

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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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.

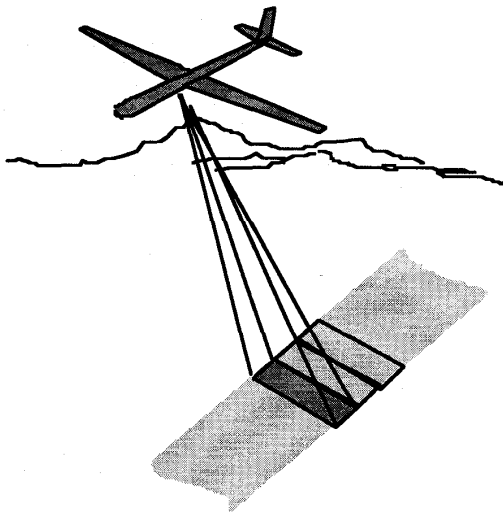


Figure 1.1.1 Wide Area Search Mode

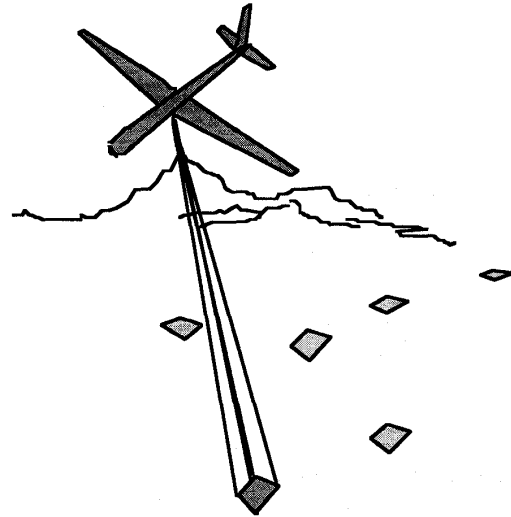


Figure 1.1.2 Spot Mode

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.

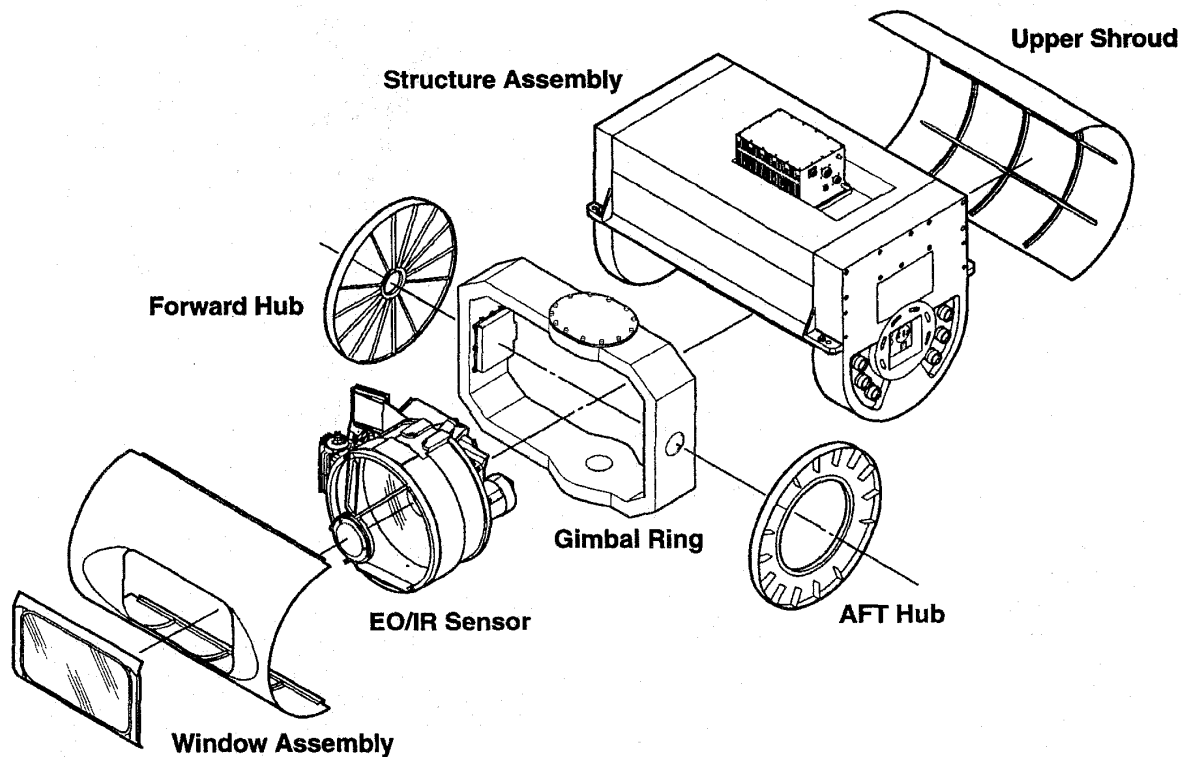


Figure 1.2.1 EO Receiver Unit Exploded View

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.

