames

ECEF to NAV is computed by the GPS/INS and is a function of the GPS/INS geodetic coordinates (latitude and longitude).

Heading Filtered Local Level (LL) Frame - (Figure 3.1.1, 3.1.2). Similar to the NAV frame, its origin is at the INS location. The X axis is in the local level plane, but is rotated about the Z_N axis through an angle which equals the filtered aircraft heading. The heading is filtered so that the frame moves slowly with respect to ECEF. Scans are constructed in this frame so that the scan bars are primarily orthogonal to the aircraft filtered heading. The filtering of the heading angle reduces scan bar overlap problems associated with a rapidly yawing aircraft. The transformation from NAV to LL is computed with a first axis rotation of the NAV frame about the Z_N axis by the filtered heading angle.

Aircraft Body (AC) Frame - (Figure 3.1.3). This frame also has its origin at the INS location. The X direction points out the nose of the aircraft and is nominally aligned with the aircraft body roll axis. Z points out the bottom of the aircraft and is nominally aligned with the aircraft body heading (yaw) axis. Y forms a RH orthogonal set and nominally points out the right wing. In this terminology, the INS body (platform) axes are assumed to be coincident with the aircraft body axes. What is critical in boresighting

the sensor is that the gimbal axes at zero gimbal angle be aligned to the INS body axes, which we are referring to as aircraft body axes for clarity. The transformation from N to AC coordinates is computed by the INS in the form of three attitude angles, Heading, Pitch, and Roll, which are used by the sensor subsystem to compute the transformation matrix.

Sensor LOS (S) Frame (e,d,r) - This frame has its origin at the IMU axes intersection. The sensor roll axis (e) is coincident with the aircraft (INS body) roll axis at zero pitch gimbal angle. The sensor pitch axis (d) is coincident with the aircraft (INS body) pitch axis at zero roll gimbal angle. r is the LOS axis and forms an orthogonal RH set. The transformation from LL to S is computed internally and is determined by two single axis rotations through the 'roll' and 'pitch/yaw' euler angles. The transformation from AC to S is also computed internally and also consists of two single axis rotations, but through the roll and pitch gimbal angles instead of the euler angles. Note that if the aircraft is locally level, the aircraft frame (INS body frame) is aligned with the local level frame and the gimbal angles are equal to the local level euler angles

In the following discussion, coordinate transforms are denoted by C_X^Y , where C is

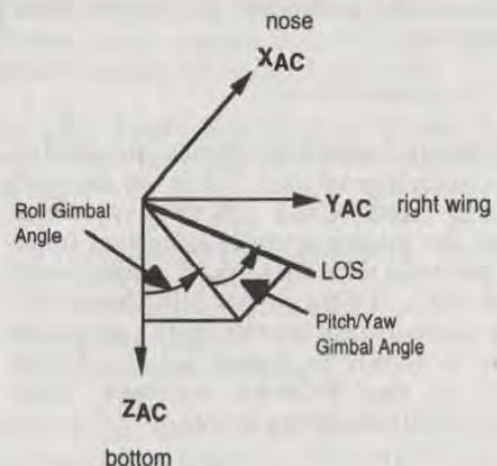


Figure 3.1.3. Aircraft Frame

the direction cosine matrix transform from Frame X to Frame Y.

3.2 LOS Inertial Rate Generator

A principal requirement for the command generation is to maintain the LOS position on the earth's surface at constant earth-fixed coordinates for the duration of one sensor integration period. During scan, this is accomplished by closing the inertial rate loops to control the sensor earth-fixed rates while backscanning the IMC mirror to null the LOS rates. The inertial rate loops attenuate aircraft angular motion sensed by the on-gimbal IMU and compensate for any unobserved angular motion induced by aircraft linear motion.

To meet coverage requirements, the sensor must be scanned with respect to an earth-fixed target at a constant rate,

$$\underline{\omega}_{S/ef}^S = \begin{bmatrix} \phi_{FOV} / \Delta T \\ 0 \\ 0 \end{bmatrix} \quad (3.2.1)$$

where

$\underline{\omega}_{S/ef}^S$ = angular rate of the sensor frame with respect to the earth-fixed frame resolved in sensor frame coordinates,

ϕ_{FOV} = sensor roll angular FOV,

ΔT = frame time = 1/30 second.

$\underline{\omega}_{S/ef}^S$ is comprised of two distinct rates:

$$\underline{\omega}_{S/ef}^S = \underline{\omega}_{S/LL}^S + \underline{\omega}_{LL/ef}^S \quad (3.2.2)$$

$\underline{\omega}_{S/LL}^S$ is the angular rate of the sensor with respect to the local level frame. This rate is further partitioned into two rates - the angular rate induced by the translation of the sensor frame with respect to the stationary earth-fixed target, $\underline{\omega}_{S/T}^S$, plus the controlled angular displacement of the earth-fixed target

(or desired sensor LOS) with respect to local level coordinates, $\underline{\omega}_{T/LL}^S$. Figure 3.2.1 illustrates these rates.

Equation (3.2.2) is expanded and equated to the FOV constraint.

$$\underline{\omega}_{S/ef}^S = \underline{\omega}_{S/T}^S + \underline{\omega}_{T/LL}^S + \underline{\omega}_{LL/ef}^S = \begin{bmatrix} \phi_{FOV} / \Delta T \\ 0 \\ 0 \end{bmatrix} \quad (3.2.3)$$

The local level frame is a 'quiet' frame to reference position and rate commands because it is uncorrelated from aircraft disturbances. The desired sensor LOS is located with respect to the local level frame through two euler angles. The rate-of-change of these euler angles defines the angular rate vector with respect to that frame, $\underline{\omega}_{T/LL}^S$, which, during gimbal scan, is a constant scan rate modified by the aircraft-induced motion and craft rates.

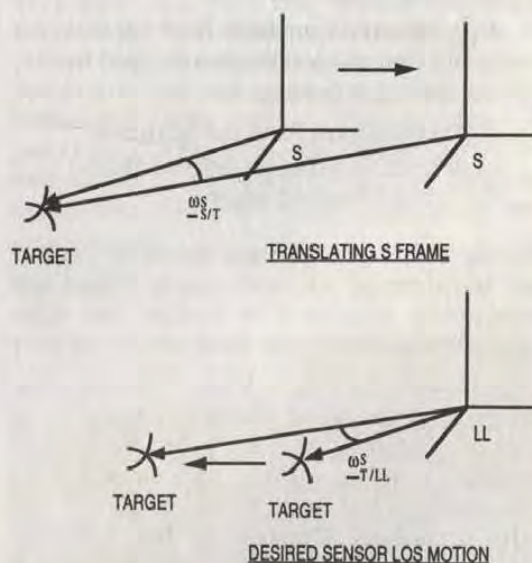


Figure 3.2.1. $\underline{\omega}_{S/LL}^S$ Components

$$\underline{\omega}_{T/LL}^S = \begin{bmatrix} \phi_{FOV} / \Delta T \\ 0 \\ 0 \end{bmatrix} - \underline{\omega}_{S/T}^S - \underline{\omega}_{LL/ef}^S, \quad (3.2.4)$$

where

$$\underline{\omega}_{S/T}^S = \begin{bmatrix} -v_2 \\ v_1 \\ 0 \end{bmatrix} \frac{1}{R_LOS}, \quad (3.2.5)$$

and

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = C_{LL}^S * C_N^{LL} * \underline{V}_{AC/ef}^N \quad (3.2.6)$$

The angular rate vector in (3.2.5) is generated in sensor LOS coordinates from the aircraft velocity and target-to-sensor slant range (R_LOS) computed by the image geolocation algorithm. The terms in (3.2.6) are defined as

$\underline{V}_{AC/ef}^N$ = aircraft velocity vector with respect to the earth-fixed frame resolved in the navigation frame provided by aircraft INS,

C_{LL}^S = desired transform from local level to sensor coordinates defined by the derived euler angles,

C_N^{LL} = transform from navigation to local level coordinates derived from the filtered heading angle.

During LOS scan, all three terms in (3.2.4) are transformed to euler angle rates and numerically integrated to update the euler angles which define the local level-to-sensor LOS transform, C_{LL}^S . During gimbal slew maneuvers, the Scan Generator analytically derives time-optimal (see Scan Generator) angular position, rate, and acceleration commands to reposition the LOS on the earth's surface. Because of the relatively large angular displacements required for a slew maneuver, the analytical solution prevents numerical integration errors from

corrupting the angular position and rate solutions.

The craft rate, $\underline{\omega}_{LL/ef}^S$, is the local level frame angular rate vector with respect to the earth-fixed frame. This frame is rotated to maintain the down axis aligned with the geodetic vertical. The angular rate vector is determined from INS aircraft velocity data resolved in navigation coordinates.

$$\underline{\omega}_{LL/ef}^N = \begin{bmatrix} v_y \\ -v_x \\ (v_x \sin \alpha + v_y \cos \alpha) \tan \lambda \end{bmatrix} \frac{1}{r_S^{ef}} \quad (3.2.7)$$

where

v_x, v_y = navigation frame local horizontal velocity components in navigation frame coordinates

α = wander azimuth angle,

λ = geodetic latitude,

$|r_S^{ef}|$ = radial distance from sensor to earth's center.

$\underline{\omega}_{LL/ef}^N$ is transformed to sensor LOS coordinates before it is applied in (3.2.4)

$$\underline{\omega}_{LL/ef}^S = C_{AC}^S * C_N^{AC} * \underline{\omega}_{LL/ef}^N \quad (3.2.8)$$

where the direction cosines in (3.2.8) are derived from INS and inductosyn outputs. Equation (3.2.4) generates the appropriate rate command to control the LOS with respect to an earth-fixed frame. However, the rate loop commands are referenced to inertial coordinates requiring the earth rate vector to be added to the rate vector in (3.2.4), $\underline{\omega}_{T/LL}^S$. The inertial rate command becomes

$$\underline{\omega}_{cmd/i}^S = \underline{\omega}_{T/LL}^S + \underline{\omega}_{ef/i}^S \quad (3.2.9)$$

3.3 Scan Generator

The Scan Generator analytically computes angle, angular rate, and angular acceleration commands as a function of time to transfer

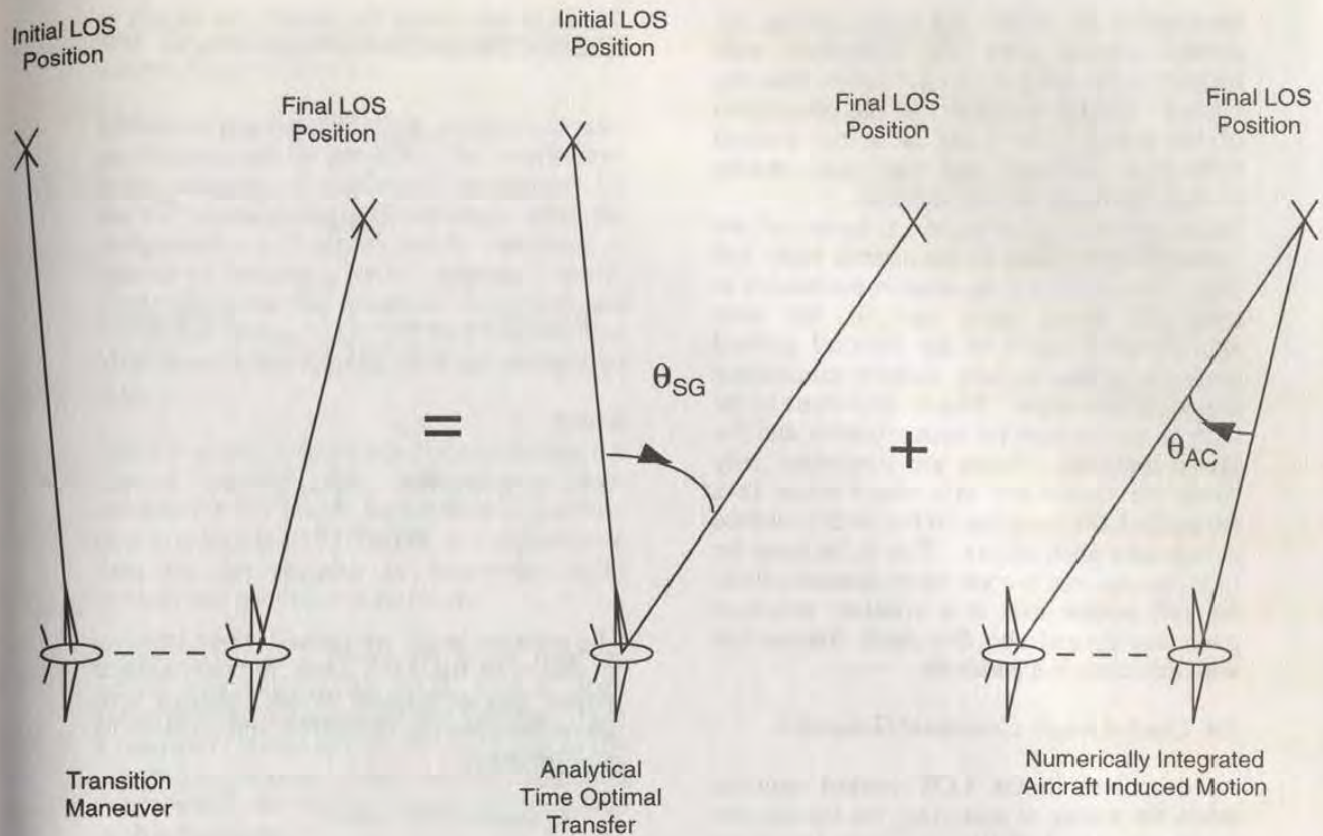


Figure 3.3.1. Scan Generator Transfer Partitioning Mechanism

the sensor from an initial state to a final desired state. In Base Reference mode, the commands are gimbal angles and accelerations while in all other modes, the commands are euler angles, rates, and accelerations.

