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ACCURATE ATTITUDE DETERMINATION OF THE LACE SATELLITE

by

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ABSTRACT

The Low-power Atmospheric Compensation Experiment (LACE) satellite, launched in February 1990 by the Naval Research Laboratory, uses a magnetic damper on a gravity gradient boom and a momentum wheel with its axis perpendicular to the plane of the orbit to stabilize and maintain its attitude. Satellite attitude is determined using three types of sensors: a conical Earth scanner, a set of sun sensors, and a magnetometer. The Ultraviolet Plume Instrument (UVPI), on board LACE, consists of two intensified CCD cameras and a gimballed pointing mirror. The primary purpose of the UVPI is to image rocket plumes from space in the ultraviolet and visible wavelengths. Secondary objectives include imaging stars, atmospheric phenomena, and ground targets. The problem facing the UVPI experimenters is that the sensitivity of the LACE satellite attitude sensors is not always adequate to correctly point the UVPI cameras. Our solution is to point the UVPI cameras at known targets and use the information thus gained to improve attitude measurements. This paper describes the three methods developed to determine improved attitude values using the UVPI for both real-time operations and post observation analysis.

INTRODUCTION

LACE Satellite Description

The LACE satellite was designed and built by the Naval Research Laboratory (NRL) in Washington, DC. The satellite was launched on February 14, 1990 into a nearly circular orbit with an altitude of 541 km and a 43° inclination. It has no orbit adjustment capability. The spacecraft weighs 1440 kg. Its body is basically box shaped, 1.2 m by 1.2 m, and 2.4 m high. Gravity gradient stabilization is provided by a 45.7 m retractable boom, emerging from the top of the spacecraft, with a 91 kg tip mass including a magnetic damper. Foldout panels on the top and bottom support the solar arrays and sensor arrays respectively. Figure 1 is a drawing of the LACE satellite. The satellite's primary purpose is to provide an orbiting instrumented target board capable of measuring the effects of active compensation of a ground based laser beam propagated through the atmosphere. The LACE spacecraft was designed to support the experiment for 30 months. NRL operates a fixed and two transportable ground stations to communicate with, and control the satellite. Built by NRL, each transportable ground station is housed in two eighteen foot truck trailers. One trailer houses the telemetry, command and radio equipment, and the other provides an uninterruptable power supply and work area. The third ground station is permanently located in Maryland. These stations provide all the command and communication links for the LACE spacecraft.

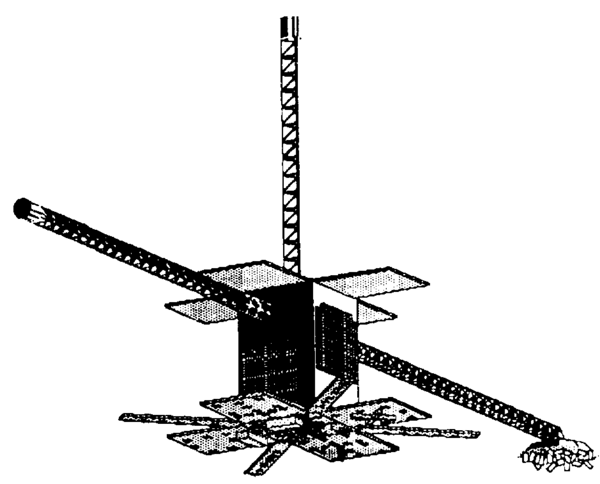

Figure 1
LACE Spacecraft

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History and Statement of the Problem

When the LACE spacecraft design was complete and major subsystems, such as structure, power, and attitude control, were being fabricated and tested, an additional experiment was proposed for integration into the spacecraft. This new experiment was the Ultraviolet Plume Instrument, or the UVPI. The purpose of the UVPI is to point to, acquire, and actively track the plume of a rocket launched from the Earth's surface, and collect images of the plume in the ultraviolet wavelengths. The UVPI was accepted for integration into the LACE spacecraft with the ground rule that it have minimum impact on the already existing LACE design. This meant minimum volume, weight, power, telemetry, and command usage. It also meant no change to the spacecraft's proposed orbit, nor to the attitude control, radio frequency, or navigation subsystems, and no operational impact on the primary mission of the satellite. To fulfill its goal, the UVPI was designed with an independently pointable camera with a field of view of about 2°. The LACE spacecraft was designed to maintain one side pointing to nadir to within ±3° and with an attitude knowledge of about ±1°. Initial UVPI pointing error analysis showed that the spacecraft attitude was the dominant source of pointing error, followed by spacecraft and target position uncertainty. The fundamental problem, then, was to be able to accurately point the UVPI when it is aboard a space platform with inadequately certain attitude. The solution that was developed during the operational planning was to use the UVPI imaging and precision pointing capability to augment the spacecraft's attitude sensor system. Using stellar and Earth fixed targets, the spacecraft attitude, both realtime and reconstructed, could be significantly improved. Three techniques to improve attitude knowledge were developed. These techniques became known as Yaw Scan, Beacon Tracking, and Star Pattern. The purpose of this paper is to describe these attitude determination techniques and show the results obtained when they were applied.

Description of the UVPI

The UVPI is mounted within the satellite and views through an aperture in the Earth oriented panel. By use of a gimballed mirror, the UVPI has a field of regard of a 50° half-angle cone about the satellite's nadir. When the UVPI is not in use, a door covers the aperture. Attached to the inside of this door is a flat mirror which, when the door is opened part way, allows the UVPI cameras to view celestial objects near the negative orbit normal or the Earth's limb. On-orbit photometric calibration is accomplished by observing stars with a known spectral signature. The UVPI has two cameras which share a common telescope and pointing system. The tracker camera has a field of view of 2.0° by 2.6°. It is sensitive in the UV and part of the blue portion of the visible spectrum, from 250 to 450 nm. The primary purpose of the tracker camera is to provide images to a closed loop tracking system. The plume camera has a field of view of 0.18° by 0.14°. It has four selectable filters and is sensitive in the UV from 195 nm to 350 nm. Open loop pointing is performed by providing, for each axis of the gimballed mirror, a polynomial function that is evaluated by an onboard computer which drives the gimbals. These polynomials are generated on the ground and transmitted the instrument as command data. When the UVPI tracker electronics detects a target in the tracker camera field of view, the centroid of the target image is computed. In addition, if the UVPI is commanded to do so, the gimballed mirror moves so as to bring the target image to the center of the plume camera field of view. This is referred to as closed loop tracking. If, during closed loop tracking, the target is lost, the UVPI will continue pointing by extrapolating the most recent gimbal readings, or revert to the polynomial pointing functions. If a target reappears, the UVPI will reacquire and track the target. Should the tracker electronics fail to identify a target, a method of manually assisted tracking is available. An operator viewing the telemetry images at a ground station can apply a vernier adjustment, using a joystick, to the gimbal position or velocity. In this way, targets of interest which are low contrast or are obscured by clutter, such as clouds, can be brought into the plume camera's field of view. This method of joystick tracking was implemented while the spacecraft was in orbit.