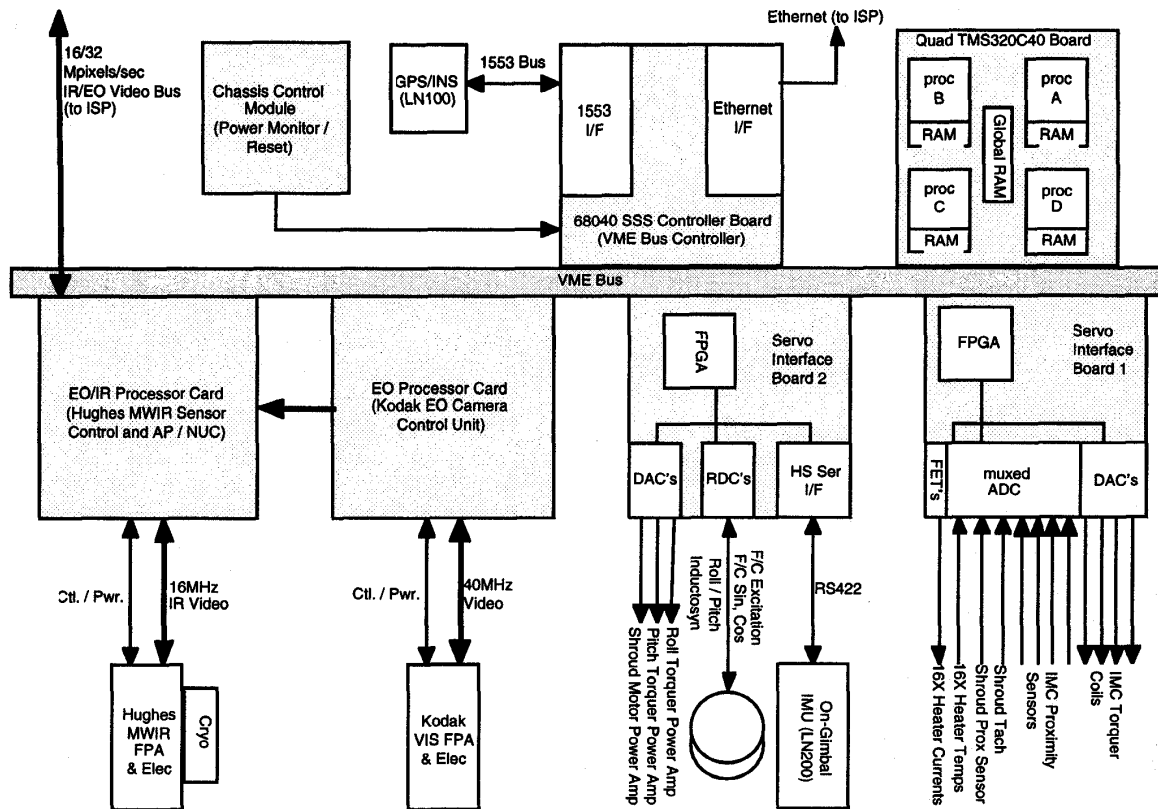


Figure 1.3.1. Sensor Electronics Unit Functional Block Diagram

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

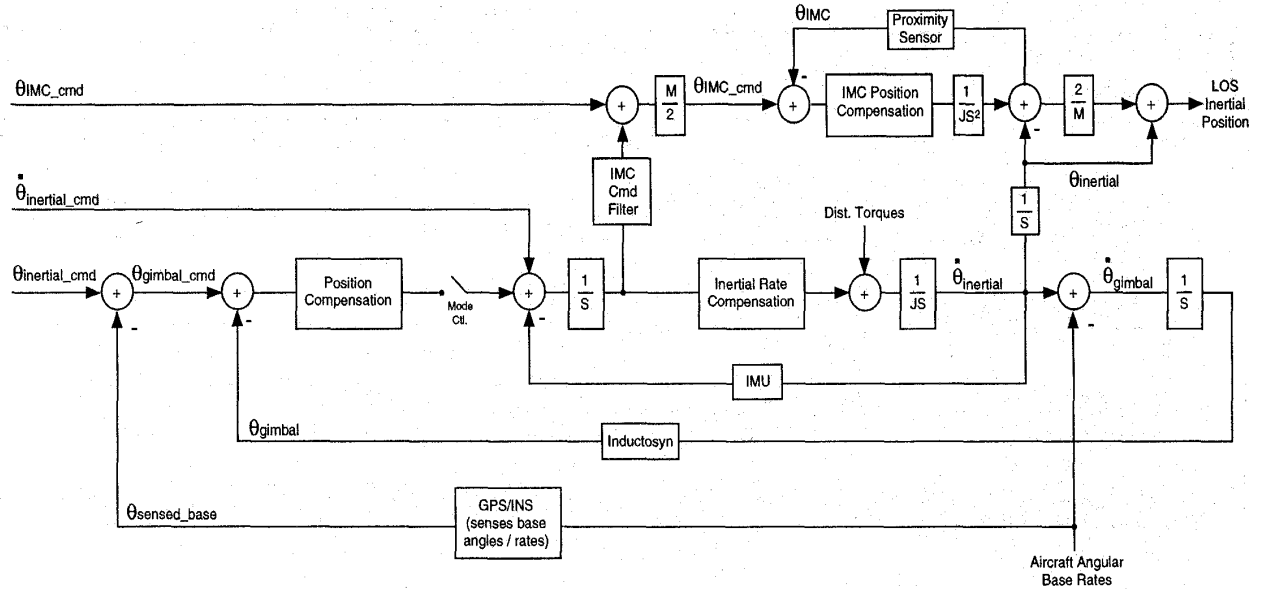


Figure 2.1.1. TIER II Plus Single Axis LOS Control Functional Block Diagram

the inertial rate and IMC loops using the 'quiet' on-gimbal IMU as the sole feedback component. Opening the inertial position loops decouples the sensor from aircraft base motion and eliminates any inductosyn noise from entering the servo feedback path. This also eliminates the computational and sampling delay errors associated with the gimbal position computations used to command the inertial position loops.

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.

Medium bandwidth (20Hz) type III gimbal position loops are used to control sensor position with respect to the gimbal base during utility modes such as stow and idle, and for IMC mirror calibration where tight control of the gimbal angle position is necessary to minimize focal plane image blur of the base-mounted light source. Figure 2.1.1 is a functional block diagram showing a simplified single axis representation of the

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.

2.2 IMC Scan / Stabilization Mirror

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.

During imaging (constant inertial rate scan), the primary source of error is the gyro time-delayed correction to the 300Hz IMC loop. This latency error is reduced by compensating the IMC command with a phase lead network. The digital compensator

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

<i>Loop</i>	<i>Qty.</i>	<i>Band width (Hz)</i>	<i>Sample Rate (Hz)</i>	<i>Type</i>	<i>Feedforward Signals</i>	<i>Feedback Transducer</i>	<i>Function</i>
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