The Scan Generator employs a time-optimal solution for all transfer maneuvers. The Scan Generator inputs are the initial angular position and rate and the final position, rate, and time to complete the transfer. The transfer time is divided into two equal periods of constant acceleration whose amplitudes are computed prior to the first time step of the transfer. The rate and position commands are analytic integrals of the acceleration profile that are sent to the servo loops every sample period.

The mechanism for performing a slew maneuver of the LOS is described graphically

in Figure 3.3.1. The typical maneuver requires the LOS to be repositioned from its present earth-fixed position to the first frame position of the next scan bar at the desired earth-fixed scan rate. This problem is partitioned such that the Scan Generator analytically generates the reposition commands while the aircraft-induced rate compensation ($\omega_{S/T}^S$ and $\omega_{LL/ef}^S$) is numerically integrated.

At the inception of a transfer, a new target is located with latitude and longitude inputs. A unit vector from the new target to the current sensor position is computed in local level coordinates from which target euler angles are derived. The Scan Generator determines the servo loop commands that will transfer the LOS from its present initial euler angle position to the target euler angle position assuming a stationary aircraft and target. To

compensate for aircraft and target motion, the aircraft-induced rates are computed with respect to the assigned target rather than the current LOS EF location. At the conclusion of the transfer, the LOS is at the desired earth-fixed location and rate that exactly cancels the linear aircraft motion.

Scans are constructed in the LL frame and are generally orthogonal to the aircraft body roll axis. The length of the scan is modulated to keep the cross track rate of the scan approximately equal to the forward ground track rate of the aircraft, thereby minimizing the pitch/yaw angle. This is important in the scan geometry both for image quality and for image footprint. Scans are conducted only about the sensor roll axis which result in a parabolic LOS footprint on the earth's surface at non-zero pitch angles. This is because the LOS sweeps out a cone when scanned about the roll sensor axis at a constant non-zero pitch angle, and the flat earth intersection with this cone is a parabola.

3.4 Gimbal Angle Command Generator

As described in the LOS control section, when the sensor is scanning, the inertial rate loops are closed and the position loops are open. During transfers which include scan bar turnarounds, the position loops are closed to remove gyro drift and servo position biases accumulated during the scan bar. The gimbal angle commands are continually updated according to the following process when the position loops are closed.

The LOS unit vector in S coordinates is expressed as,

$$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

and is transformed to aircraft coordinates using the direction cosine matrices defined in previous sections.

$$\underline{u}_{LOS}^{AC} = C_N^{AC} * C_{LL}^N * C_S^{LL} * \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (3.4.1)$$

The LOS unit vector in aircraft coordinates is related to the gimbal angles according to

$$\phi = \arctan\left(\frac{-u_2}{u_3}\right) \quad \text{roll} \quad (3.4.2)$$

$$\theta = \arctan\left(\frac{u_1}{\sqrt{u_2^2 + u_3^2}}\right) \quad \text{pitch/yaw}$$

where

$$\underline{u}_{LOS}^{AC} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

The position loops are opened when imaging to decouple the LOS from aircraft angular motion that is induced by the inherent time delays between the GPS/INS and inductosyn measurements.

3.5 Command Processor

The Command Processor (CP) is the backbone of the command generation. As mentioned in the LOS control section on digital servo implementation, command generation is executed at the same sample rate as the loops being commanded. Thus, the LOS Inertial Rate Generator, Scan Generator, and Gimbal Angle Command Generator execute at 2kHz, and the IMC backscan command executes at 6kHz. All time steps are synchronized to an IMU clock signal. The CP runs at 500Hz.

The CP handles mode transitions and is the source of most of the arguments to the command generation algorithms. For example, if the sensor is commanded to leave an idle mode and begin a WAS pattern at a start latitude and longitude, the CP computes the initial and final euler angles for the transfer to the new earth-fixed location and calls the LOS Inertial Rate Generator, Gimbal Angle Command Generator, Scan Generator,

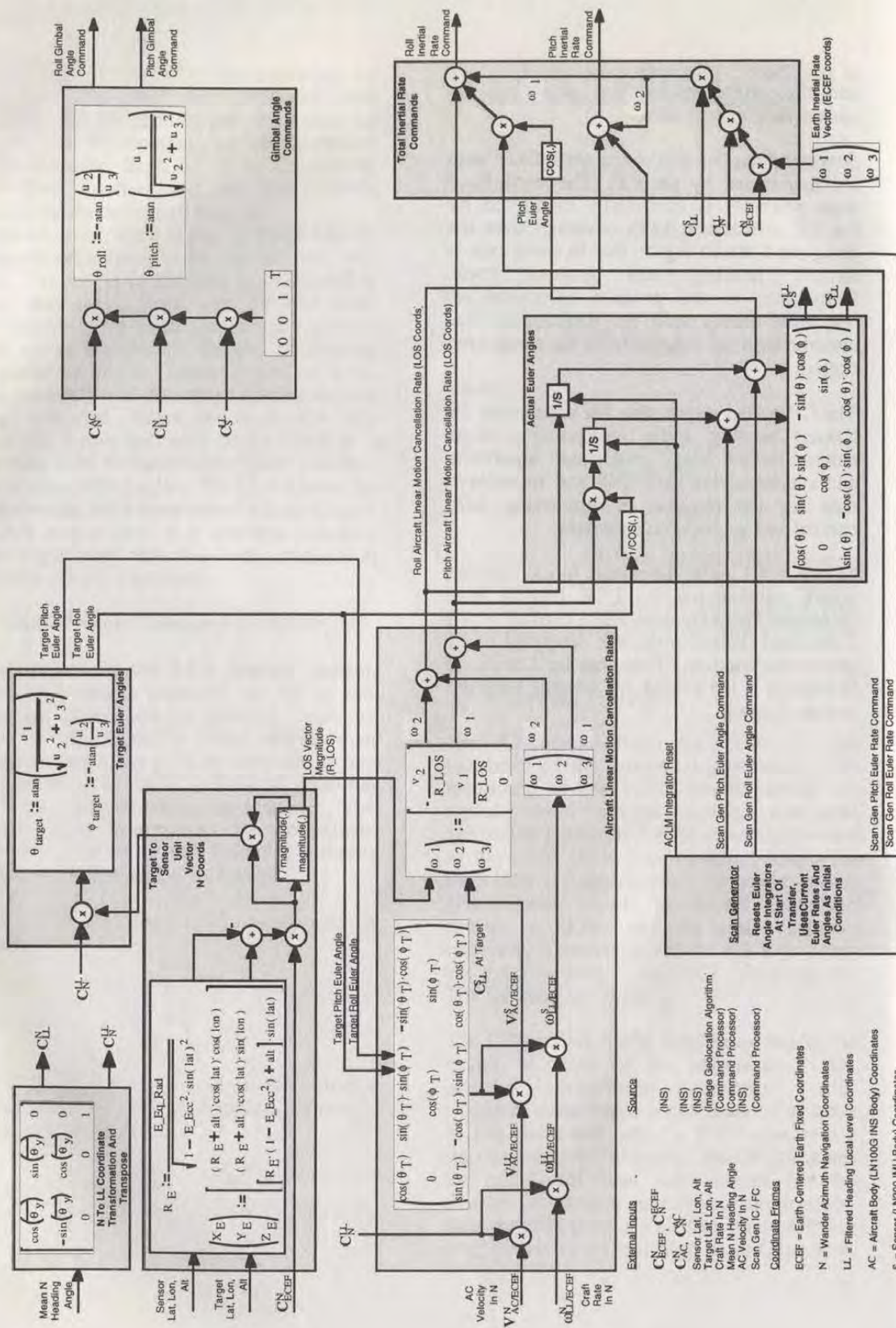
and the image geolocation algorithm for current target range data.

Several of the features of the earth-fixed scan are maintained by the CP. The earth-fixed scan geometry is continually monitored by the CP to maintain LOS coverage over the designated search region due to variations in aircraft heading and ground track. Corrections to the position command are computed during scan bar turnarounds that alter the scan bar lengths to fit the designated region.

The CP is also responsible for computing the filtered heading angle, interpolating target altitude for the image geolocation algorithm, and synchronizing GPS/INS and inductosyn data for the purpose of improving LOS control and geolocation estimates.

Figure 3.5.1 is a functional block diagram which summarizes the LOS Inertial Rate Generator, Scan Generator and Gimbal Angle Command Generator that are described in the above four sections. Note that the Command Processor is the source for several variables in this diagram.

Figure 3.5.1. LOS Inertial Rate and Gimbal Angle Computation Functional Block Diagram



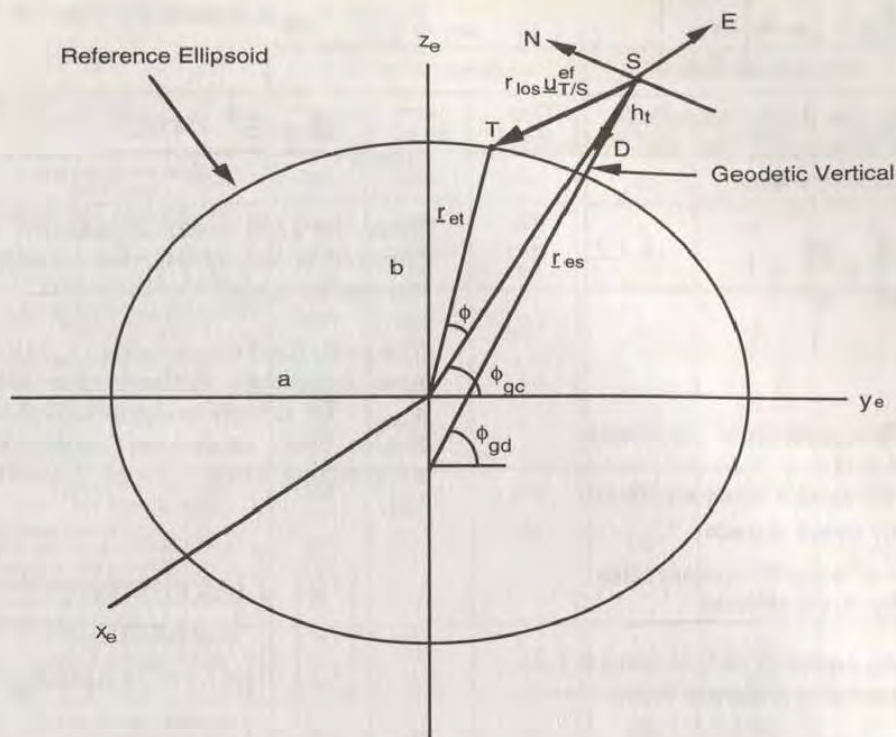


Figure 4.1.1 LOS / Reference Ellipsoid Geometry

4.0 IMAGE GEOLOCATION

4.1 Frame Locator Algorithm

The purpose of the frame locator algorithm is to locate the terrestrial position of a sensor video frame on the earth's surface. The frame location data has two functions.

- (1) To assist in the post-flight processing of video frame mosaicking
- (2) To correct for frame location errors accumulated during Wide Area Search scans

The frame locator algorithm design utilizes the WGS84 ellipsoidal earth model. Given an aircraft latitude, longitude, and altitude above the reference ellipsoid, the algorithm determines the sensor LOS intersection with the reference ellipsoid using the LOS pointing direction derived from aircraft navigation data (LN-100 INS) and gimbal inductosyn readout angles.

Figure 4.1.1 depicts the frame locator geometry of the line-of-sight (LOS) that is defined by its earth target intersection (T) and its sensor location (S).

The frame locator algorithm determines the geodetic latitude and longitude of the LOS target vector on the reference ellipsoid (r_{et}), given the sensor's earth-fixed position vector (r_{es}), the target altitude above the reference ellipsoid (h_t) and the LOS unit vector resolved in earth-fixed coordinates ($u_{T/S}^{ef}$). Since the LOS direction is known, only its magnitude is needed to completely define its intersection with the reference ellipsoid.