All the necessary commands and pointing functions can be stored onboard the spacecraft to perform one or several complete observations over remote parts of the Earth. The resulting image data is recorded by a 3 1/2 minute tape recorder. As of this date, four rockets launched from the Earth's surface have been tracked and imaged by the UVPI.

LACE Attitude Determination and Control

The attitude control system used for LACE was designed to meet the requirements of the primary experiment. This experiment required one side of the spacecraft to point toward nadir with a ±3° accuracy. In addition, it was required that a leading, retractable boom remain within ±2° of the orbit plane (see figure 1 for a drawing of the spacecraft). To meet these needs, a gravity gradient system was used. This system consists of a boom with a 92 kg tip mass, rising from the top of the spacecraft. A magnetic damper makes up part of the tip mass. A momentum wheel with its axis perpendicular to the orbit plane is used for yaw stiffening.

Three types of sensors are employed to make attitude measurements. These are: A five eye sun sensor system which provides the direction to the sun from the spacecraft, a conical Earth scanner which identifies the nadir direction by sensing the Earth's limb, and a magnetometer which measures the spacecraft's orientation with respect to the Earth's magnetic field. These sensors were selected to meet the requirement that the spacecraft's attitude be determined to ±1° after post observation processing. In practice, the conical Earth scanner alone provided spacecraft roll and pitch measurements accurate to about ±0.5°. The yaw, however, remained uncertain to about ±1°. In addition, the sun sensors provided no data during nighttime operations when most of the UVPI rocket target and stellar target observations were made. Figure 2 is a plot of typical spacecraft attitude for two complete spacecraft orbits. Although roll and pitch have a relatively smooth and predictable behavior, instrument calibration and alignment contribute to measurement uncertainty. The yaw component shows large (~1°) discontinuities when the spacecraft transitions from light to dark. The sinusoidal oscillation pattern of the spacecraft attitude is a typical feature of gravity gradient stabilized systems. The dominant period of these oscillations is equal to the spacecraft orbital period.

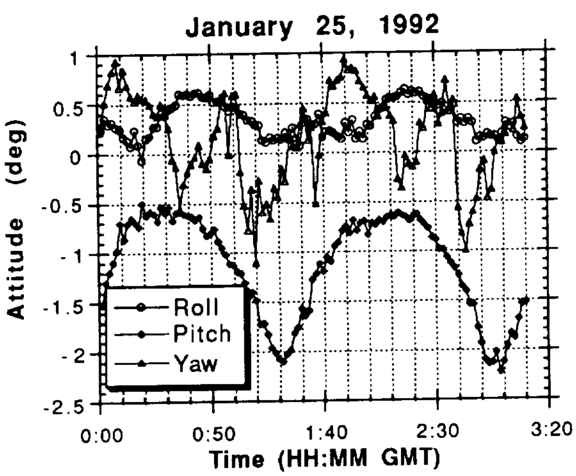

Figure 2.
Typical Spacecraft Attitude Values

The attitude sensors can be sampled at various rates and the data transmitted to the ground station in real time, or stored onboard for later transmission. Typically, real-time data is sampled about once per second and the non-realtime data is sampled and stored at a rate of once per 100 seconds. The QUaternion ESTimator (QUEST) program is used to process the measurements (both realtime and non-realtime) into attitude estimates. In addition the Real Time Attitude Computation (RTAC) program is also used to estimate the attitude using realtime measurements.

TECHNIQUES AND APPLICATIONS

Yaw Scan of Star

Description of Method

Since the uncertainty of the spacecraft's yaw was about ±1°, about the distance form the center to the edge of tracker camera field of view, a method of searching for targets was developed. To aid in locating stellar targets, a search pattern was superimposed onto the open-loop pointing function. This search pattern was a sinusoidal scan in the spacecraft's yaw direction. It typically had an amplitude of about 1° and a period of about 16 seconds. An operator, viewing the downlinked images in real time, observes the target entering the field of view. Noting the exact time when the target crossed the center line of the tracker camera, the operator, using ground based computer programs, can compute the spacecraft's yaw value and re-compute the UVPI pointing polynomials, transmit them, and center the target in the tracker camera. This method worked particularly well for stellar objects. The UVPI can only view stellar objects near the negative orbit normal direction. With this geometry, the errors in spacecraft roll and pitch have little effect on the image. The error in yaw, however, is nearly coincident to the error in pointing. To help the operator identify targets, stars were selected which were relatively bright in the blue and UV, and which were isolated by a few degrees from other bright objects. In addition, an estimate of the star's intensity, as seen in the downlinked image, was made so the operator was confident that the correct star was in view.

Application

Once a value for yaw was determined using the star scanning technique, it could be used as input to any UVPI pointing function in the next few minutes. Since the spacecraft oscillates in the yaw direction with an amplitude of about 0.4° and a period of about 95 minutes, the maximum rate of change of the yaw value would be about 0.03°/min. Over the next 10 minutes the change in yaw would be less than 0.3°; comparable to the uncertainty in the roll and pitch values. The roll and pitch values used to compute the UVPI pointing functions were determined from the spacecraft attitude sensors.

Results

Table 1 lists the results of determining the yaw on 23 occasions using the yaw scanning technique. The data spans a little more than one year of instrument operation. The table shows the yaw value which was determined by the image scan method and by the spacecraft attitude sensing system. What is evident from these data is that the peak-to-peak oscillation of the yaw is much less than what is indicated by the attitude sensors alone. In fact, the total variation in yaw based on the scanning technique, from 0.2° to 1.0°, is less than the uncertainty of ±1° ascribed to the attitude sensor measurements. Recent stellar observations which used a fixed yaw value of 0.3° resulted in good initial pointing and did not require any pointing adjustment based on the location of the target star in the image field of view.