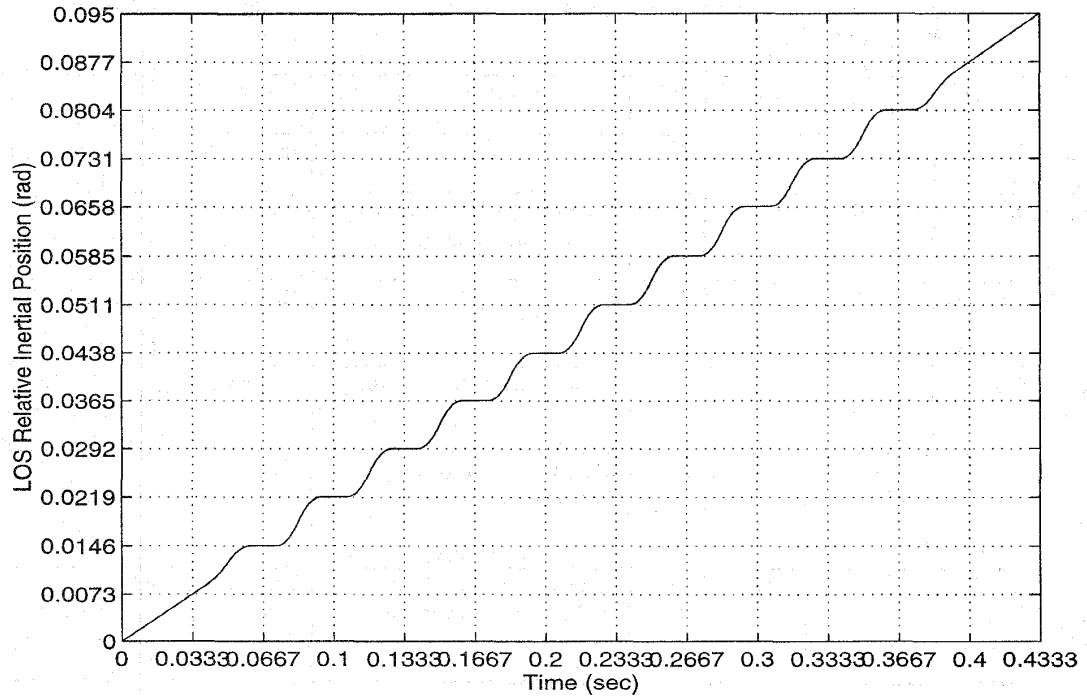
also has the capacity to attenuate any gyro or IMC loop dynamics through transfer function cancellation techniques.

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

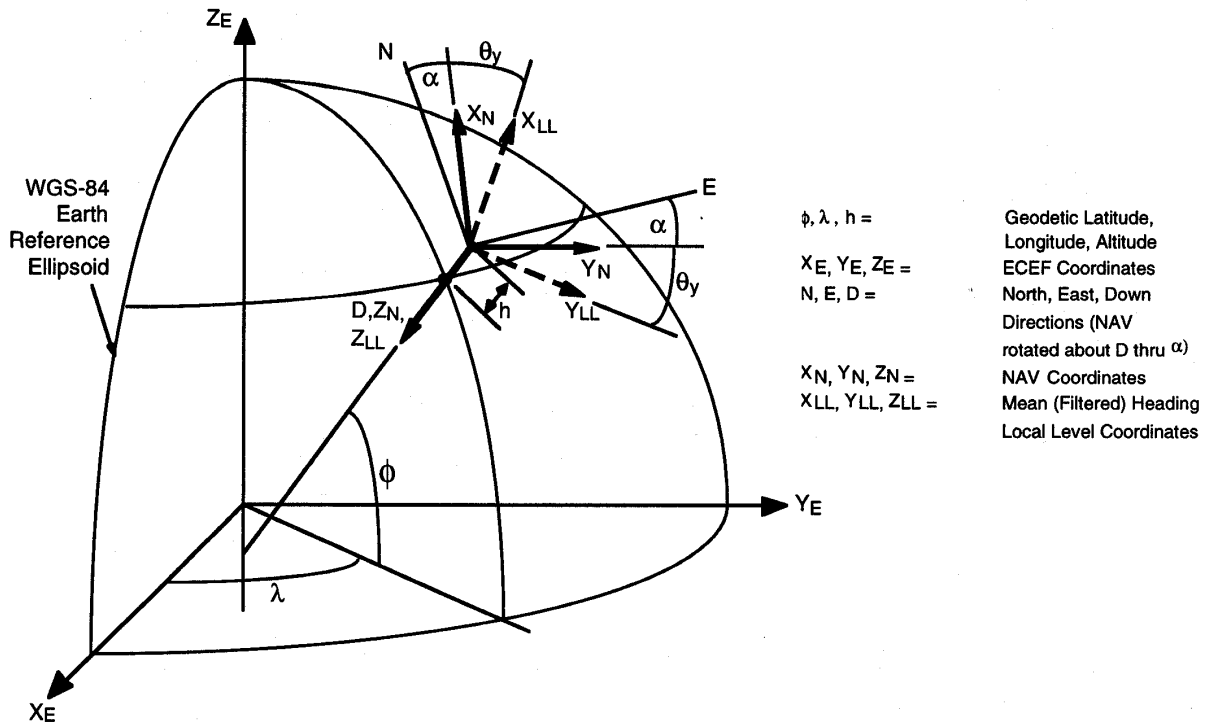


Figure 3.1.1. TIERII Plus Fundamental Coordinate Frames For Command Generation

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

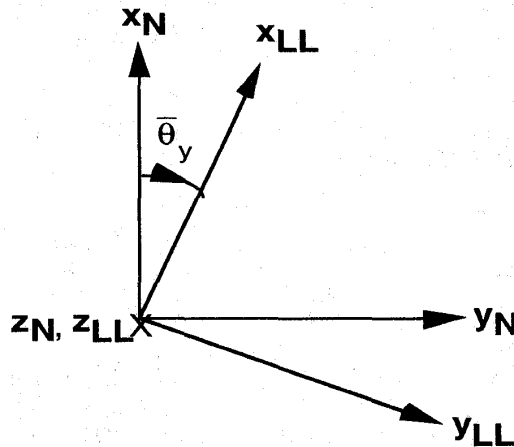


Figure 3.1.2. Navigation And Local Level Scan Frames

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

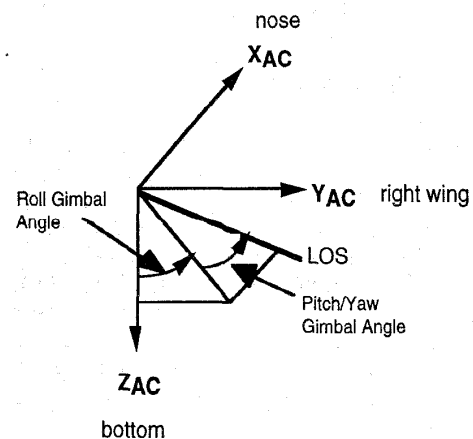


Figure 3.1.3. Aircraft Frame

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.