The LOS magnitude is derived from the target vector equation which equals the sum of the sensor and LOS position vectors expressed in earth-fixed coordinates,

$$\underline{r}_{et} = r_{los} \underline{u}_{T/S}^{ef} + \underline{r}_{es} = \begin{bmatrix} x_{et} \\ y_{et} \\ z_{et} \end{bmatrix} \quad (4.1.1)$$

with r_{los} as the LOS magnitude. The mathematical expression for the reference ellipsoid is expressed as,

$$\frac{x_e^2}{a^2} + \frac{y_e^2}{a^2} + \frac{z_e^2}{b^2} = 1 \quad (4.1.2)$$

where

x_e, y_e, z_e = earth-fixed coordinates (Figure 4.1.1)

$a = a_e + h$ = earth's equatorial radius adjusted by target altitude

$b = a\sqrt{1-e^2}$ = earth's polar radius adjusted by target altitude

By substituting equation (4.1.1) into (4.1.2), r_{los} is expressed in a quadratic form.

$$Ar_{los}^2 + Br_{los} + C = 0 \quad (4.1.3)$$

where

$$A = b^2(u_1^2 + u_2^2) + a^2u_3^2$$

$$B = 2[b^2(u_1x_{es} + u_2y_{es}) + a^2u_3z_{es}]$$

$$C = b^2(x_{es}^2 + y_{es}^2) + a^2z_{es}^2 - b^2a^2 \quad (4.1.4)$$

and

$$\underline{r}_{es}^{ef} = \begin{bmatrix} x_{es} \\ y_{es} \\ z_{es} \end{bmatrix}$$

$$\underline{u}_{T/S}^{ef} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

Finally, r_{los} is determined from the quadratic formula.

$$r_{los} = \frac{-B \pm (B^2 - 4AC)^{1/2}}{2A} \quad (4.1.5)$$

Since the LOS vector pierces the reference ellipsoid at two points, the solution having the smaller magnitude is selected.

The earth-fixed target vector ($\underline{r}_{et}$) in (4.1.1) is now completely defined after determining r_{los} . To determine latitude and longitude angles, the earth-fixed target vector is expressed in terms of its geodetic coordinates [2].

$$\underline{r}_{et} = \begin{bmatrix} x_{et} \\ y_{et} \\ z_{et} \end{bmatrix} = \begin{bmatrix} (\rho + h) \cos \phi_{gd} \cos \lambda \\ (\rho + h) \cos \phi_{gd} \sin \lambda \\ [\rho(1 - e^2) + h] \sin \phi_{gd} \end{bmatrix} \quad (4.1.6)$$

The ellipsoid's eccentricity is defined as,

$$e^2 = 1 - \frac{b_e^2}{a_e^2} \quad (4.1.7)$$

with the normal radius of curvature expressed as,

$$\rho = \frac{a_e}{(1 - e^2 \sin^2 \phi_{gd})^{1/2}} \quad (4.1.8)$$

and

h = target altitude above the reference ellipsoid

ϕ_{gd} = geodetic latitude

λ = longitude

The longitude angle, λ , is determined directly from the x_{et} and y_{et} components defined in (4.1.6).

$$\lambda = \tan^{-1} \left(\frac{y_{et}}{x_{et}} \right) \quad (4.1.9)$$

Table 4.2.1. Cal vs. Uncal LOS Pointing Error Results For TIER II Plus LOS Control

Coordinate Frames	Uncalibrated			Calibrated		
	1 Sigma Misalignments			1 Sigma Misalignments		
	Yaw (μrad)	Pitch (μrad)	Roll (μrad)	Yaw (μrad)	Pitch (μrad)	Roll (μrad)
Local Level-to-LN100 IMU Axes	200	200	200	200	200	200
LN100 IMU Axes-to-LN100 Mounting Surface	141	141	141	0	0	0
-imu to INS case	100	100	100			
-INS case to mount surface	100	100	100			
LN100 Mounting Surface-to-Roll Gimbal Axis	226	226		0	0	
-bulkhead holes to LN100 mounting surface	111	111				
-roll base tilt	190	190				
-outer bearing housing tilt	27	27				
-bearing runout	27	27				
-inner bearing housing tilt	33	33				
Roll Gimbal Axis-to-P/Y Gimbal Axis	289		100	100		100
-roll readout error			100			100
-P/Y axis non-orthogonality	289			100		
-gimbal ring boss tilt	267					
-axis orthogonality in ring	111					
-bearing housing radial runout	5					
-bearing runout	1					
P/Y Gimbal Axis-to-EO-IR Sensor Base		100			100	
-p/y readout error		100			100	
EO-IR Sensor Base-to-Optical Train	75	75	75	75	75	75
Optical Train-to-LOS		50	50	50	50	
1 Sigma Pointing Errors (μrad)		361	281		240	238

The geodetic latitude angle is determined through iteration because it appears in multiple transcendental functions. Since latitude angle varies monotonically within a quadrant, there is little concern for the solution not converging. However, some precautions are necessary across quadrant transitions.

The geodetic latitude angle is determined by incrementing ϕ_{gd} until the z_{et} component in (4.1.6) agrees with z_{et} in (4.1.1). z_{et} is initialized at the sensor geodetic latitude. The latitude increments are computed by applying the z component difference to the difference equation relating incremental latitude changes to z.

$$\Delta z = z_{et} - z_e \quad (4.1.10)$$

and

$$\Delta\phi_{gd} = \frac{\Delta z}{\left[\rho\sqrt{1-e^2} + h \right] \cos\phi_{gd} + \frac{\rho e^2 \sin^2\phi_{gd} \cos\phi_{gd} (1-e^2)}{1-e^2 \sin^2\phi_{gd}}} \quad (4.1.11)$$

ϕ_{gd} increments the geodetic latitude angle for a couple of iterations when the Δz error converges to a small quantity.

$$\phi_{gd} = \phi_{gd} + \Delta\phi_{gd} \quad (4.1.12)$$

The above computations locate the boresight of the sensor field-of-view (FOV). It is necessary that the FOV corners be computed for reporting purposes and overlap

Table 4.2.2 Cal vs. Uncal CEP Results For TIER II Plus Frame Location Algorithm

ERROR SOURCE	UNCALIBRATED		CALIBRATED	
	DR (m)	CR (m)	DR (m)	CR (m)
LOS POINTING	11.3	10.2	9.6	6.8
TARGET ALTITUDE	5.0 (10.0)	0	5.0 (10.0)	0
OWNSHIP HORIZONTAL POSITION	5.0	5.0	5.0	5.0
OWNSHIP ALTITUDE	7.0	0	7.0	0
RSS	15.0 (17.3)	11.4	13.8 (16.3)	8.4
CEP	15.6 (16.9)		13.1 (14.6)	

computations. To locate the corners, the LOS unit vector is modified in sensor coordinates by the FOV azimuth and elevation dimensions and subsequently transformed to earth-fixed coordinates. Once these unit vectors are determined, the above latitude and longitude computations are repeated for each corner location.

4.2 CEP Analysis

The frame locator algorithm accuracy needed evaluating to see if it satisfied the 20 meter circular error probability (CEP) requirement. A CEP analysis was performed that included all the significant error contributors to the frame locator - the sensor LOS pointing vector, the INS attitude and misalignment errors, the target altitude uncertainty, and the INS errors associated with locating the aircraft's earth-fixed position vector.

The sensor LOS unit vector is determined with respect to the base-mounted INS local level reference frame. Its errors include the aircraft attitude error with respect to the INS frame along with all the misalignment buildup from the INS-sensitive axes to the sensor LOS. The CEP analysis examined the pointing accuracies with and without gimbal

calibration to determine if the less accurate uncalibrated solution is viable. These errors are summarized in Table 4.2.1 below showing that the uncalibrated solution will satisfy the CEP requirement if the gimbal mechanical tolerances are held to within specified values.

Table 4.2.1 shows that gimbal calibration removes misalignment errors between the LN100 sensitive axes and the on-gimbal IMU sensitive axes, but leaves the significant 200 microradian navigation errors intact. The LOS pointing error is the most significant error, but is not the only contributor to the LOS CEP errors, which are described in Table 4.2.2. Ownship position errors and the highly uncertain target altitude error are also significant contributors, and the resulting conclusion is that the calibrated results are an insignificant improvement over the uncalibrated results.

5.0 MODELING AND ANALYSIS

Development of the command, control, and geolocation algorithms for the TIERII Plus EO/IR control subsystem was aided by extensive math modeling and analysis. All of the embedded LOS control and command software is directly based on math model results. The models use a combination of MATLAB/SIMULINK and C language modules linked to the MATLAB simulator. Some of the algorithms, such as image geolocation, are written initially in C and then ported directly from the simulation platform (Unix machines and Macintosh) to the target embedded system (Quad TI TMS320C40 DSP card and PC based C40 simulator).

5.1 Model Description

The command generation, LOS control, and subsystem plant models are simulated as linear and nonlinear dynamic models. Some elements of the command generation and the image geolocation algorithm are incorporated as CMEX functions, written in C and linked to SIMULINK. Figure 5.1.1 shows the general structure of the model.

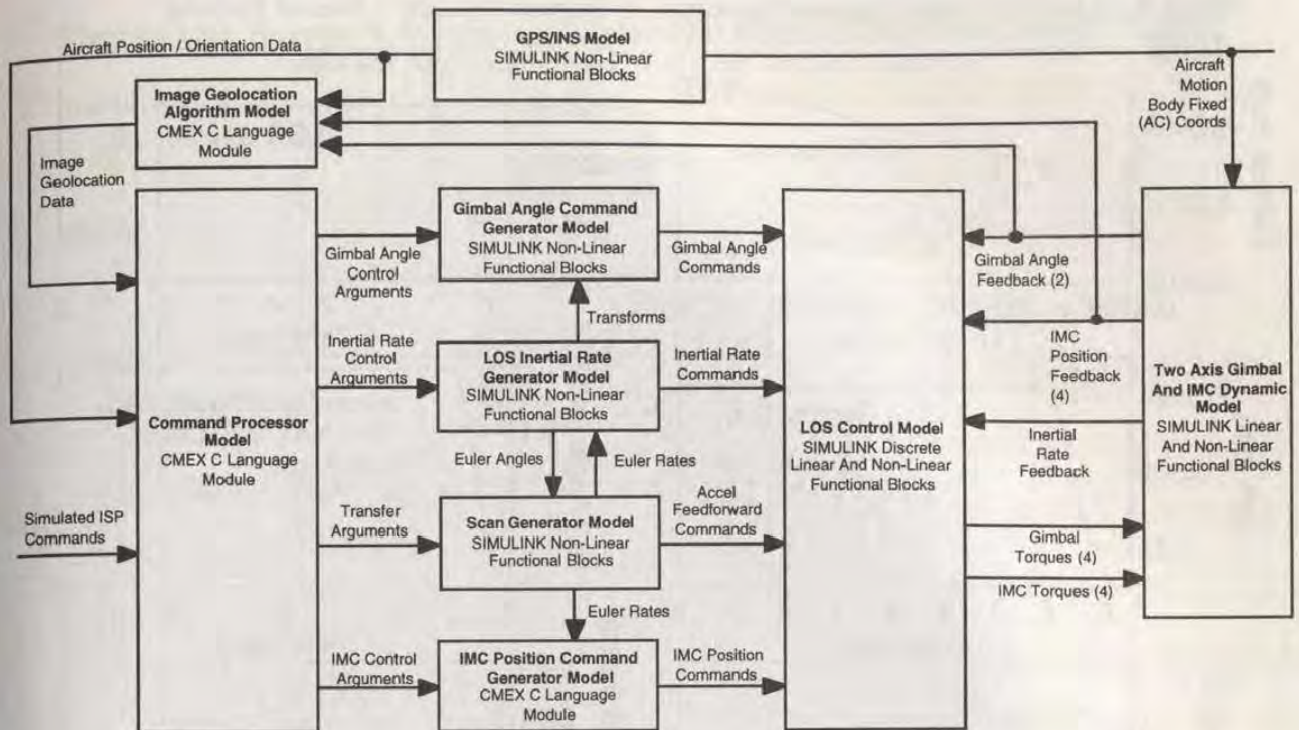


Figure 5.1.1. TIERII Plus Pointing And Stabilization Subsystem Math Model Structure

All of the algorithms are implemented digitally and perform computations at the specified sample rate for each functional module. In the LOS control model, D/A and A/D time and level quantization effects are incorporated, as well as the measurement readout errors for the inductosyns and IMU, torquer saturation and ripple, and a variety of other effects inherent in the electromechanical system.