Beacon Tracking

Description of Method

The roll and pitch attitude measurements, provided primarily by the conical Earth scanner, were thought to be precise (i.e., repeatable) to within about 0.25°. Figure 2 shows very consistent roll and pitch measurements. The uncertainty of 0.5° assigned to roll and pitch were due mainly to biases or offsets in the Earth scanner and alignment of the UVPI to the attitude reference frame. By determining accurate attitude values using the UVPI alone, independent of the spacecraft attitude measuring system, any mutual offset or misalignment could be measured. This measured offset could then be applied to improve spacecraft attitude measurements.

Table I
Comparison of the Yaw as Determined by the UVPI Star Scan and by the Spacecraft Attitude Sensors

Date DD-MM-YY	Scanned with UVPI (deg)	Measured by Spacecraft (deg)	Diff. (deg)
11-11-90	0.88	0.16	-0.72
12-11-90	1.00	1.08	0.08
16-12-90	0.24	-0.40	-0.63
18-12-90	0.41	-0.35	-0.76
19-12-90	0.47	1.02	0.55
20-12-90	0.41	-0.08	-0.49
13-2-91	0.26	-0.60	-0.86
14-2-91	0.36	-0.67	-1.03
15-2-91	0.76	1.07	0.31
14-4-91	0.64	-0.71	-1.35
22-4-91	0.64	0.72	0.08
23-4-91	0.47	0.98	0.51
24-4-91	0.65	0.74	0.09
25-4-91	0.57	0.78	0.21
13-6-91	0.43	0.84	0.41
14-6-91	0.81	0.79	-0.02
8-8-91	0.29	0.87	0.58
9-8-91	0.31	1.11	0.80
14-9-91	0.28	-0.40	-0.68
16-11-91	0.21	-0.85	-1.07
18-11-91	0.22	-0.84	-1.06
19-11-91	0.22	-0.78	-1.01
9-1-92	0.60	-0.92	-1.52
Average	0.48	0.15	-0.33
Std.	0.23	0.78	0.70
Max.	1.00	1.11	0.80
Min.	0.21	-0.92	-1.52

The approach used, was to have the UVPI track a fixed, known location on the surface of the Earth. The UVPI's gimballed pointing mirror provided a sequence of unit vectors pointing to the target in the body frame of the spacecraft. For each measurement there was a corresponding computed unit vector pointing from the spacecraft to the target in the local reference, or attitude frame. The difference between these two unit vectors was viewed as the attitude. A more detailed description of this method is provided in Appendix A. Since the spacecraft's attitude in each axis was always less than about ±3°, and oscillates at orbital periods (about 95 minutes), it could be assumed that the spacecraft attitude did not change over the solution period, which was typically 5 seconds.

A portable ground beacon was used as the target for the UVPI. The beacon consists of four 6 kW metal halide bulbs, each with its own power supply. About 10% of the bulbs output is in the bandwidth of the UVPI tracker camera which, at night, provides a target bright enough for the UVPI to track. This beacon was used for various instrument calibration and tracking tests, and has been located at: Southern Maryland; Wallops Is., Virginia; Titusville, Florida; Vandenberg AFB, California; Table Mt., California; and Hawaii.

Results

Table 2 shows the results of the attitude determination using seven different UVPI ground beacon observations. The table also shows the attitude measured by the spacecraft attitude sensing system at the same time, and the difference between the two values. A bias of 0.7° is clearly evident in the roll measurements. A standard deviation of the differences in roll values of only 0.1° indicates that the roll measurements made by the spacecraft attitude sensing system are quite accurate once the bias is accounted for. The pitch parameter shows no systematic offset. It is known that the spacecraft has a natural pitch bias due to an offset of the spacecraft center of mass. The calculated yaw values show an average of 0.4° with a standard deviation of 0.2°. This is consistent with the previous results where the yaw was calculated using the star scanning technique. The difference between the calculated yaw and the yaw measured by the spacecraft attitude sensors is too uncertain to estimate any possible offset.

The seven observations used for this analysis tracked the ground beacon target from 20 seconds to over 2 minutes. Attitude values were calculated using 5 second data segments. This resulted in a sequence of solutions spanning the observation interval. Figure 3 is a plot of the sequence of attitude solutions for one of these observations. This plot, typical of the seven cases, shows a larger variation in each attitude component than could be expected from the natural oscillations of the spacecraft. From the observed amplitudes of oscillation in each axis, 0.25°, 0.9°, and 0.3° for roll, pitch, and yaw, the maximum rates of change are $2\pi A/P$, where A is the amplitude and P is the period of about 95 minutes. This gives maximum rates of change of 0.02°/min, 0.06°/min, and 0.02°/ min for roll, pitch, and yaw which are clearly smaller than the calculated values shown in Figure 3.

Table II
Comparison of Attitude Calculated Using UVPI Tracking Beacon and Measured by Spacecraft Attitude Sensing System

	Calculated Using UVPI Beacon Track			Measured Using S/C Attitude Sensors			Difference (Measured - Calculated)		
Date DD-MMM-YY	Roll (deg)	Pitch (deg)	Yaw (deg)	Roll (deg)	Pitch (deg)	Yaw (deg)	Roll (deg)	Pitch (deg)	Yaw (deg)
	-0.25	0.10	0.29	0.41	-0.25	-0.32	0.66	-0.35	-0.61
22-Apr-91	-0.18	-0.44	0.25	0.49	-0.75	0.72	0.67	-0.31	0.47
24-Apr-91	-0.27	-0.68	0.64	0.47	-0.76	0.74	0.74	-0.09	0.10
25-Apr-91	-0.04	-0.66	0.43	0.44	-0.77	0.78	0.48	-0.11	0.35
13-Jun-91	-0.37	-0.36	-0.02	0.45	-0.26	0.84	0.82	0.10	0.86
14-Jun-91	-0.19	-0.59	0.50	0.40	-0.52	0.79	0.60	0.07	0.28
11-Nov-90	-0.28	-1.09	0.29	0.55	-0.58	0.97	0.83	0.51	0.67
					Average		0.69	-0.02	0.30
					Std. Dev		0.12	0.29	0.47