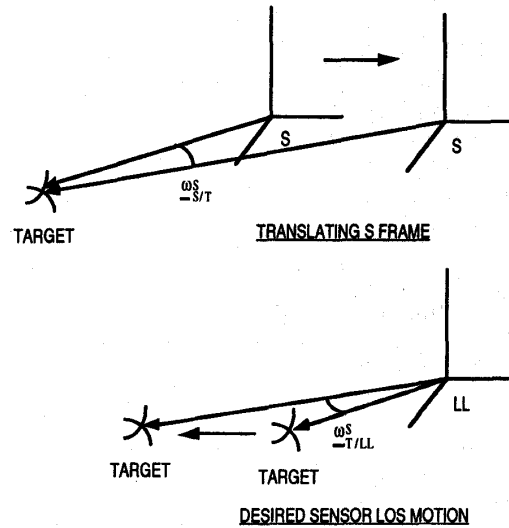


Figure 3.2.1. $\underline{\omega}_{S/LL}^S$ Components

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

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

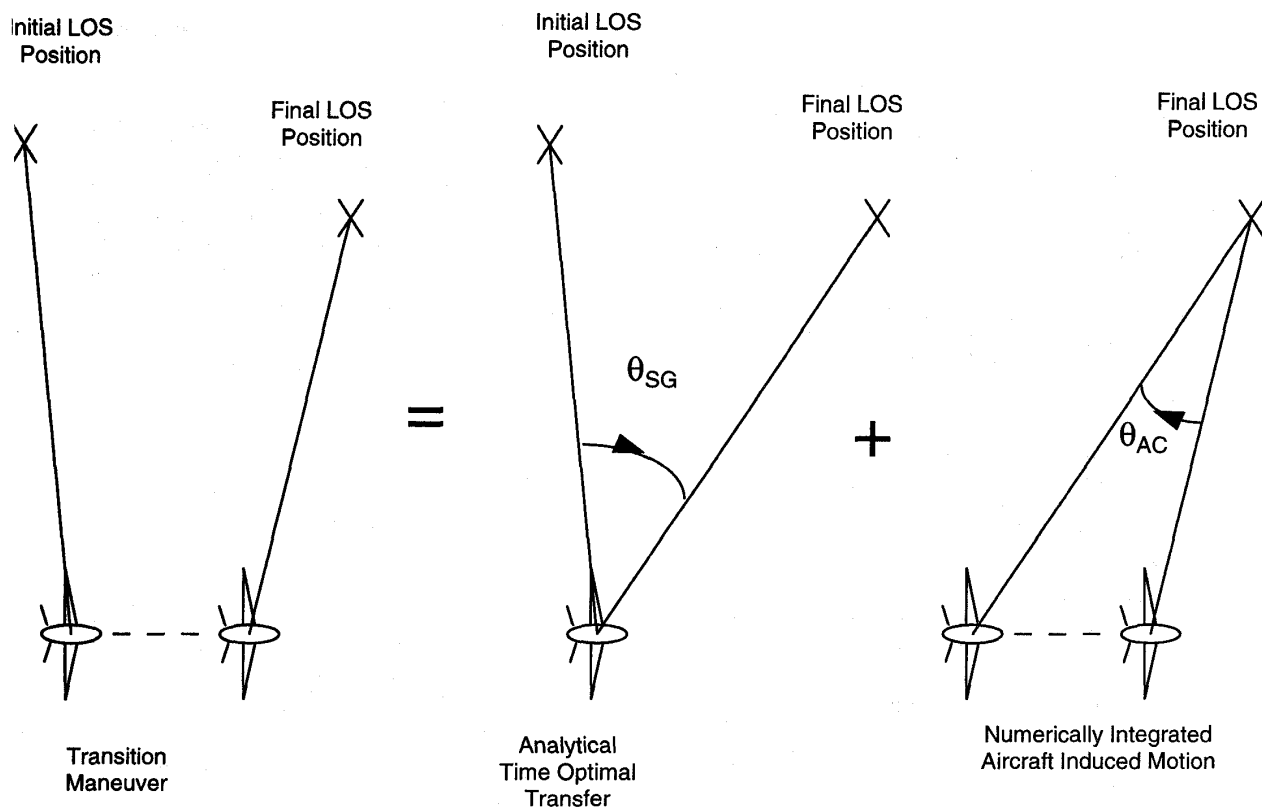


Figure 3.3.1. Scan Generator Transfer Partitioning Mechanism

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,

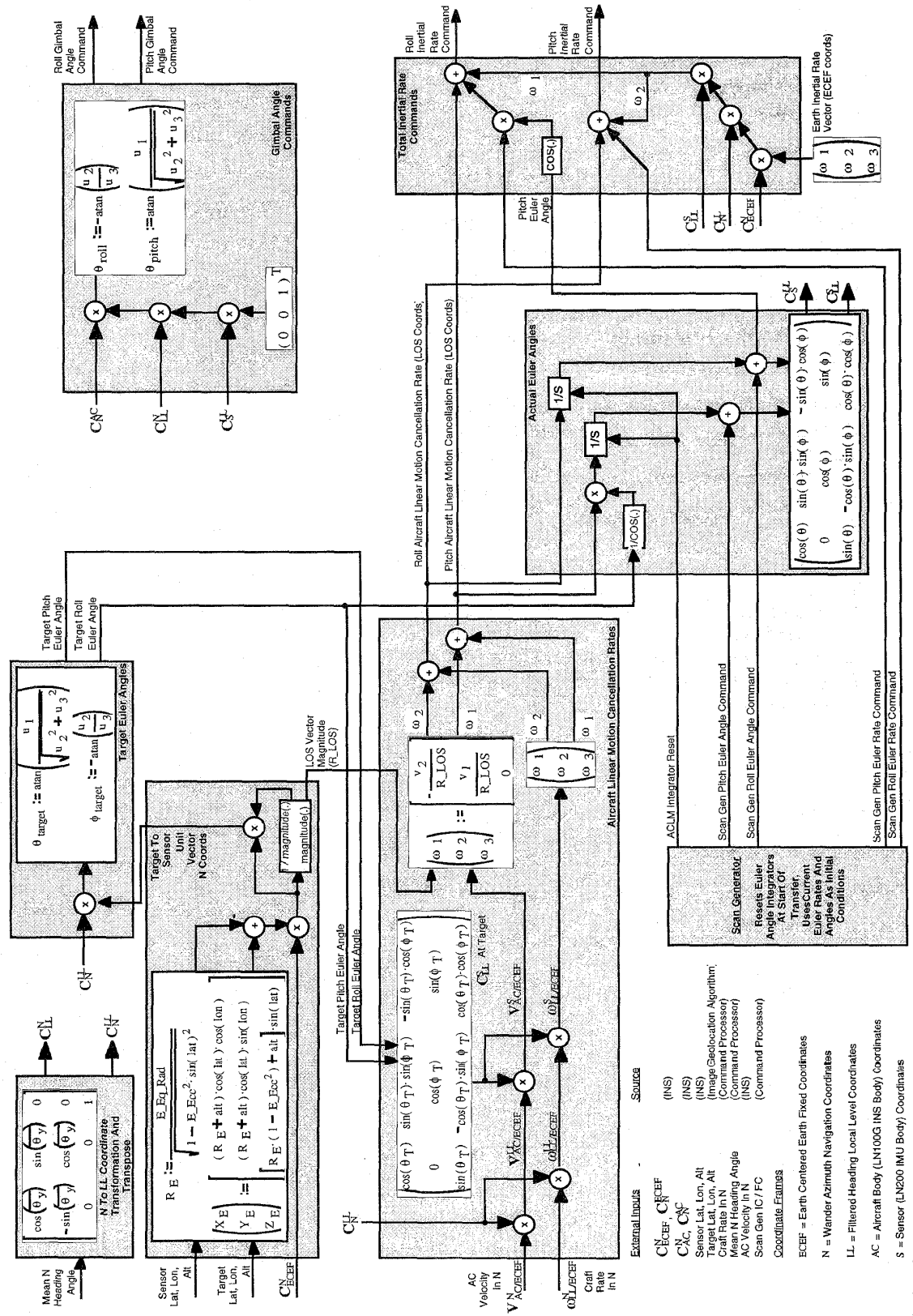
and the image geolocation algorithm for current target range data.

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



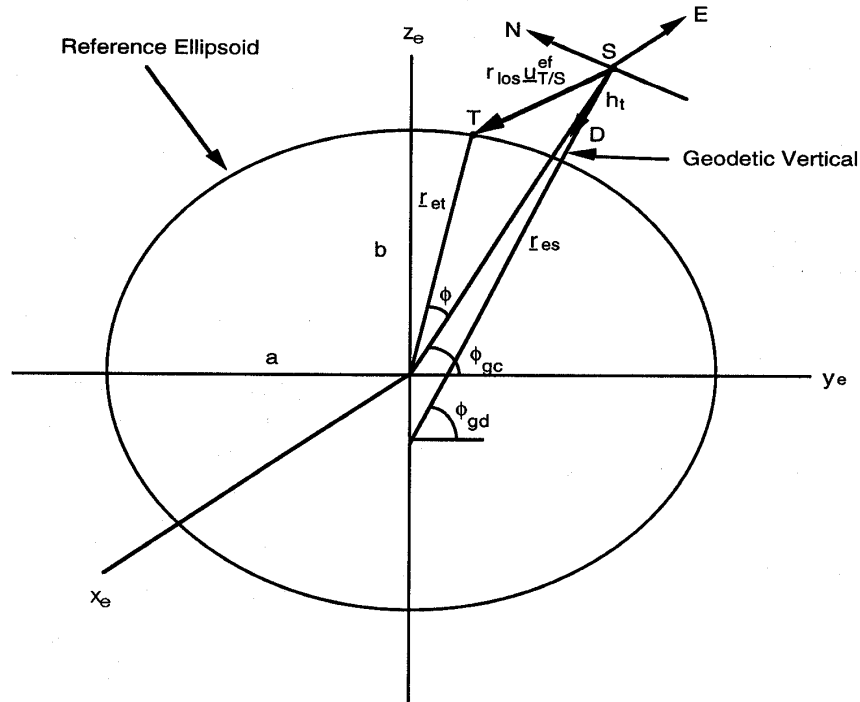


Figure 4.1.1 LOS / Reference Ellipsoid Geometry

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 ($\underline{r}_{et}$), given the sensor's earth-fixed position vector ($\underline{r}_{es}$), the target altitude above the reference ellipsoid (h_t) and the LOS unit vector resolved in earth-fixed coordinates ($\underline{u}_{T/S}^{ef}$). 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

$$\begin{aligned} A &= b^2(u_1^2 + u_2^2) + a^2u_3^2 \\ B &= 2[b^2(u_1x_{es} + u_2y_{es}) + a^2u_3z_{es}] \\ C &= b^2(x_{es}^2 + y_{es}^2) + a^2z_{es}^2 - b^2a^2 \end{aligned} \quad (4.1.4)$$

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

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

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

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 .

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.