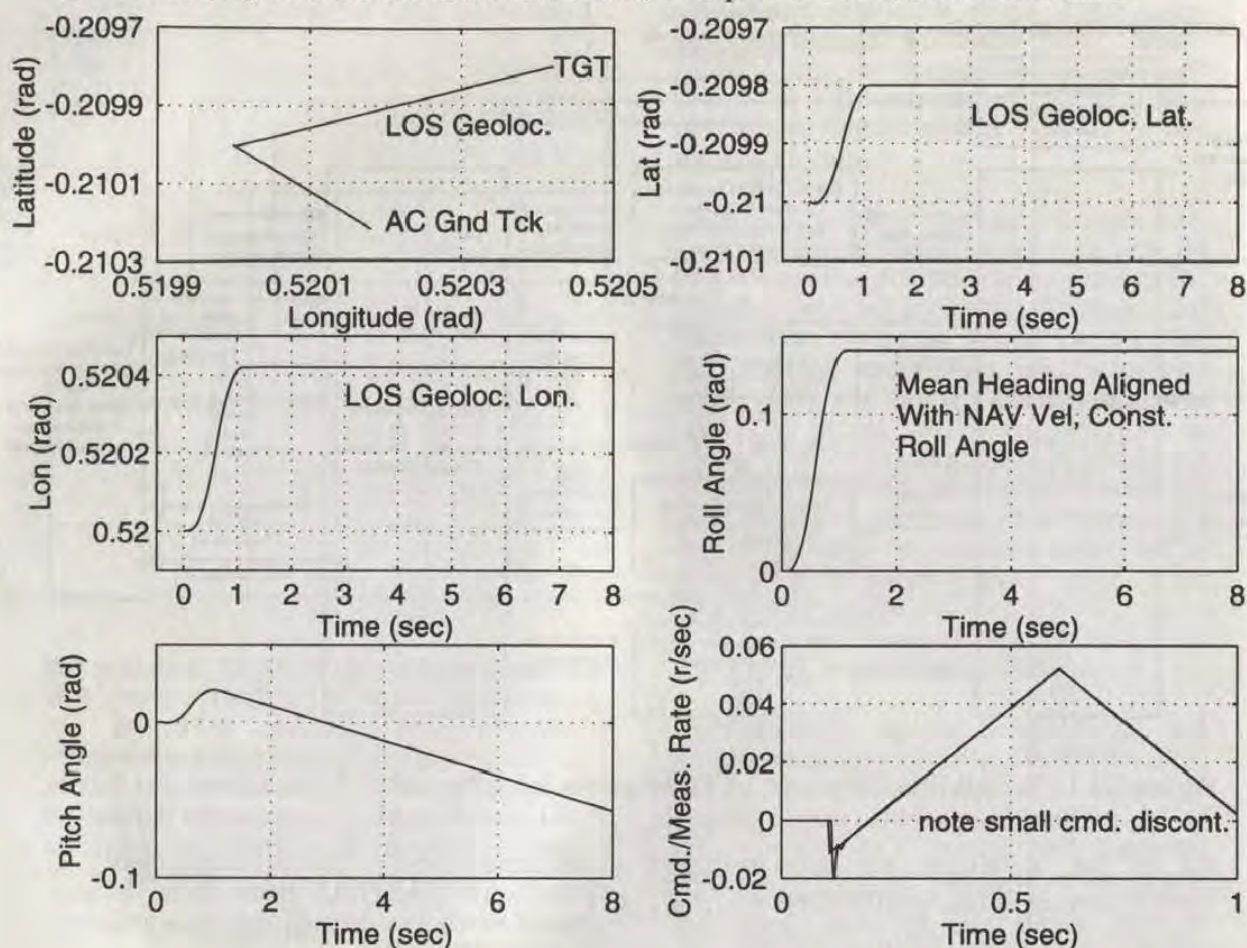
The plant model is based on linear and non-linear SIMULINK blocks which simulate the kinematics and dynamics of the two axis gimbal and IMC system. In order to accurately evaluate the LOS jitter caused by high frequency base motion effects, the non-linear kinematic model is replaced by a linearized structural model. The structural model is intended to point out possible stability problems caused by structural modes in the load path between the torquers and inductosyns or IMU and also to analyze unmeasured motion of the LOS due to sensor

structural modes. The structural model is based on a NASTRAN linear finite element model which was reduced for this simulation to about 150 states.

The command generation blocks shown in Figure 5.1.1. simulate the command generation described in Command Generation (3.0). Although only a very general description of the Command Processor is given in Section 3.0, it is a critical element of both the simulation and the embedded system. The simulation results presented in Section 5.2 demonstrate several of the interesting features of the scan geometry which the Command Processor is required to maintain during WAS patterns.

Two key elements of the simulation are the GPS/INS simulator and the Image Geolocation algorithm, both of which are based on the WGS-84 earth model and are shown in Figure 5.1.1. The GPS/INS inputs to the command generation algorithms must

Figure 5.2.1 (a-f) EF Point Command Execution, 8 Elapsed Seconds, 1 Second Transfer



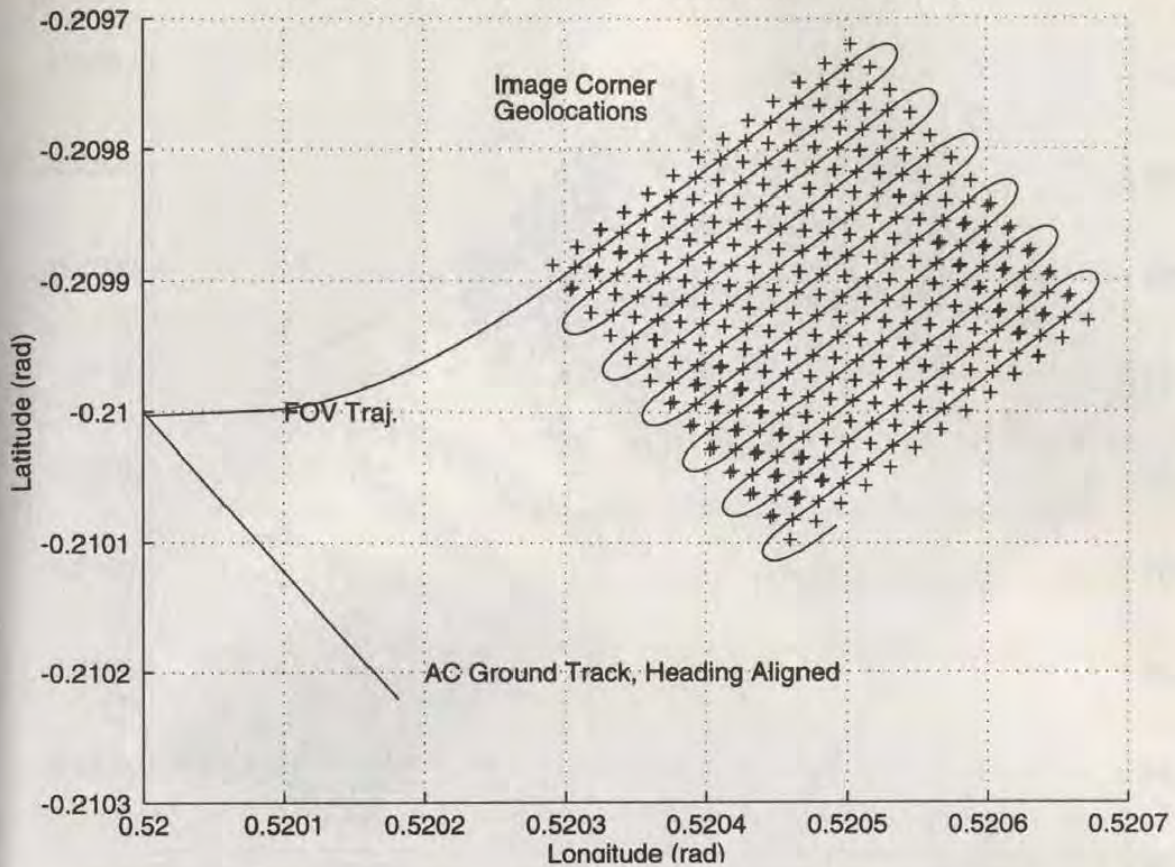
be simulated accurately in order to evaluate the accuracy of the command generation algorithms. For example, In EF Point mode, the command generation should transfer the LOS to the requested lat/lon location and maintain its position as the aircraft flies by the target. The feedback element for this simulation is the Image Geolocation algorithm. If the algorithms are working, the computed image geolocation should equal the requested location at the conclusion of the transfer and thereafter.

5.2 Simulations

Figures 5.2.1 (a-f) show a simulated EF Point command being executed. The intent is to transfer the LOS to a desired target location and maintain that position as the aircraft flies

past the target. Figure 5.2.1a shows the LOS trajectory as the LOS is transferred from its initial geolocation to a target at (-0.20980 rad Lat, 0.52042 rad Lon). The servo is operating in an inertial rate / inertial position mode where the rate commands are partitioned as described in Section 3.0. An unavoidable transient in transferring the LOS occurs because the LOS inertial rate used during the transfer is the rate which cancels aircraft translational motion with respect to the desired earth fixed target. This is not the initial rate at which the sensor is moving, and hence will involve a small velocity command step into the inertial rate loops. Figure 5.2.1f illustrates this discontinuity, which occurs any time the LOS is transferred. In general, it is not significant because it occurs at the start of a transfer where imaging is not taking

Figure 5.2.2a. Example Wide Area Search Pattern For Nominal TIER II Plus Aircraft Velocity, Heading Aligned To Ground Track and Lat/Lon Trajectory

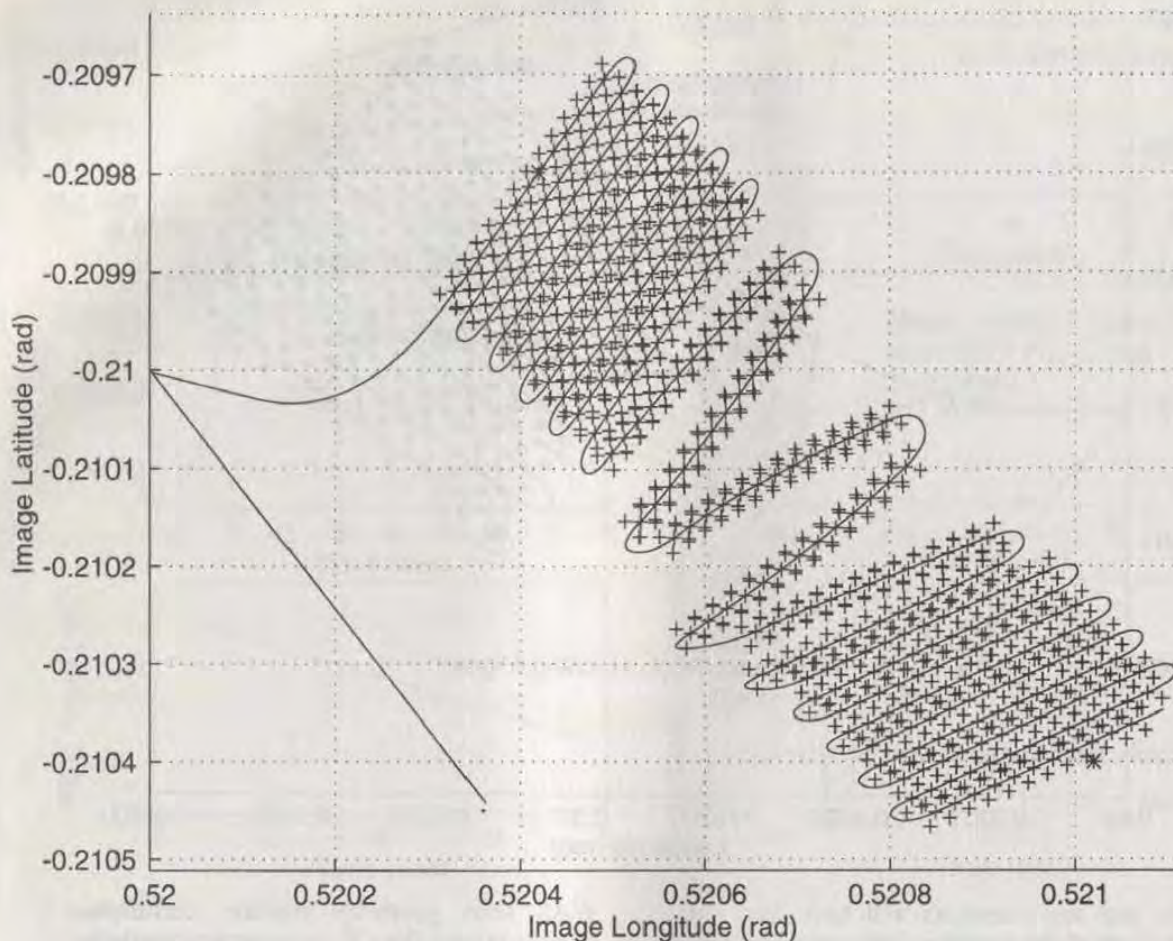


place, and any transients will have died out by the end of the transfer. The same problem applies at both the start and finish of transfers in WAS mode (during scan turnarounds). Since the scan is constructed in local level (euler angle coordinates), the transformation from sensor to local level coordinates must be applied to obtain the target euler rates for the transfer end conditions. Since exact knowledge of these rates is impossible, a small discontinuity will enter the command as the sensor transitions to constant rate scan. This discontinuity can be accommodated by allowing a short ($<1/30\text{sec}$) settling time so that the IMC correction angles are small for the entire scan bar. This is the type of command generation problem that the simulations have uncovered throughout the program.