To determine if the large variations in the calculated attitude parameters could be attributed to errors in other model parameters, a sensitivity analysis was performed. Using simulated data, errors were introduced one at a time in selected model parameters. These parameters and errors were: 0.5 km in the North and East components of the location of the ground beacon, 1.5 km in the along track direction of the spacecraft, and 0.01° in the azimuth and elevation angle of the UVPI gimballed mirror. The ground beacon was located at various sites in the continental US. Its location was determined, for each of these locations, either by estimates from the proximity to known geodetic locations such as fixed tracking antennas, or from a Global Positioning System receiver. The spacecraft position is obtained from the Naval Center for Space Surveillance (NAVSPASUR) in Dalhgren Virginia, and is accurate to within 1.5 km during the time period of ground beacon tracking. These orbit elements are provided especially for UVPI operations and use special propagation models to attain high accuracy. The pointing error due to the UVPI gimballed mirror was assumed to be two times the readout of the least significant bit in the telemetry. Gimbal measurement noise, estimated from gimbal readings and target image centroiding, is estimated to be about 0.002°. Figures 5, 6, and 7 are the results of this analysis for roll, pitch, and yaw respectively. Comparing these results to the calculated results in Figure 3 shows that none of the examined error sources are sufficient to account for the wide variation in the calculated attitude.

Verification

Two methods of verification were used. First, images of the ground beacon, where the UVPI was pointing but not tracking, were adjusted by 0.7° in the roll direction during post observation processing. Figure 7 shows several observation results, plotting the original location along with the location after an adjustment for roll bias. In each case the adjustment resulted in the ground beacon target being moved closer to the center of the UVPI field of view (FOV). The second method used was to apply the 0.7° roll bias to the UVPI pointing functions when attempting to acquire the ground beacon target. Previously, the approach had been to perform a circular scan of about 0.5° about the nominal pointing function to ensure that, at some point during the scan, the target would enter the FOV and could be identified and acquired. Recent operations have applied the roll bias identified in this analysis and did not apply a scan pattern. In all cases where this was done, the target beacon fell well within the camera's FOV.

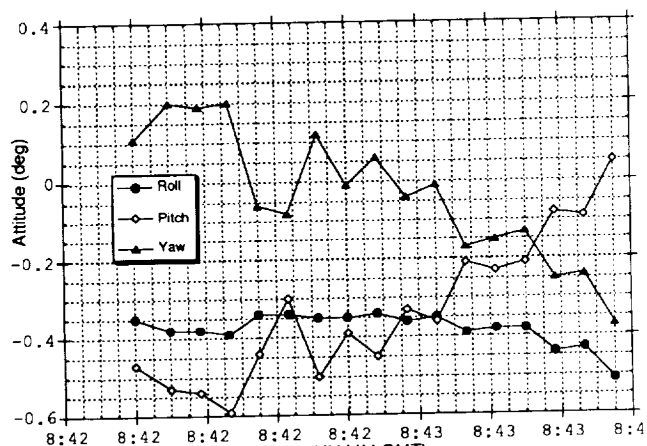

Figure 3
Calculated Attitude Values using Beacon Tracking. June 13, 1991

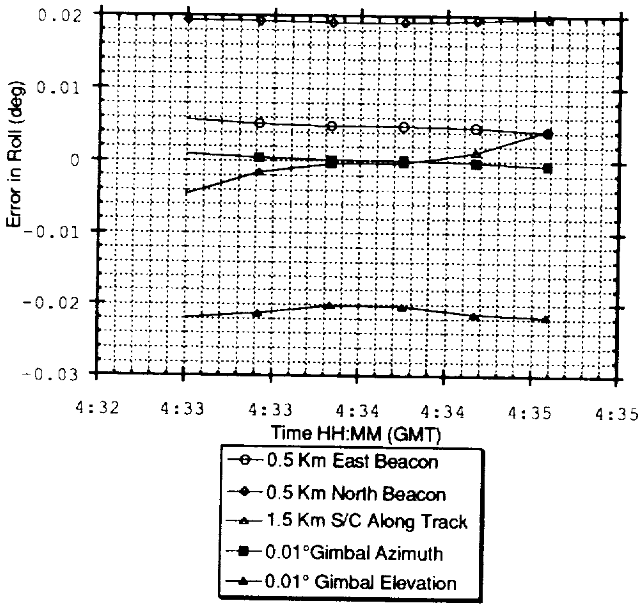

Figure 4
Sensitivity of the Calculated Roll to Model Parameters and Legend for Figures 4, 5, and 6