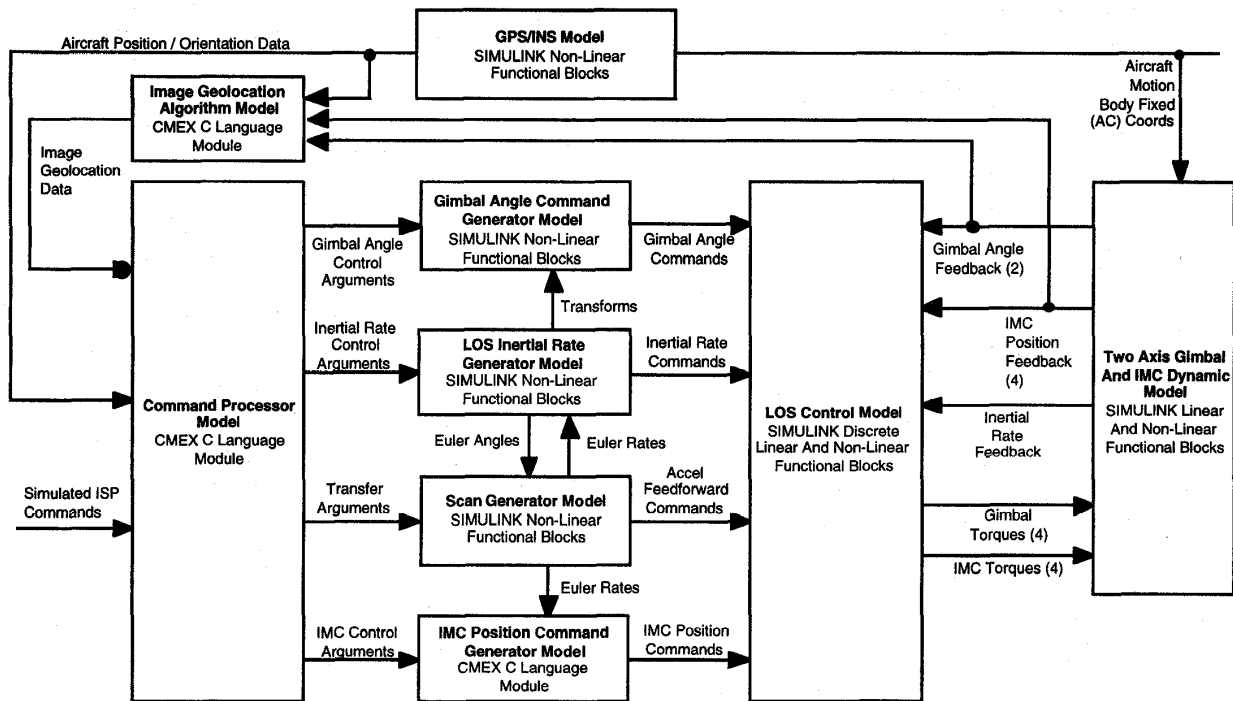


Figure 5.1.1. TIERII Plus Pointing And Stabilization Subsystem Math Model Structure

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.

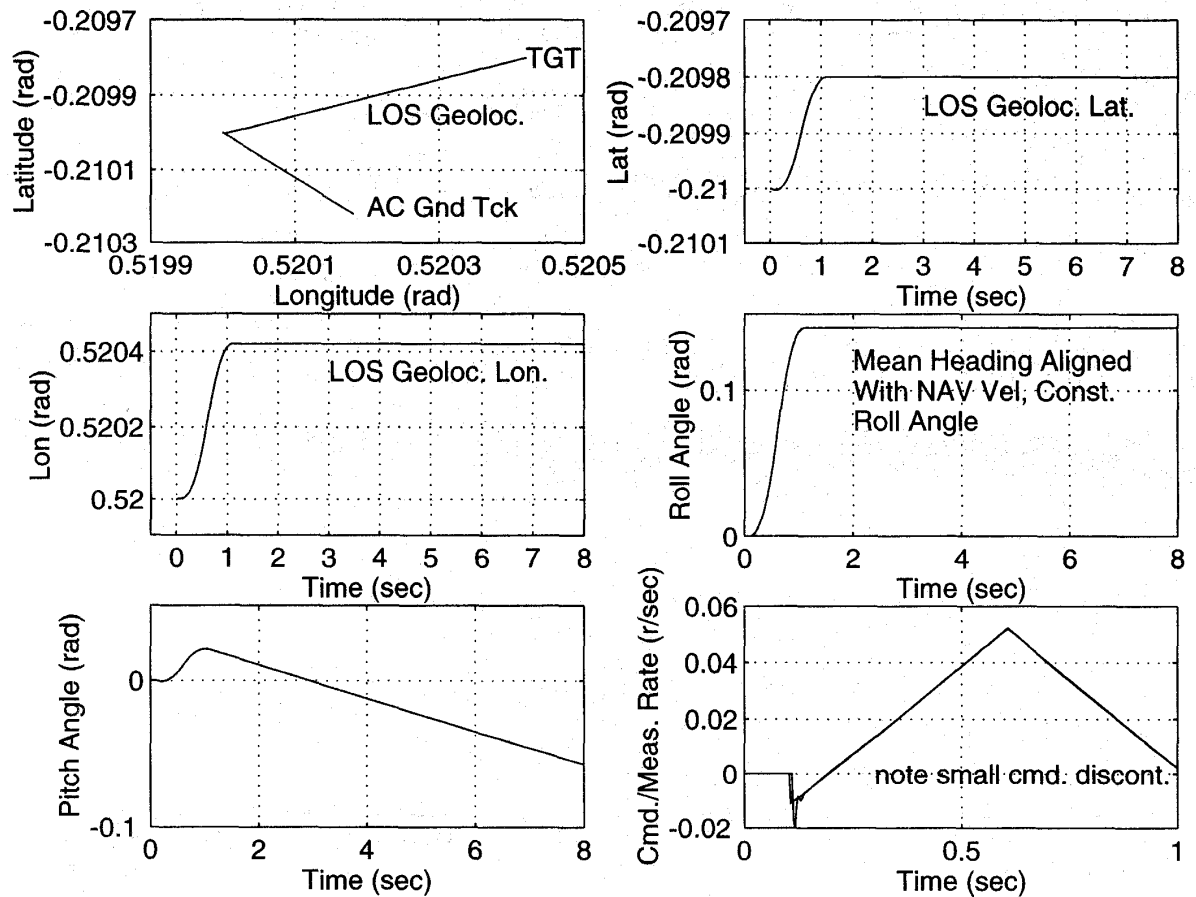
The plant model is based on linear and non-linear SIMULINK blocks which simulate the kinematics and dynamics of the two axis gimbal and IMC system. In order to accurately evaluate the LOS jitter caused by high frequency base motion effects, the non-linear kinematic model is replaced by a linearized structural 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