WAS scan geometry requires continuous monitoring by the CP to maintain constant gap-free coverage of the designated search region. The WAS search region is bounded in length by a pair of latitude/longitude angles. The aircraft is directed to fly a trajectory such that its ground track parallels this search region. Sensor scan bar length defines the search region width that varies with aircraft velocity. Any adjustments to scan bar length are made at the far-field leaving near-field frames aligned to facilitate image post-processing.

The scan pattern is referenced to the LL frame which varies in orientation by the filtered aircraft heading angle. If aircraft heading varies rapidly, the scan pattern will 'walk off' the designated search region. The CP checks the near-field frame locations and repositions

Figure 5.2.2b. Example WAS Pattern For Sudden AC Heading Change, No Heading Filter, Showing Scan Bar Location Adjustments For Uniform Near-Edge Track



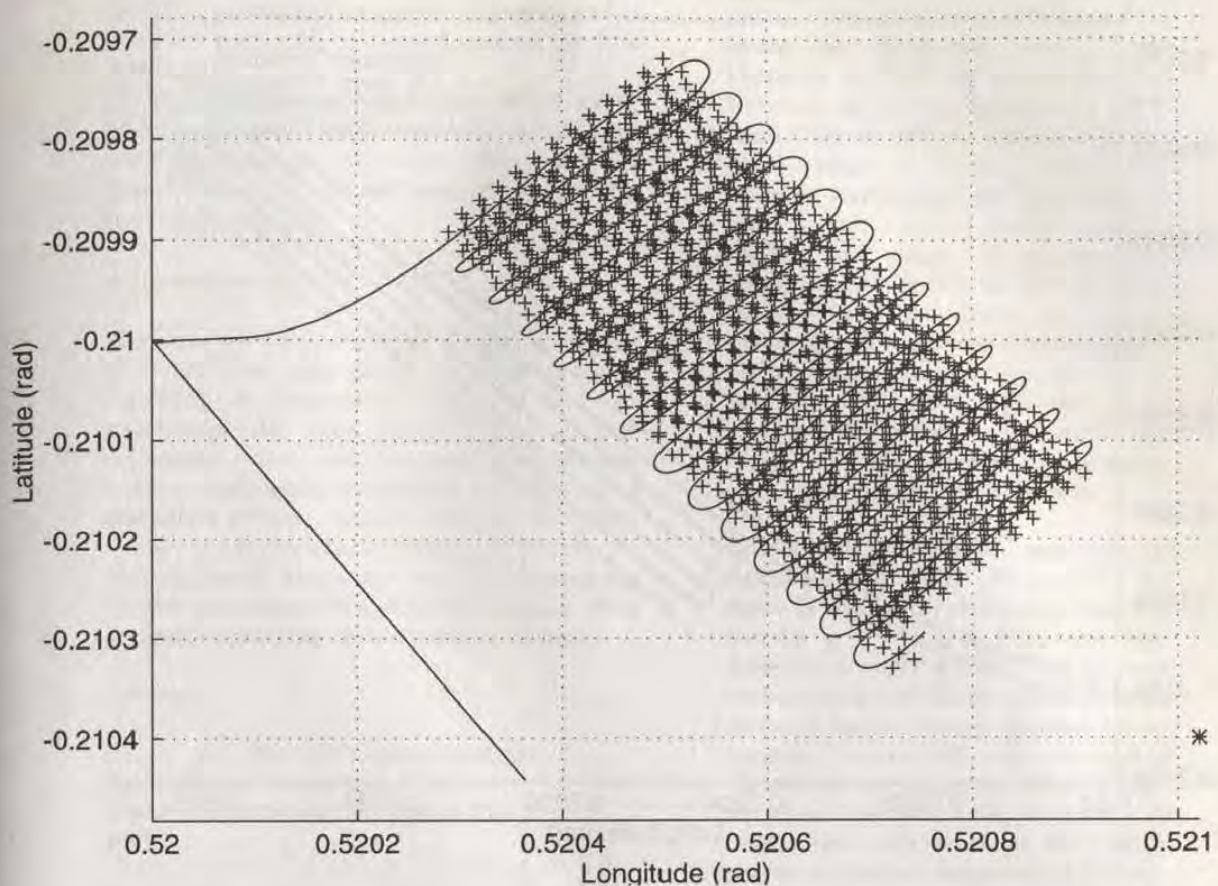
the next scan bar to account for any heading deviations.

Figure 5.2.2a is the math model output of a simulated WAS pattern where the x's locate the four corners and center position of each frame. For this case, the aircraft heading is aligned with the ground track so that the scan bars edges are parallel to the ground track trace.

Figure 5.2.2b shows a 16-second WAS pattern, with an exaggerated maneuver which causes the aircraft heading to be misaligned from the ground track. The heading varies from $+15^\circ$ to -15° with respect to the ground

track at the 11th scan bar, settling at the 15th scan bar, which is a time interval of about 4 seconds. The important thing to note is that the local level frame is following the aircraft heading (zero filter weight, or all-pass filter), so the WAS pattern is directly coupled to the heading angle. Fast variations of aircraft heading such as this will be removed by changing the heading filter weight to decouple the scan pattern from the heading angle variations. Figure 5.2.2c shows the same exaggerated scenario with the local level scan frame decoupled from the aircraft heading. This solves the image overlap problem, but causes another problem. Since the position commands are based on the local

Figure 5.2.2c. Example WAS Pattern For Sudden AC Heading Change, LL Scan Frame Decoupled From AC Heading

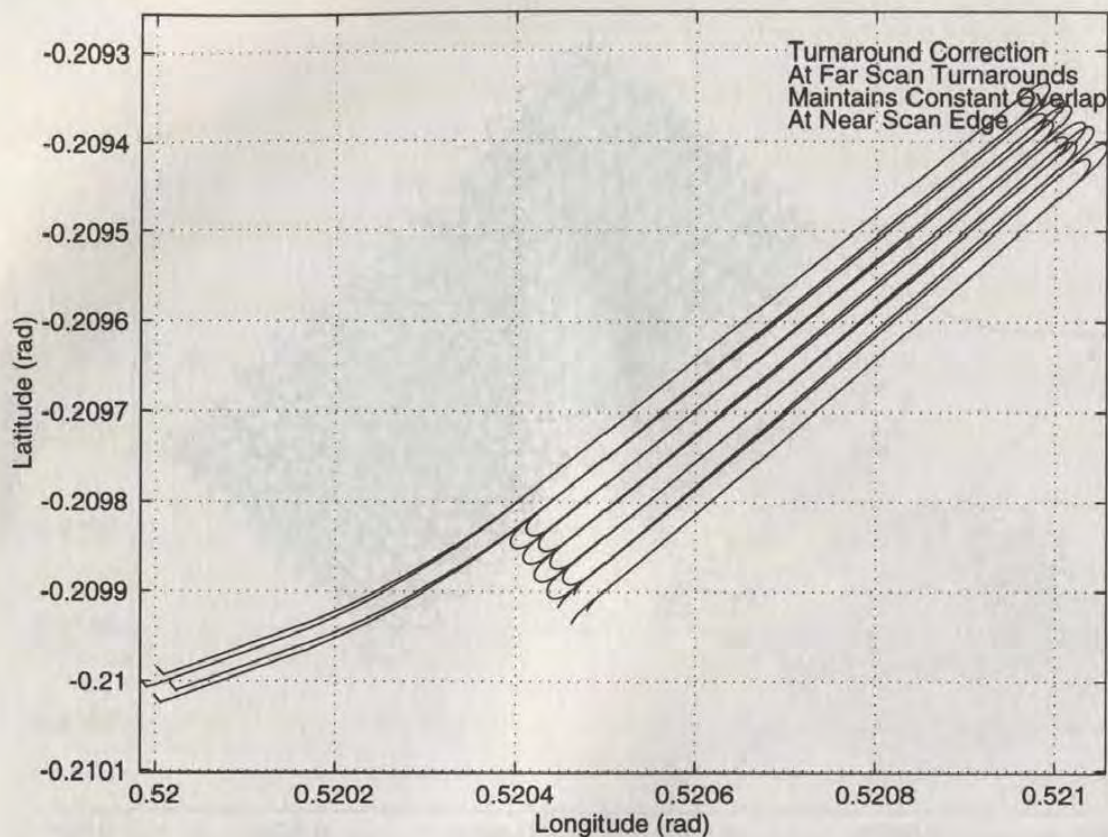


level frame orientation, the only way for the inertial rate commands and position commands to create equivalent scan patterns is if the aircraft heading and local level frame are attached, as in Figure 5.2.2b. Otherwise, the constant inertial rate scan (which is about *sensor roll only*, due to optical constraints) will result in different gimbal angles than the ones which are being computed by the Gimbal Angle Command Generator(3.3) based on the local level frame orientation. This will result in a transient at the conclusion of each scan bar where the position loop is closed and the correct gimbal angles are forced. Figure 5.2.2c shows the case where both loops are always closed, because that more clearly demonstrates the fact that these two are in contention when the local level

frame is not aligned with the aircraft heading. The selection of the aircraft heading filter weight is a trade off between the effects in Figure 5.2.2b and 5.2.2c. The overlap and image quality will be strongly influenced by the heading motion of the TIER II Plus aircraft because it can only be scanned about one axis. Fortunately, the base motion that is expected is very benign and the overlap requirements will be met.

Figure 5.2.2d illustrates another key performance feature of the WAS and Spot command generation. Images must overlap on the surface of the reference spheroid to avoid gaps in the scanned region. Linear aircraft motion complicates this. The angular rate variations needed to keep the scan earth

Figure 5.2.2d. Example WAS Pattern (Exaggerated AC Velocity And Scan Bar Extent) Showing Scan Bar Overlap Geometry



fixed cause gaps at the frames which are closest to the aircraft if the cross scan steps at the far end of the scan bars are not adjusted appropriately. The geometry for this problem is quite subtle, and computations are performed at each far field turnaround to estimate the compensation needed to ensure zero gap coverage at the near edge of the scan pattern.

6.0 CONCLUSIONS

This paper is a detailed review of the LOS control, command, and geolocation algorithms used in the TIER II Plus program. The prominent features emphasized in this paper are

- (1) gimbal angle command algorithms enable the LOS to be positioned at a specified latitude and longitude on the earth's surface
- (2) gimbal angle command algorithms enable a time-optimal LOS slew between earth-fixed positions or LOS angular positions to ensure gap-free FOV coverage during earth-fixed scans
- (3) geolocation algorithms locate the LOS position on a WGS-84 reference ellipsoid from which LOS slant range to the target is used to estimate aircraft-induced rates
- (4) inertial rate algorithms command the LOS at either constant earth-fixed rates or time-optimal rates eliminating any aircraft-induced angular rates with respect to the target
- (5) rate command algorithms partition the slew and aircraft-induced rates when updating rate and position commands during

slew maneuvers to minimize numerical integration errors

(6) IMC scale factor accuracy is a prominent factor in generating smear-free imagery and is a major cost and risk consideration in this program.

(7) An intensive math modeling effort using MATLAB/SIMULINK dynamic simulation tools enabled us to verify the algorithm concepts and provide test cases for validating the real-time code.