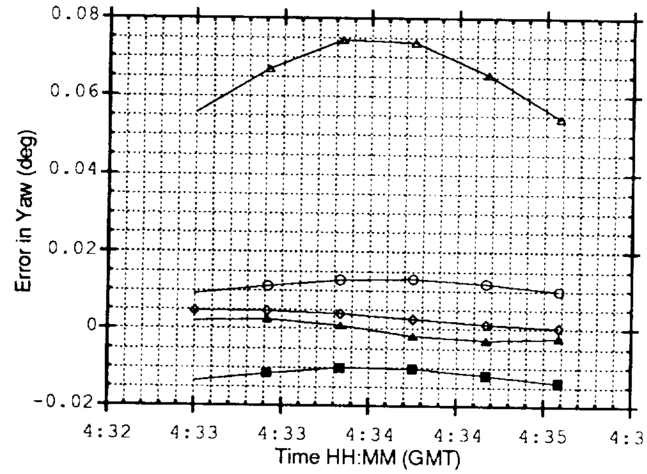

Figure 6
Sensitivity of the Calculated Yaw to Model Parameters

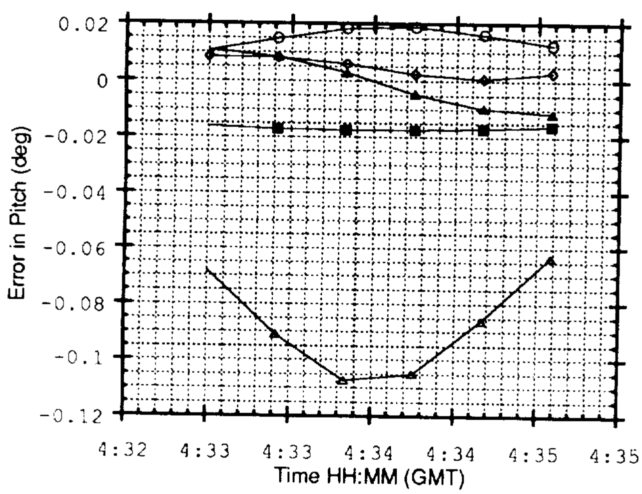

Figure 5
Sensitivity of the Calculated Pitch to Model Parameters

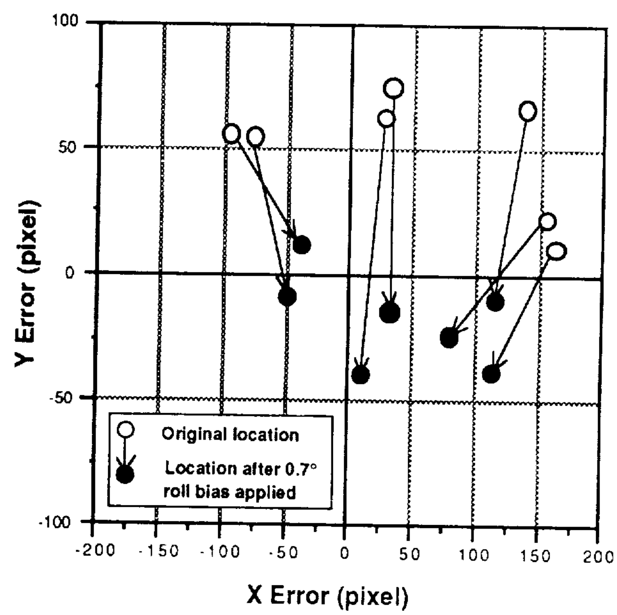

Figure 7
Applied 0.7° Roll Bias Post-pass to Three Ground Beacon Observations

Star Pattern

Technique

One mission of the UVPI is to gather rocket plume images. Since the instrument's data collection mission was expected to last for at least one year, with plume observations made throughout this period, it was felt necessary to regularly verify the UVPI radiometric response. The method used to do so is to image one or more stars whose spectra and magnitudes are known. Based on the photon counts from these known stars, UVPI calibration parameters are calculated. A typical calibration observation consists of pointing the instrument in the appropriate direction, and tracking a star for some time. Pointing direction is determined by calculating needed gimbal functions and door mirror angles using projected satellite location and attitude. Because of LACE attitude uncertainty and the requirement that the star or stars imaged be positively identified, stars and star patterns imaged by UVPI are compared with a star map after the observation. After stars in a pattern are matched to an image, as required for a positive identification, error in the LACE attitude sensors can be easily determined using the following technique.

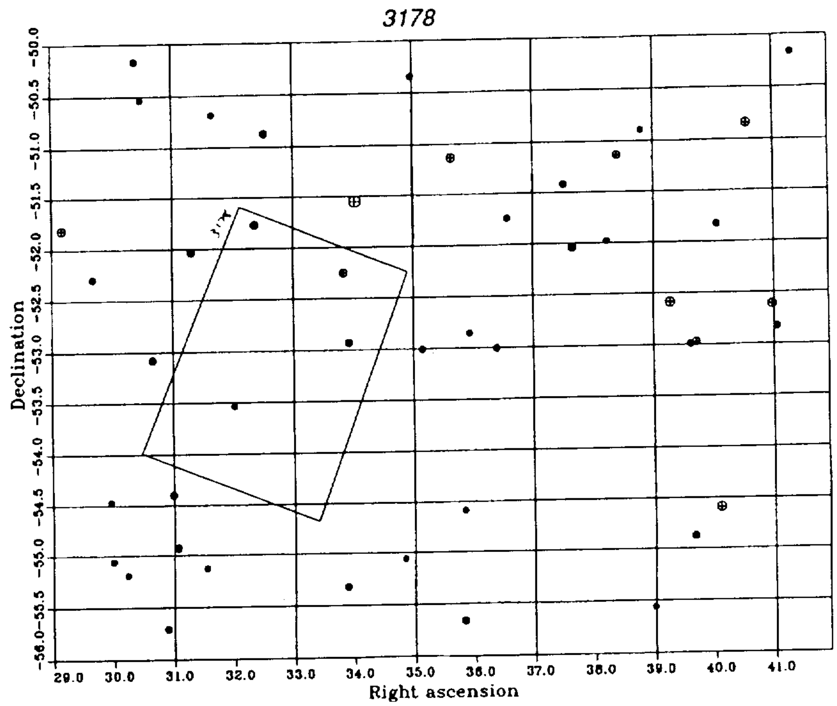

Figure 8
Star Map with Calculated UVPI tracker Camera FOV Superimposed
September 23, 1991

After a star observation is performed, a computer program, called the Line of Sight (LOS) program, is used to calculate the Right Ascension and Declination of the four corners of the FOV box. Inputs to this program are: LACE position, LACE attitude (LACE attitude sensor data smoothed to fit a 2nd order curve), UVPI gimbal angles, and UVPI door angle (since the observed star images are reflected on the door mirror). A plot is then produced which shows a star map in the vicinity of the calculated FOV of a particular frame and includes the calculated FOV box. Figure 8 shows an example of this type of plot. The corresponding frame showing the star pattern actually imaged by the camera is then transferred to hard copy for comparison to the star map. By scaling the hard copy of the image properly, the star pattern in the image can be matched to a star pattern on the star map. Once a match is found, it provides the actual location of the FOV, which is manually traced onto the FOV/star map plot. The relative offset of the two FOV rectangles is the result of program input uncertainties, of which the predominant ones are inaccuracies in the LACE attitude inputs. Rotation between the two boxes is attributed to pitch error. Pitch error is difficult to measure accurately so frames showing large pitch errors have not been included in this analysis. Small apparent pitch errors are approximated to zero. Linear offset between the actual and calculated FOV's is attributed to error in roll and yaw. Roll error is manifested as offset in a direction parallel to the short sides of the FOV rectangle. Yaw error is manifested as offset in a direction parallel to the long sides of the FOV rectangle. Error is defined as actual attitude minus calculated attitude. The simplification of decoupling roll and yaw is valid and yields sufficiently accurate results for the small angles usually encountered. It should be noted that, for this technique, any error in the roll includes error caused by inaccurate door angle measurements.