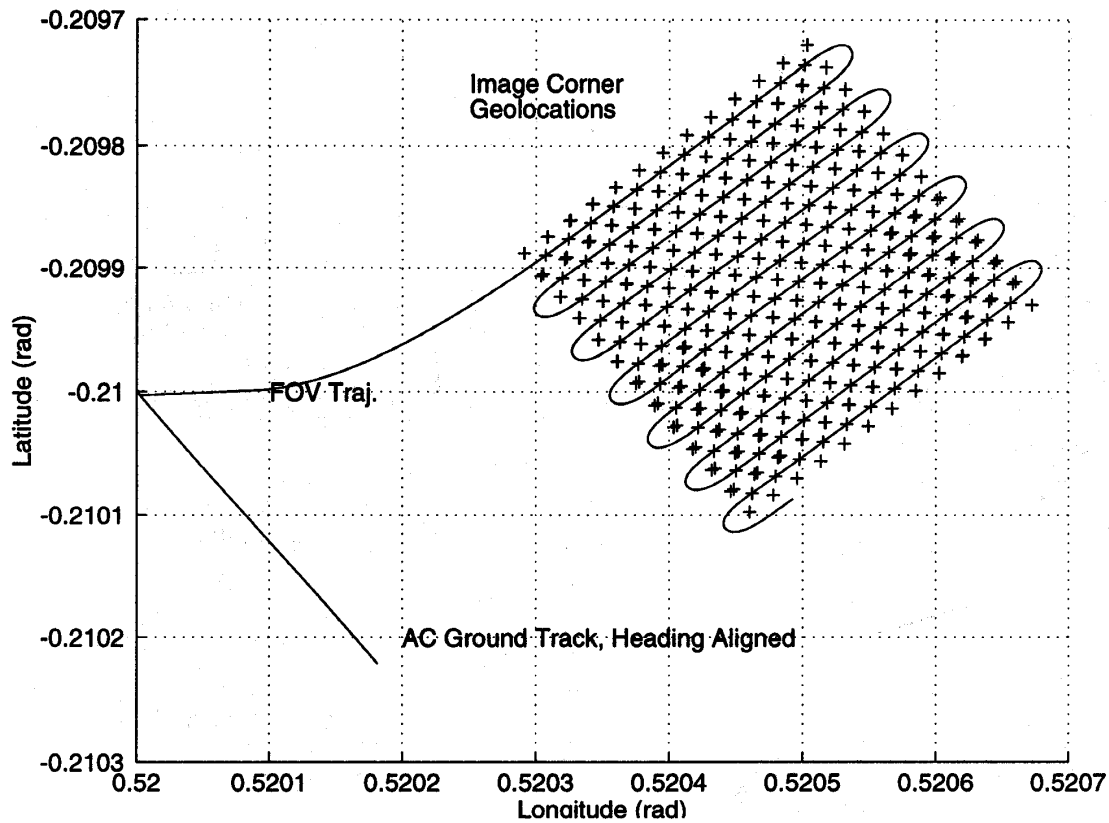
be simulated accurately in order to evaluate the accuracy of the command generation algorithms. For example, In EF Point mode, the command generation should transfer the LOS to the requested lat/lon location and maintain its position as the aircraft flies by the target. The feedback element for this 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

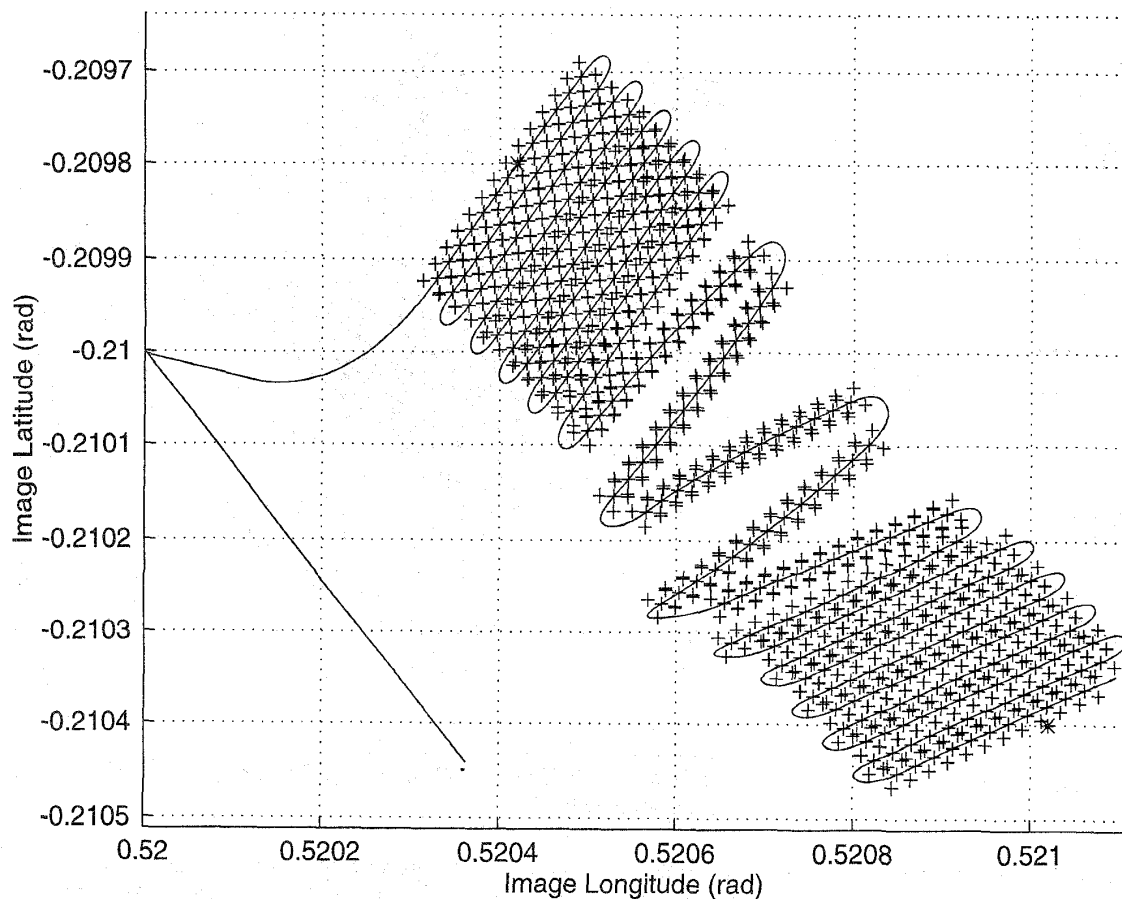


place, and any transients will have died out by the end of the transfer. The same problem applies at both the start and finish of transfers in WAS mode (during scan turnarounds). Since the scan is constructed in local level (euler angle coordinates), the transformation from sensor to local level coordinates 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