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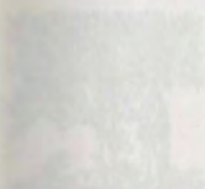
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Digital image georeferencing from a multiple camera system by GPS/INS

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Abstract

In this paper, the development and testing of an airborne fully digital multi-sensor system for digital mapping data acquisition is presented. The system acquires two streams of data, namely, navigation (georeferencing) data and imaging data. The navigation data are obtained by integrating an accurate strapdown inertial navigation system with a differential GPS system (DGPS). The imaging data are acquired by two low-cost digital cameras, configured in such a way so as to reduce their geometric limitations. The two cameras capture strips of overlapping nadir and oblique images. The GPS/INS-derived trajectory contains the full translational and rotational motion of the carrier aircraft. Thus, image exterior orientation information is extracted from the trajectory, during post-processing. This approach eliminates the need for ground control (GCP) when computing 3D positions of objects that appear in the field of view of the system imaging component. Two approaches for calibrating the system are presented, namely, terrestrial calibration and in-flight calibration. Test flights were conducted over the campus of The University of Calgary. Testing the system showed that best ground point positioning accuracy at 1:12,000 average image scale is 0.2 m (RMS) in easting and northing and 0.3 m (RMS) in height. Preliminary results indicate that major applications of such a system in the future are in the field of digital mapping, at scales of 1:5000 and smaller, and in the generation of digital elevation models for engineering applications. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: GPS/INS; Georeferencing; Mobile mapping; Multi-sensor systems; Airborne digital mapping; Digital camera

1. Multi-sensor systems for mobile mapping

During the past two decades, the mapping sciences have progressively moved towards digital mapping, making use of multi-disciplinary developments in the geomatics field. Instead of regarding geodesy, photogrammetry, and remote sensing as separate sciences, they are seen more as an inte-

grated discipline today. Part of this development has been spurred on by systems capable of acquiring and fusing accurate globally referenced data in fully digital form with short turn-around-time in a cost-effective fashion. A mobile-mapping multi-sensor system is, thus, the product of integrating the concepts of kinematic geodesy and digital photogrammetry, to acquire, store, and process, measurable quantities that sufficiently describe spatial and/or physical characteristics of a part of the Earth's surface.

Various applications in GIS, airborne remote sensing, and resource mapping often require data

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capture in fully digital form, with sufficient accuracy and in a cost-effective and fast manner. Therefore, integrated digital image acquisition and navigation systems have been developed for such applications (cf. Cramer et al., 1997; Mostafa et al., 1997; Toth and Grejner-Brzezinska, 1998). Such systems are part of a continuing effort which started earlier for the development of GPS-aided inertial navigation systems in support of geomatics applications [see Schwarz et al. (1993) for the mathematical model and proposed applications, and Abdullah (1997), El-Sheimy (1996), Reid et al. (1998), Schwarz (1995), Škaloud et al. (1996) and Toth and Grejner-Brzezinska (1998) for applications].

2. Direct georeferencing model

As shown in Fig. 1, direct georeferencing of digital images can be described by first introducing the collinearity concept rearranged for object coordinates as:

$$\mathbf{r}_G^M = \mathbf{r}_E^M(t) + s_g \mathbf{R}_c^M \mathbf{r}_g^c(t) \quad (1)$$

where $\mathbf{r}_G^M$ is the georeferenced 3D vector of coordinates of an arbitrary object point G in the mapping frame (M-frame); $\mathbf{r}_E^M(t)$ is the 3D vector of coordinates of the exposure station E , of any imaging sensor, at the instant of exposure, in the M-frame; s_g

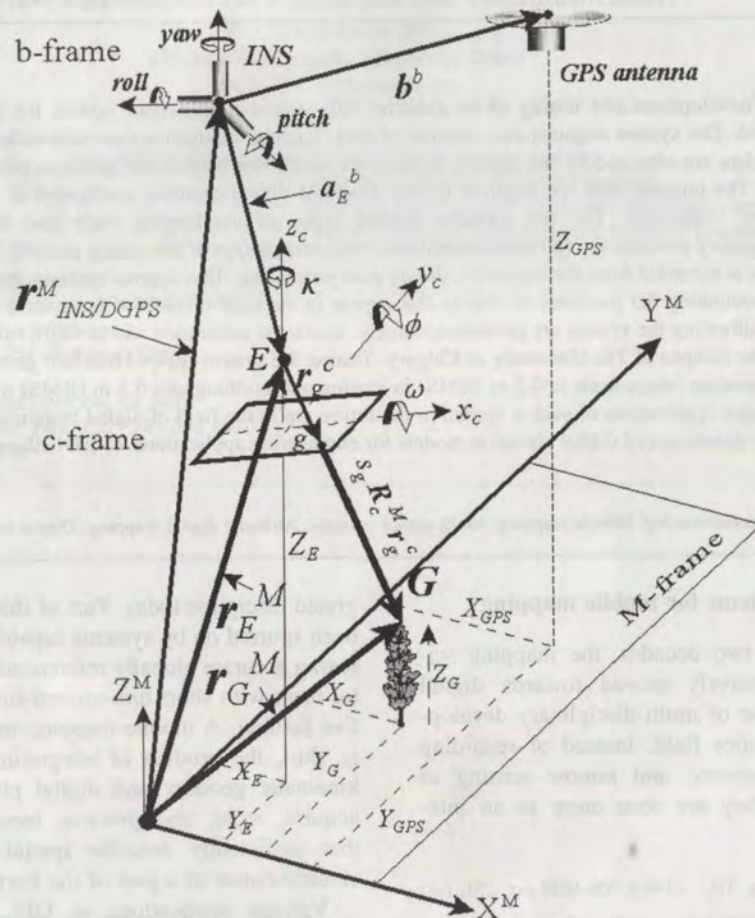


Fig. 1. Elements of direct georeferencing (see explanations in text).

is a scale factor per point per image for each imaging sensor, implicitly derived during the 3D photogrammetric reconstruction of objects using image stereopairs and therefore not explicitly computed in practice; $\mathbf{R}_c^M(t)$ is a matrix rotating each imaging sensor camera frame (c-frame) into the M-frame utilising the three photogrammetric rotation angles ω , φ and κ (cf. Moffit and Mikhail, 1980); and $\mathbf{r}_g^c(t)$ is the 3D vector of coordinates of the image point g in the c-frame, expressed by:

$$\mathbf{r}_g^c(t) = \left(x_g^c - x_{pp}^c; \frac{y_g^c - y_{pp}^c}{k}; -f \right) \quad (2)$$

where x_g^c and y_g^c are the image coordinates of point g corresponding to the object point G ; x_{pp}^c and y_{pp}^c are the principal point offsets from the CCD format centre; k is a scale factor accounting for the non-squareness of the CCD pixels; f is the calibrated focal length of the lens in use.

Since the imaging sensor(s), the GPS antenna, and the INS centre do not occupy the same point in 3D space, Eq. (1) can be modified to include the

position and orientation offsets which is expressed by the formula:

$$\mathbf{r}_G^M = \left(\mathbf{r}_{\text{INS/DGPS}}^M(t) + \mathbf{R}_b^M(t) \mathbf{a}_E^b \right) + s_g \left(\mathbf{R}_b^M(t) \mathbf{R}_c^b(t) \mathbf{r}_g^c(t) \right) \quad (3)$$

where $\mathbf{r}_{\text{INS/DGPS}}^M(t)$ is the 3D vector of coordinates of the INS centre in the M-frame; $\mathbf{R}_b^M(t)$ is a matrix rotating the INS body frame (b-frame) into the M-frame; $\mathbf{a}_E^b$ is an offset vector between the INS centre (b-frame origin) and the imaging sensor exposure station E ; $\mathbf{b}^b$ is an offset vector between the INS centre and the GPS antenna centre that is measured and compensated for during GPS/INS data post-processing; $\mathbf{R}_c^b$ is a matrix rotating each imaging sensor c-frame into the INS b-frame.

3. Multi-sensor system configuration

The configuration shown in Fig. 2 acquires two separate streams of data, namely, the navigation and



Fig. 2. Hardware configuration.

the imaging data. The navigation data is collected using a Honeywell LRF III inertial navigation system, and an Ashtech ZXII GPS receiver, connected to a portable computer for raw data acquisition and storage for subsequent post-mission processing. The image data is collected by two low-cost Kodak DCS420c digital cameras equipped with a 1.5×1 K CCD chip ($9 \mu\text{m}$ pixel resolution). To synchronize the INS, GPS, and image data in a common time frame, the INS records are stamped in real-time by the Ashtech GPS receiver PPS (pulse per second) signal, while a Trimble GPS receiver event marker pulse is used to store the instant of time when an image is captured by one of the cameras. Therefore, all the data are synchronized in the GPS time frame during data logging. The data acquisition is controlled by a real-time data logging software which downloads the GPS/INS/imagery data to the host computers, and time tags the imagery and INS records by the GPS receiver-derived time pulse.

4. Geometric design of a multi-camera system

Several researchers reported on the point positioning accuracy achievable from digital imaging sensors such as the three-line CCD sensors (Cramer et al., 1997), or digital frame cameras (DFCs) (cf. Mostafa et al., 1997). Height determination with the small format cameras is poorer by a factor of three to five compared to horizontal coordinate accuracy (Schwarz et al., 1993; Mostafa et al., 1998). These results were confirmed by simulations. Poor height determination accuracy is due to the poor quality of the 3D space intersection, which can be demonstrated by the intersection (parallax) angle γ between individual camera exposure stations and an arbitrary single ground object, which can be expressed by Eq. (4).

$$\gamma = 2 \tan^{-1} \left(\frac{w P_s (1 - O)}{2f} \cos \left(\frac{L_{\text{FOV}}}{2} \right) \right),$$

$$L_{\text{FOV}} = 0^\circ \quad \text{GP at image centre}$$

$$L_{\text{FOV}} = 2 \tan^{-1} \left(\frac{L_p}{f} \right) \quad \text{GP at image edge} \quad (4)$$

where, w is the image size (in pixels) parallel to flight direction; P_s is the pixel size; O is the overlap

percentage between two stereo images; L_{FOV} is the camera lateral field of view angle; and L_p is the lateral location of a ground point (GP) in an image. Note that γ is mainly a function of w , for the same overlap percentage.

Since positioning accuracy depends on the intersection geometry γ (which is dependent on image size), the theoretical accuracy of height determination can be derived by standard error propagation techniques. This yields:

$$\sigma_{Z_G} = \sqrt{2} \sigma_{\text{pxl}} \frac{(Z_E - Z_G)^2}{2Z_E \cdot f \cdot \tan \left(\frac{\gamma}{2} \right)} \quad (5)$$

where, σ_{Z_G} is the height standard deviation of ground object point G; σ_{pxl} the image measurement precision; and Z_E and Z_G the height of the exposure station and the ground point G, respectively, in the M-frame.

Note that the effect of image position and orientation has been neglected in order to separate and emphasize the effect of intersection geometry. Fig. 3 shows σ_{Z_G} for different intersection angles and different flight altitudes. In Fig. 3, three ranges have been identified. They correspond to $\gamma < 20^\circ$, $20^\circ \leq \gamma \leq 40^\circ$, and $\gamma > 40^\circ$. The poorest accuracy is achieved in the first range. In the second range, a significant accuracy improvement is obvious, while the accuracy improvement is minimal in the third range. On the other hand, the typical intersection angle for the 1.5×1 K cameras used in this system ranges from 3° to 10° . This leads to the lowest theoretical height accuracy. Larger format DFCs can provide better intersection quality. At the time of system development, however, they are more expensive for such a low-cost system and their image acquisition data rate is much poorer than that of the 1.5×1 K cameras. Therefore, the imaging component of the system has been designed to include two low-cost 1.5×1 K digital cameras, one of which is nadir, and the other is oblique. This allows for covering the same ground scene with a nadir and an oblique image that, when simultaneously processed, provides a wider intersection angle and thus better height accuracy. This concept has been validated through computer simulations, which showed that height determination accuracy is improved by a factor of 3.5 using such a

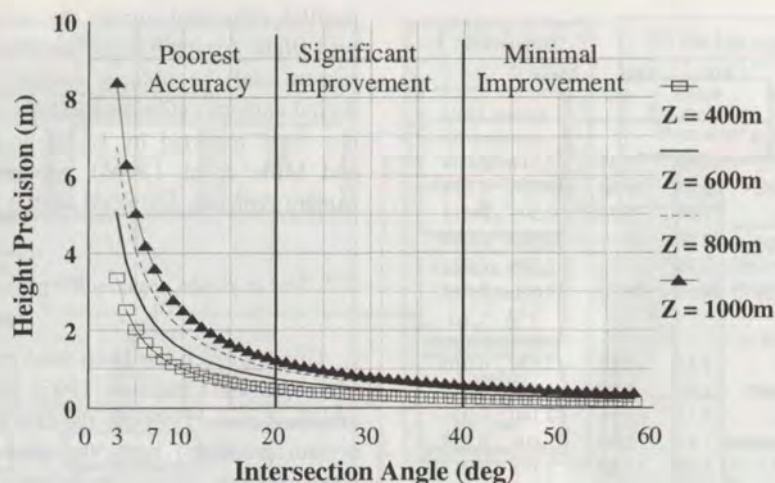


Fig. 3. Height determination precision as a function of the image ray intersection angle.

system. Stereo image matching becomes involved in this case; see Cochran (1995) for a detailed discussion.

5. System calibration

The overall system calibration is required to relate GPS-derived positions, INS-derived attitude parameters, and imagery-derived object point coordinates. Two approaches were followed to calibrate the system. Next, each of these approaches is discussed in some details.