Application

Figure 8 shows a plot of a typical star map with the calculated FOV of UVPI for a particular frame included. Figure 9 shows the corresponding image that was recorded in the UVPI camera. When the two are superimposed and the pattern in the image is matched to stars in the star map, the actual FOV can be traced onto the star map. Figure 10 shows both the actual and calculated FOV traced onto a star map. The error in attitude is quantified using the angular dimensions of the UVPI FOV as a scale. As mentioned earlier the UVPI FOV is 2.0° by 2.6°. In Figure 10 it is seen that pitch error is minimal, yaw error is also small, and roll error is approximately -0.6°.

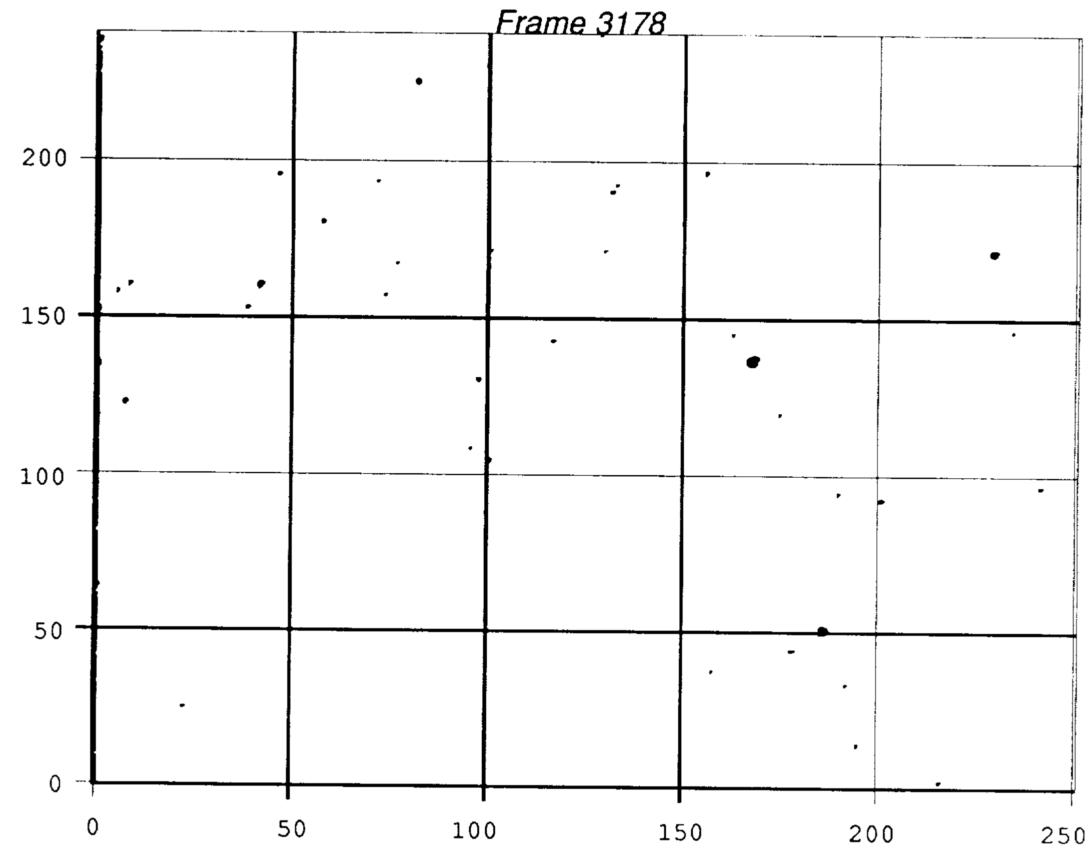

Figure 9
UVPI Tracker Camera Image, September 23, 1991

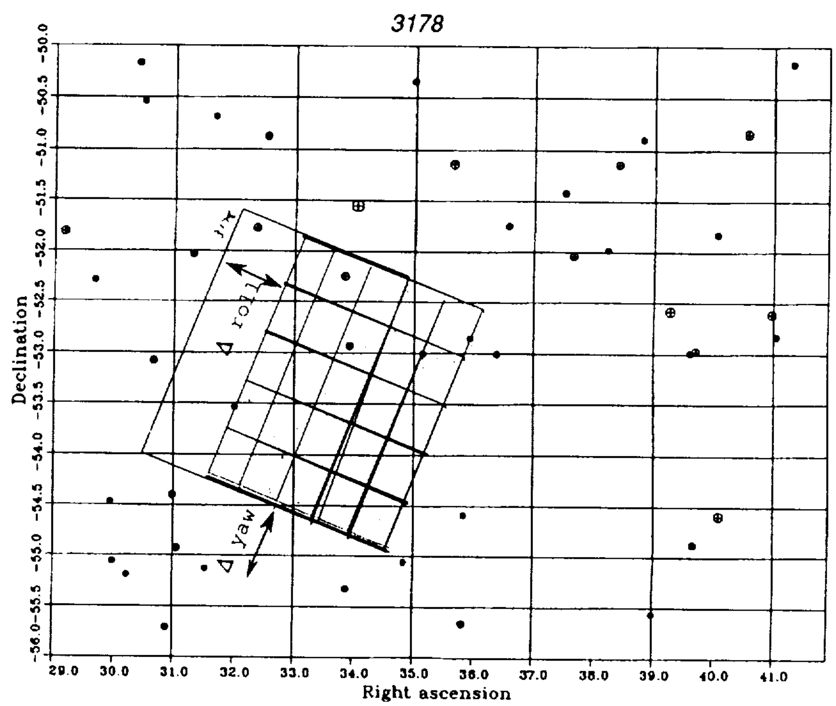

Figure 10
Star Map with Calculated and Actual FOV, September 23, 1991

Results

Table III lists the mean and standard deviation of the corrected roll, pitch, and yaw calculated from over 50 individual frames spanning a little over one year of UVPI operations. Notice that the mean of yaw is near zero. This indicates that there is no detectable rotational offset in yaw between the UVPI and the LACE coordinate systems. The large standard deviation in the yaw shows that data from the sensors is especially inaccurate for yaw measurements. The 0.7° mean for the roll represents a rotational offset between the UVPI and LACE coordinate systems. The large standard deviation in roll error is attributed to random door angle error. The 0.7° offset is corroborated by findings from beacon observations, shown in Table II. The relatively small standard deviation in roll error shown in Table II results from the fact that beacon observations do not use the door mirror. Hence this source of error is eliminated from beacon observation derived measurements. Appendix B contains the data used to calculate values shown in Table III.