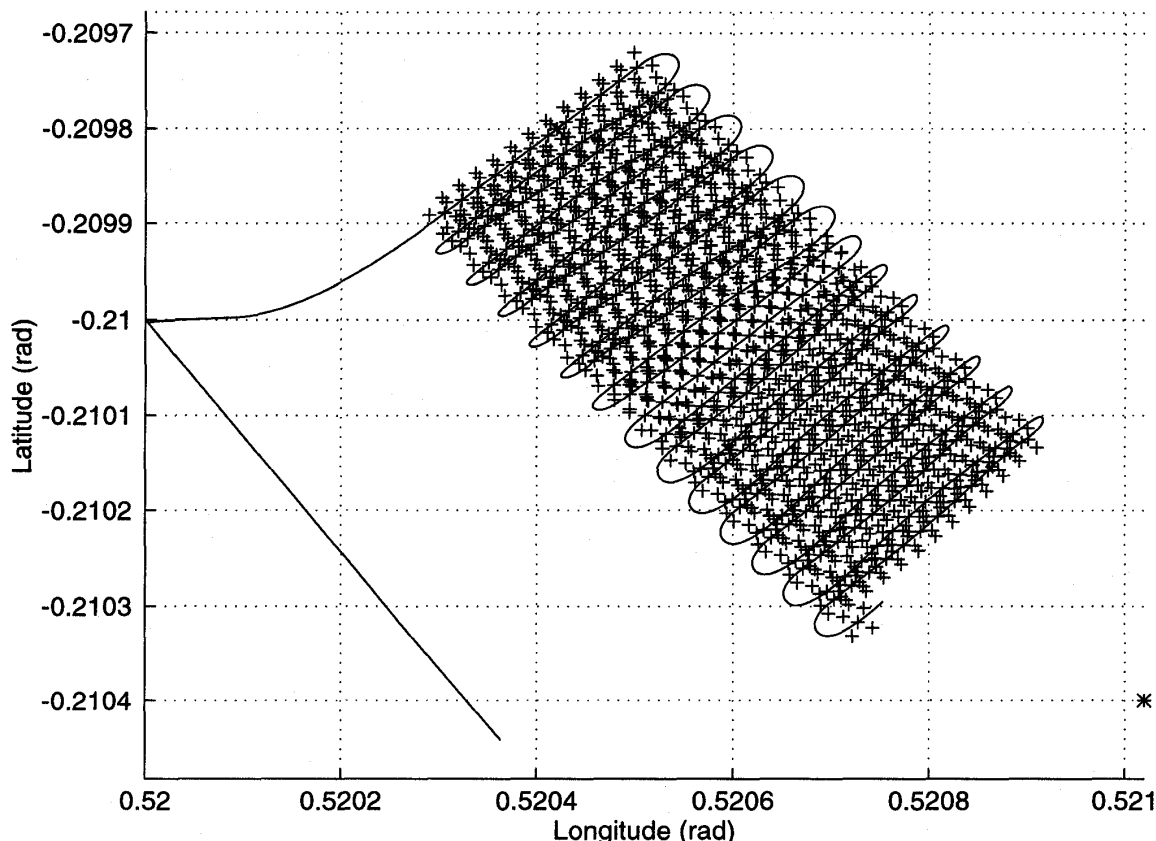
the next scan bar to account for any heading deviations.

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

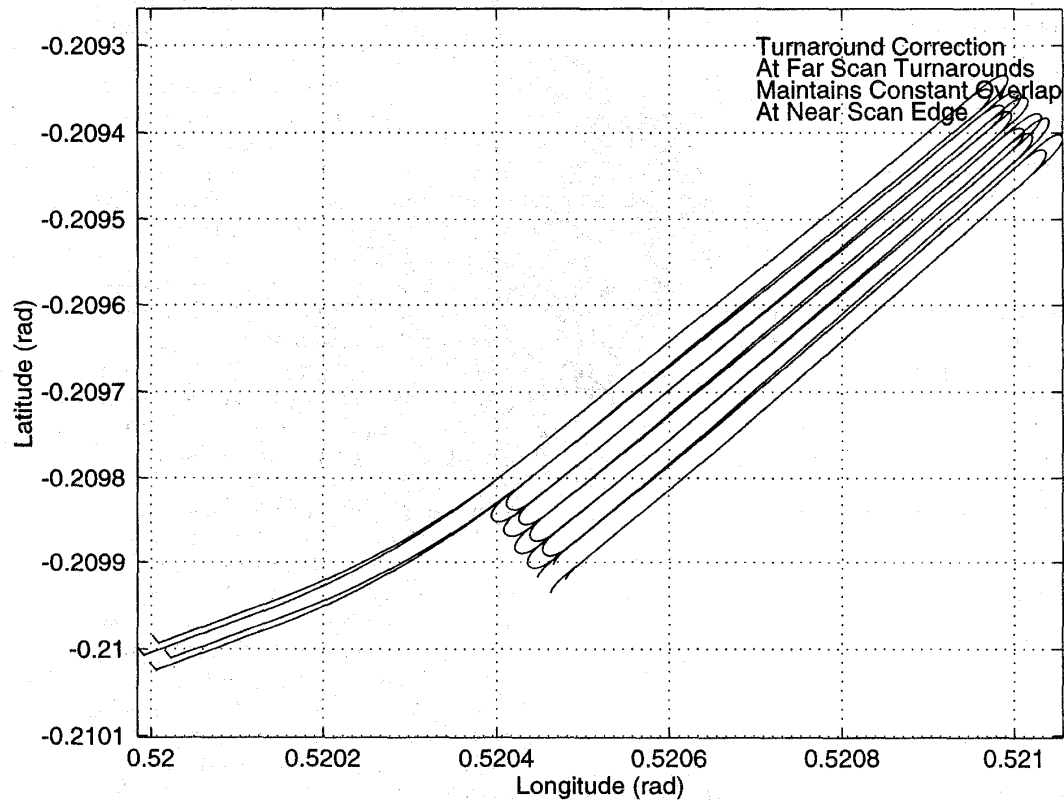


level frame orientation, the only way for the inertial rate commands and position commands to create equivalent scan patterns is if the aircraft heading and local level frame are attached, as in Figure 5.2.2b. Otherwise, the constant inertial rate scan (which is about *sensor roll only*, due to optical 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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References

- [1] Y.A. Wu, "EO Target Geolocation Determination", Proceedings of the 34th Conference on Decision and Control, Dec., 1995.
- [2] George M. Siouris, *Aerospace Avionics Systems - A Modern Synthesis*, Academic Press, Inc., 1993

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