5.1. The terrestrial approach

This approach is implemented in a static terrestrial fashion, where the digital cameras and the INS are tightly coupled using a metal frame, so as to ensure a fixed orientation offset (constant boresight), which is a key assumption in such an approach. The digital cameras are used to acquire a number of images to a precisely surveyed target field, from which their interior geometry, lens distortions, and, for each image, the position of the exposure station and the image rotation angles can be determined (for details, see Mostafa and Schwarz, 1999). The system was set up for 45 min at each station collecting inertial data while an image per camera was captured

to the target field. A total of 10 stations was occupied by the system. The 10 images per camera, together with 36 other images per camera that were captured before attaching the cameras to the frame, were introduced to a self-calibrating adjustment software (Lichti and Chapman, 1997), together with approximate orientation angles for each image, and accurate exposure station positions, to resolve for the camera interior geometry, lens distortions, and exterior orientation parameters. The extra 36 images per camera were captured in a configuration that was optimised to strengthen the network for high precision determination of the camera calibration parameters (cf. Fraser, 1997).

The inertial measurements were processed using KINGSPAD in a static mode imposing zero velocities constraint to avoid system position drifts. The calibration procedure was repeated after the test flight using the same approach of data acquisition. Table 1 shows the statistics of the orientation offset (boresight) between the INS b-frame and each camera c-frame in the pitch and roll angles for both nadir and oblique cameras resulting from the pre- and post-flight calibration, respectively. Note that the changes in the angles are within their estimated precision. The azimuth component is, however, of poorer quality than that of the pitch and roll. The precision of each camera yaw angle is about 40" and 30" for the pre- and post-flight calibration, while

Table 1
INS/camera relative pitch and roll (°)

Calibration parameter		Min.	Max.	Mean	σ
<i>INS/camera relative pitch</i>					
Pre-flight	INS-Nadir	2.30	2.33	2.312	0.009
	INS-Oblique	29.55	29.60	29.570	0.016
Post-flight	INS-Nadir	2.29	2.34	2.305	0.013
	INS-Oblique	29.56	29.59	29.580	0.009
In-flight	INS-Nadir	2.26	2.35	2.308	0.021
	INS-Oblique	29.53	29.76	29.660	0.045
<i>INS/camera relative roll</i>					
Pre-flight	INS-Nadir	3.11	3.15	3.130	0.010
	INS-Oblique	-1.43	-1.39	-1.410	0.013
Post-flight	INS-Nadir	3.12	3.16	3.140	0.011
	INS-Oblique	-1.41	-1.40	-1.406	0.009
In-flight	INS-Nadir	3.09	3.20	3.147	0.021
	INS-Oblique	-1.53	-1.36	-1.450	0.039

those of the INS are 2.9' and 3.2', respectively. The reason for that can be explained by the lack of horizontal accelerations exposed to the system during such static calibration procedure.

The estimated distortion parameters of the lenses used by each camera agreed within their estimated precision for both the pre- and post-flight calibration. For instance, Fig. 4 shows the radial lens distortion

profiles estimated during the pre- (solid lines) and post-flight (dashed lines) calibration for the nadir camera and the oblique camera, respectively. The digital camera calibration results agree with a previous work reported by Lichti and Chapman (1997) and Mills et al. (1996), especially for the nadir camera typically equipped with a 28-mm lens.

5.2. The in-flight approach

This approach has been used by Abdullah (1997), Cosandier and Chapman (1995), Mostafa et al. (1997) and Reid et al. (1998). In the case of the multi-camera system presented here, the geometry and imaging configuration differ significantly from those published by the aforementioned authors and, thus, this approach was first studied by simulations and, then, was verified using the test flight data. The general data-flow is shown in Fig. 5.

Due to the poor space resection geometry provided by the digital cameras at hand, the ground control used in the test flight was spatially distributed to strengthen the geometry as indicated in a nadir and an oblique digital images of the test flight shown in Fig. 6. The flight pattern was also designed to help reduce the correlation between the interior and exterior orientation parameters. The image

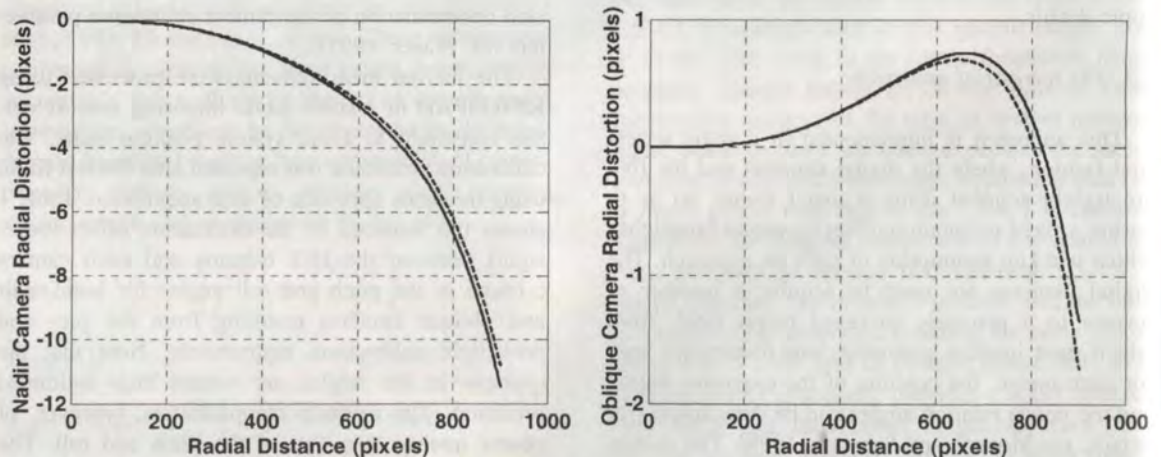


Fig. 4. Lens distortion profiles of the nadir camera (left) using a 28-mm lens and the oblique camera (right) using a 52-mm lens, for pre-flight (solid lines) and post-flight (dashed lines).

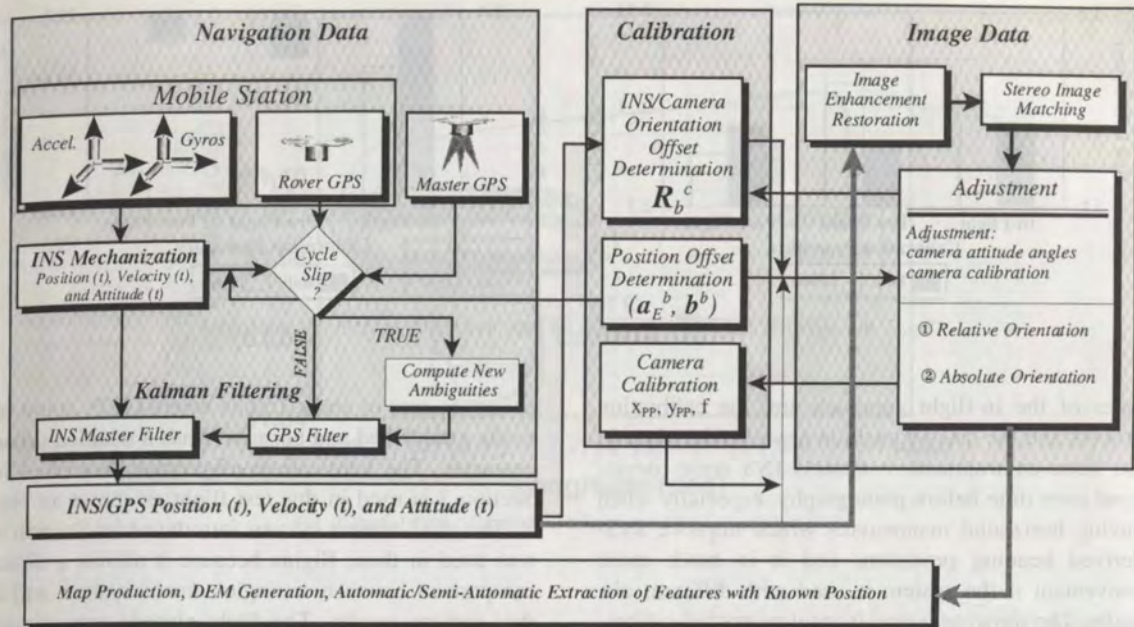


Fig. 5. The multi-sensor system data-flow (in-flight calibration case).

dataset was first processed using GPS-assisted aero-triangulation to decorrelate image exposure station positions from image attitude angles, for better recovery of image attitude angles, to subsequently determine each INS/camera boresight. Table 1 shows the estimated INS/camera roll and pitch offsets for both cameras.

5.3. Terrestrial versus in-flight calibration—a comparison

It is obvious that the terrestrial approach provides a higher precision calibration of the roll and pitch components of the orientation offset. However, it is the opposite in the heading component. The advan-

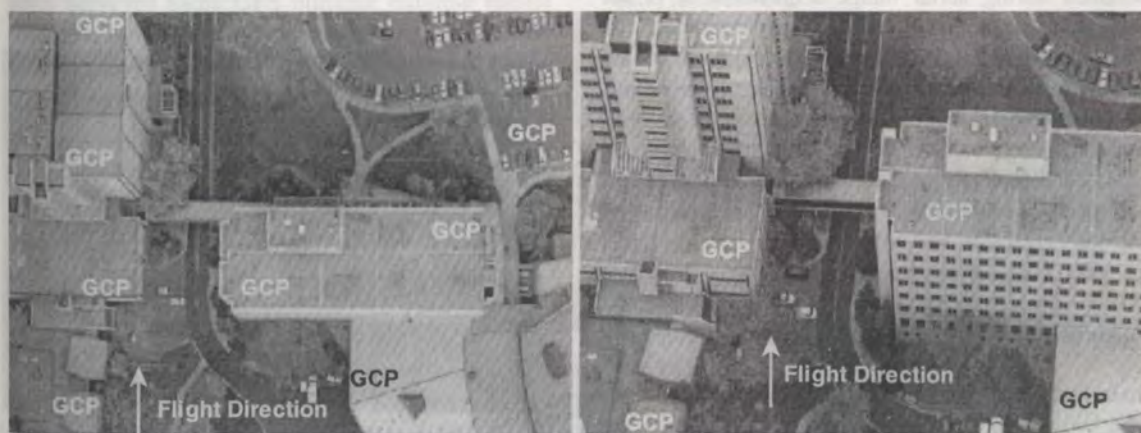


Fig. 6. A nadir digital image (left) and an oblique digital image (right), October 1998 flights.

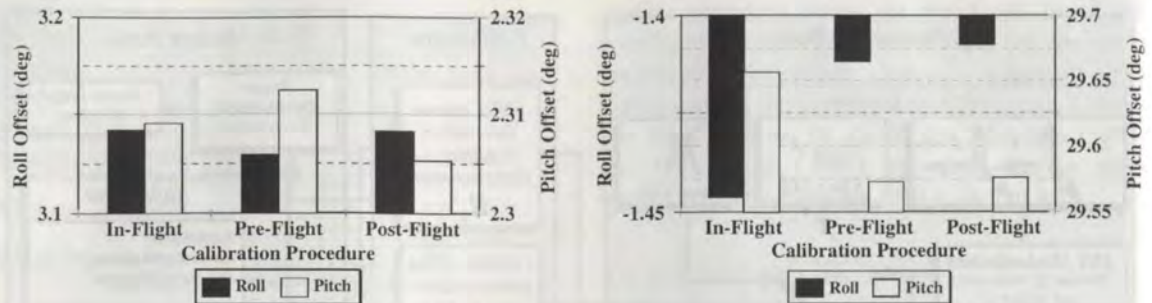


Fig. 7. Boresight roll and pitch components for INS/nadir (left) and INS/oblique (right).

tages of the in-flight approach are: the calibration process and the data acquisition process take place in the same environment; it cancels INS errors developed over time before photography, especially when having horizontal manoeuvres which improve INS-derived heading precision; and it is much more convenient if the system is used with different aircrafts. The drawbacks are: it requires special calibration field, and the calibration accuracy is dependent on the accuracy, density and configuration of the GCP calibration field, the sensor geometry (poorer results for smaller image size) and image point measurement precision.

The advantages of the terrestrial approach are: it provides stronger network geometry for aerotriangulation, higher precision target mensuration in imagery (typically 1/20–1/50 pixel), and is much more controlled than the in-flight approach. The drawbacks are: its geometry is different from that obtained during aerial image acquisition; it is not consistent with the operational environment; the INS-derived azimuth is of poorer quality than that achieved in airborne case; and any error in equipment installation would result in the loss of calibration parameters and the calibration would have to be repeated. Fig. 7 shows the calibrated boresight roll and pitch components for both cameras, while their statistics are listed in Table 1.