Table III
Attitude Error Data from Star Pattern Technique

	Attitude Error Roll	Yaw
Mean	0.74	0.07
Standard Deviation	0.78	0.80

Table III shows that while statistical analysis of attitude error data from many passes can reveal systematic attitude errors, even error from a single frame during an observation can help in improving attitude data. If it is assumed that attitude error stays constant during the time period of a typical observation (5 to 10 minutes) then it follows that the attitude error measured for a single frame can be applied to every frame in that pass. This procedure represents the second step in attitude data processing (the first is 2nd order smoothing) and is called enhancement. When this enhanced attitude data is used as an input to the LOS program, each and every FOV rectangle should be very close to where the UVPI was actually looking. This idea has been tested and was found to be valid for most cases. This enhanced attitude data represents the best attitude of UVPI for the particular time period. Figures 11 and 12 show the yaw and roll error versus frame number (i.e., time). It is seen that unsmoothed roll and yaw show significant error and scatter while enhanced roll and yaw show average error near zero and very little scatter. It is noted that smoothing alone reduces scatter significantly. Applying the observed error back to the data simply moves the average error closer to zero. The data shown in the following graphs was generated using the error calculated from Figure 10. Again, it is noted that for this technique, roll error includes LACE attitude sensor error and door mirror angle error. It is known that as long as the door mirror is not moved, the door mirror angle error also remains constant. This is the case for most star tracking sequences. Figures 11 and 12 demonstrate that these assumptions are valid. Note that the time period shown in Figures 11 and 12 begins some time after the frame depicted in Figure 10. Therefore, what appears to be an inconsistency in the calculation of roll and yaw error between Figure 10 and Figures 11 and 12, is in fact due to sensor measurement noise at two different times. Enhancement of attitude data as described above has become a standard procedure in UVPI data processing and has shown to result in average attitude errors of approximately .1°.

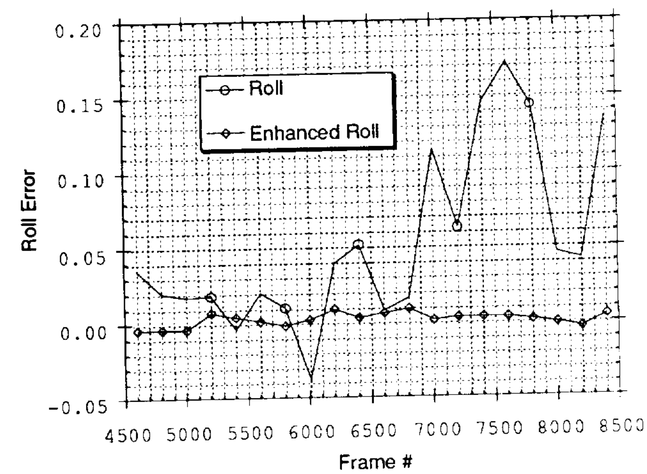

Figure 11
Roll Error Before and After Enhancement

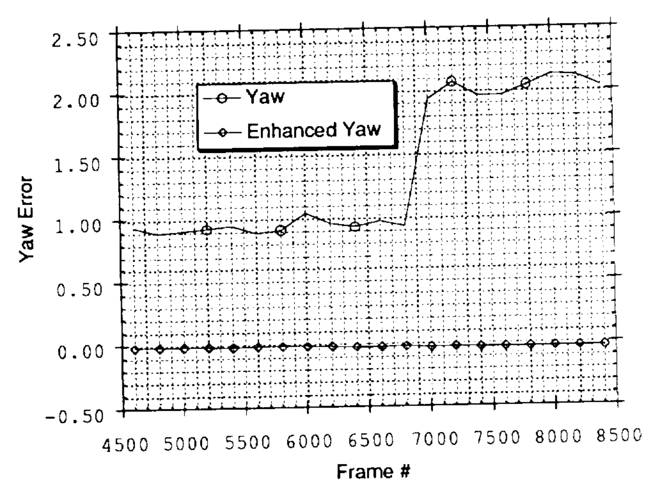

Figure 12
Yaw Error Before and After Enhancement

Other Applications

Another application of this technique has automated some of the processing. Once a star pattern has been identified, a computer program is used to directly calculate the attitude of the spacecraft. This is an improvement over the preceding technique in that roll, pitch, and yaw are calculated as a triplet. While valid, this technique is a recent development and has little supporting data. The basic technique is shown in Appendix A.

SUMMARY

The precision pointing and imaging capability of the UVPI has been used to improve the LACE spacecraft attitude sensing and determination. Utilizing these capabilities, the instrument was used to determine attitude in real time, estimate offsets, and to more accurately characterize the spacecraft's attitude sensing system. This was accomplished by viewing stars which were near the normal to the orbit plane, and by tracking a ground target with a known location. Based on these results three conclusions were reached: (1) There was an offset between the attitude reference frame and the imaging instrument of 0.7° in the roll direction, (2) The roll and pitch provided by the spacecraft attitude sensors were better than expected, and (3) The total variation in the yaw was much less (±0.4° vs. ±1.0°) than the spacecraft sensors indicated. These results were then implemented into instrument operations resulting in improved camera pointing accuracy.

The experience with the LACE spacecraft and the UVPI has demonstrated that a precision pointing instrument can be operated from a spacecraft with simple and inexpensive attitude control and sensing systems. The imaging instrument itself can be used to improve the spacecraft attitude determination.

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Appendix A

Attitude Determination Technique

for Ground Beacon Tracking or Star Pattern Observation

Let L be an orthogonal coordinate system having L1, L2, L3 as its axes where L3 is along the spacecraft radial, L2 is pointing opposite to the orbit normal, and L1 completes the right-handed rectangular coordinate system.