6. Multi-sensor system testing in flight

In October 1998, a test flight was conducted over The University of Calgary (U of C) campus for two consecutive days. The campus was chosen because it

covers an area of about 150 ha where GCPs could be easily established and because it has a detailed urban character. The hardware configuration described in Section 3 is used in this test flight as shown in Fig. 8. The dual-camera system introduced in Section 4 was used in these flights because it allows a direct comparison between a single-camera system and a dual-camera system. The flight altitude was chosen at 400–500 m, and the flight pattern was designed to cover the entire campus by a block of 50–60% endlap and 30–40% sidelap, using repeated west-to-east flight lines and a single flight per strip in the opposite direction. Two cross strips were also flown from south to north and vice versa. The flight pattern is partially shown in Fig. 9.

Almost 100 GCPs were painted all over the campus. They are needed to provide an independent reference to test the overall system performance when using the airborne data (GPS, INS, and nadir



Fig. 8. The multi-sensor system used in the October 1998 test flights.

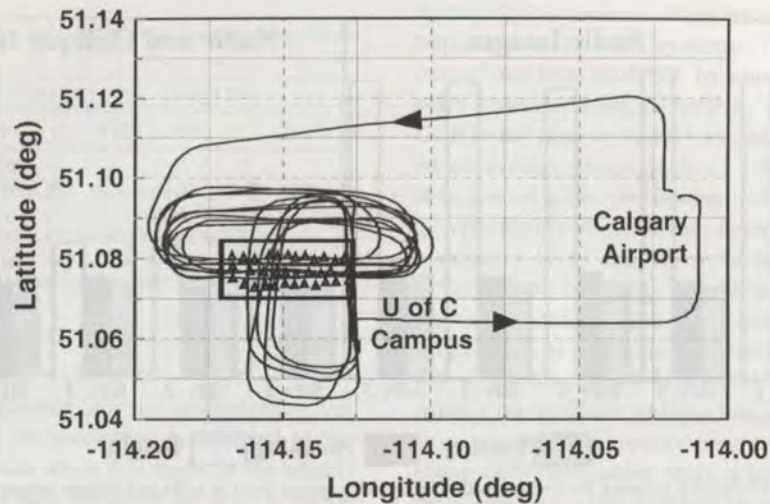


Fig. 9. Partial GPS/INS-derived trajectory of the Calgary test flight.

and oblique images) for positioning objects on the ground. In addition, the in-flight aerial calibration of the entire system, as discussed in Section 5.2, can be tested in this way. Fifty-three percent of the GCPs were placed on roads and parking lots, 27% on medium-height building rooftops, and 20% on highest building rooftops, to end up with a 67-m maximum elevation above the ground. This is to obtain large height differences between adjacent points (e.g., on the ground and on building rooftops) to be able to calibrate the digital cameras and the entire system in-flight, as for example, shown in Fig. 6. All GCPs were surveyed using GPS utilizing multiple master stations. A network adjustment was finally performed to double-check the GPS-fixed baselines. The network adjustment yielded GCP coordinate precision at the level of about 1 cm (1σ) in planimetry and 2.0 cm (1σ) in height.

The flight was done with wide turns to avoid signal blockage by aircraft banking and, thus, the roll angle was typically smaller than 15° . Further, mission planning was done to ensure a good sun angle and good satellite sky distribution. Two master stations were kept running during the test period. One was located close to the airport and was occupied by a Trimble 4000 SSI, the other was on the rooftop of the engineering building and was occupied by an Ashtech Z XII receiver. This resulted in two inde-

pendent GPS trajectories which, when compared, agreed to be better than 10 cm, which is typical for a 2–8-km baseline. These values indicate that each of the two independent solutions provides sufficiently high-precision camera exposure station position. The Ashtech GPS raw data together with the INS measured specific force and angular velocity raw data were processed using the KINGSPAD software. The Kalman filter-derived estimates of the positioning precision are 0.04, 0.05 and 0.09 m, for latitude, longitude and height, respectively. For attitude, they are 0.0075° , 0.0097° and 0.0152° , for roll, pitch and yaw, respectively.

The GPS/INS interpolated position and attitude angles at each exposure station were used together with the imagery to analyse the system performance when using nadir plus oblique images. After preprocessing the GPS/INS data to compensate for the position and orientation offsets between the navigation and imaging sensors, the compensated position and attitude parameters were used as observable exterior orientation parameters (in M-frame) together with their standard deviations and the image point measurements from the commercial software package PCI OrthoEngine.

The resulting GCP coordinates from processing stereopairs in direct georeferencing mode, or adjusting strips or blocks, were compared to the reference

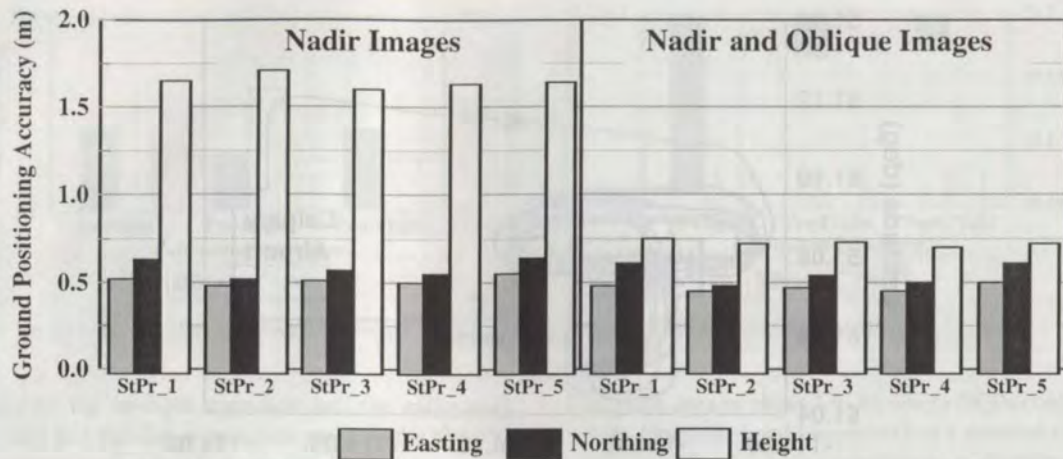


Fig. 10. Positioning accuracy for five stereopairs using nadir images (left) or nadir and oblique images (right).

values on the ground, to analyse both the direct georeferencing approach using stereopairs or GPS/INS-assisted strip or block aerotriangulation. The analysis was done as follows: using a stereopair of nadir images; using a stereopair of nadir images plus an extra oblique image; using a strip of five nadir images; using a strip of five nadir images plus extra oblique images as available; using a block of 3×3 nadir images; and using a block of 3×3 nadir images and oblique images in addition to cross strips in both directions.

Fig. 10 shows the RMS of the differences between the GCP coordinates as determined by GPS/INS imagery data using direct georeferencing and the GCP determined by the land survey, for five stereopairs (StPr_1 to StPr_5). Each stereopair had four to seven targeted points. Fig. 10 shows the results when using nadir images (left panel) and when using the nadir and oblique images (right panel). From Fig. 10, it is clear that the ground coordinate determination accuracy is consistent in all stereopairs and according to the expectations. The

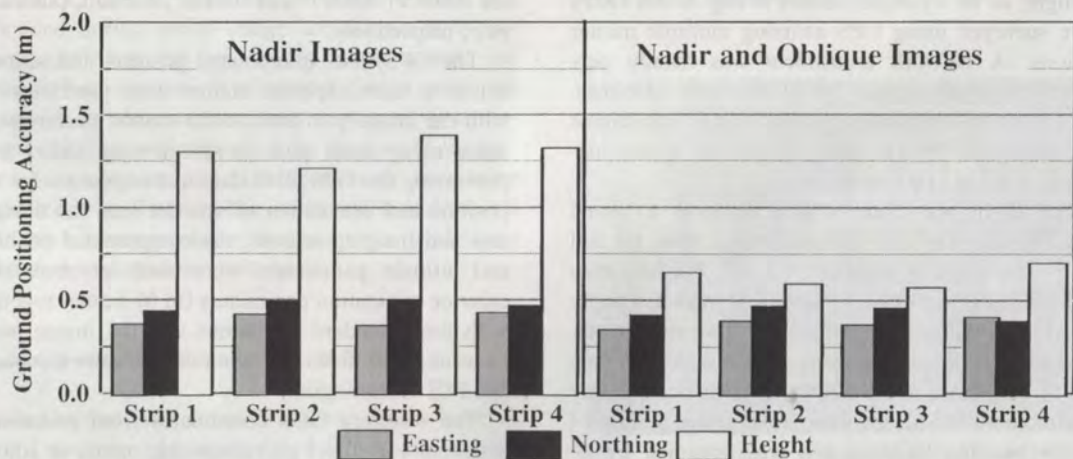


Fig. 11. Positioning accuracy for four strips using nadir (left) and nadir and oblique images (right).

Table 2
Positioning accuracy for nadir and oblique imagery using block configuration

Easting (m)			Northing (m)			Height (m)		
Max.	σ	RMS	Max.	σ	RMS	Max.	σ	RMS
<i>Nadir image block results</i>								
0.69	0.3	0.31	0.71	0.3	0.3	1.93	0.79	0.8
<i>Nadir and oblique and cross strips image block results</i>								
0.54	0.2	0.22	0.61	0.2	0.24	0.86	0.3	0.34

improvement in accuracy due to incorporating the oblique imagery in the processing is minimal in the horizontal components while it is major in the height. The horizontal accuracy improved by only a factor of 1.1. The height accuracy is improved by a factor of about 2.3.

Fig. 11 shows the RMS of the differences between the ground coordinates as determined by GPS/INS/imagery data and the land-surveyed reference coordinates, for four strips. GPS/INS-assisted strip triangulation is used to determine ground point coordinates without the use of ground control. The left panel of Fig. 11 shows the accuracy when using the nadir images only, while the right panel shows the accuracy when using nadir and oblique images. The first three strips were collected in the first day of flight (October 8th) while the fourth strip was collected in the second flight (October 9th) using the same calibrated parameters of the first day. It is clear that the absolute accuracy is consistent between different days of flight.

Table 2 shows the 3D ground positioning accuracy statistics when processing all the available imagery in block mode.

7. Summary and outlook

This paper described the development and testing of an integrated airborne imaging/navigation system for digital mapping. The major research and development component in this project is the integrated system design and software development. The multiple camera system developed here can overcome some of the inherent geometric limitations of small

format digital cameras. They are the key to accuracy improvement in such systems. The system performance has been analysed by comparing the ground point positions using GPS/INS/image data without GCP to the land-surveyed coordinates of such points. At an average image scale of 1:12,000, the achievable ground point positioning accuracy in the direct georeferencing mode using stereopairs is 0.5 m in planimetry (1σ) and 1.6 m in height. Adding one extra oblique image to a nadir stereopair improved the height accuracy to 0.7 m. Using GPS/INS-aided single strips of nadir imagery, the system accuracy is 0.4 m in planimetry (1σ) and 1.3 m in height. Adding the available oblique imagery to those image strips resulted in improved height accuracy of 0.6 m. Using GPS/INS-aided block triangulation with the nadir imagery only resulted in ground positioning accuracy of 0.3 m in planimetry (1σ) and 0.8 m in height. Adding available oblique images to the block improved the ground positioning accuracy to 0.2 m in planimetry (1σ) and 0.3 m in height.

Replacing the initial one-camera system by a dual-camera system improved the overall accuracy by factor of 2.3 when using stereopair processing. Using a block of vertical and nadir images and longitudinal and cross strips improved the overall accuracy by a factor of 4.8. Consistently repeatable results were achieved when testing the system in flight over the campus on two different days in October 1998. The internal consistency of the system is higher than the absolute accuracy with respect to reference ground truth. Since system calibration is a major contributor to the overall system error, especially for multi-sensor systems, two approaches have been used, an in-flight approach and a terrestrial one. In the terrestrial calibration, the environment is very well controlled and repeatable, especially for camera calibration. It is well suited to study different factors affecting system accuracy. In the in-flight calibration, the separation of error sources becomes a more complex task; yet it yields more accurate boresight determination. In-flight and terrestrial calibration methods have advantages and disadvantages. The two different methods provide good enough boresight determination for some mapping applications. A comparison between the two approaches needs further tests and detailed discussion, possibly in a future paper.

The system developed here is at the prototype level and, thus, data acquisition was also implemented at the prototype level. For example, the multi-camera system containing two cameras for testing was implemented using two separate laptops and a GPS receiver to synchronise the acquired imagery to the GPS time frame. In addition, the navigation data was collected using a different host computer with a different GPS receiver. Further, a full inertial system and GPS receivers were used to acquire only the raw data from the IMU and the GPS cards. This significantly adds to the system budget and reduces system portability. It is, therefore, recommended to design an industrial computer system that can accommodate the necessary boards for simultaneous navigation and image data acquisition. This would greatly improve system portability and cost. Besides the work presented here, map production using the Kodak DCS series has been reported (cf. Congalton et al., 1998). However, since these cameras are not designed for aerial surveys, the long-term stability of their calibration could be problematic and has to be well studied before using them in mapping.

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