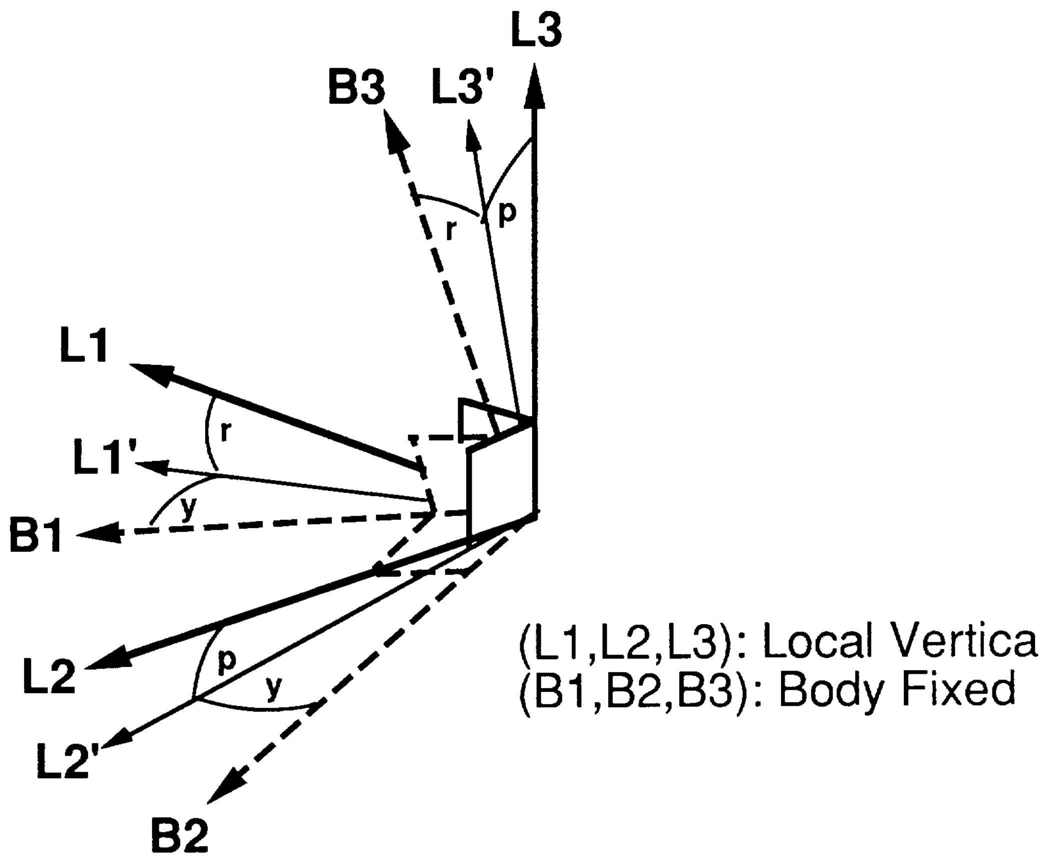

Figure A1
Coordinate System

Let B be an orthogonal coordinate system attached to the body of the spacecraft whose axes are B1, B2, and B3 such that if the attitude of the spacecraft is zero (i.e., roll = pitch = yaw = 0°), then the coordinate systems L and B are identical. Figure A1 illustrates the two coordinate systems.

To establish a relationship between the two coordinate systems, we rotate the L system first about the L1 axis in the clockwise direction an angle equal to +p, forming the (L1, L2', L3') system. Next rotate counter clockwise about the L2' axis an angle equal to +r, forming the (L1',L2',B3) system. Finally, rotate counter clockwise about the B3 axis an angle equal to +y, forming the (B1,B2,B3) system.

The rotational matrices that correspond to the three rotations described above can be expressed as:

$$[P] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & +\cos(p) & -\sin(p) \\ 0 & +\sin(p) & +\cos(p) \end{bmatrix}$$

$$[R]=\begin{bmatrix} +\cos(r) & 0 & -\sin(r) \\ 0 & 1 & 0 \\ +\sin(r) & 0 & +\cos(r) \end{bmatrix}$$

$$[Y]=\begin{bmatrix} +\cos(y) & +\sin(y) & 0 \\ -\sin(y) & +\cos(y) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The three rotations can be combined into a single rotational matrix [A], the attitude matrix, by multiplying the rotational matrices [Y], [R], and [P] in that order to give:

$$[A]=\begin{bmatrix} \cos(y)\cos(r) & -\cos(y)\sin(p)\sin(r)+\sin(y)\cos(p) & -\cos(y)\cos(p)\sin(r)-\sin(y)\sin(p) \\ -\sin(y)\cos(r) & \sin(y)\sin(p)\sin(r)+\cos(y)\cos(p) & \sin(y)\cos(p)\sin(r)-\cos(y)\sin(p) \\ \sin(r) & \sin(p)\cos(r) & \cos(p)\cos(r) \end{bmatrix}$$

the attitude matrix [A], an orthonormal matrix such that $[A]^{-1} = [A]^T$, transforms vectors expressed in the L coordinate system to the B coordinate system.

Let $\vec{l} = (l_1, l_2, l_3)^T$ be the LOS unit vector from the spacecraft to the target (a ground beacon or a star) in the L coordinate system. Then $\vec{l}$ is a function only of the spacecraft ephemeris and target position. Next let $\vec{b} = (b_1, b_2, b_3)^T$ be the LOS unit vector from the spacecraft to the target expressed in the B coordinate system. The vector $\vec{b}$ is a function of the characteristics of the body-fixed pointing system which, for UVPI, included the location of the target (in terms of the x- and y-pixels location on the focal plane) relative to the center of the FOV of the camera and the azimuth and elevation of the gimbal mirror (and of the UVPI door angle if the target is a star). The vectors $\vec{l}$ and $\vec{b}$ are then related by:

$$[A]\cdot\vec{l} = \vec{b} \qquad \text{Eq. (1)}$$

Since the attitude of the spacecraft is within ± 3°, the small angle approximations can be made. The matrix [A] can be linearized, keeping only the zeroth and first order terms, to give:

$$[A]\approx[A]_0=\begin{bmatrix} 1 & +y & -r \\ -y & 1 & -p \\ +r & +p & 1 \end{bmatrix} \qquad \text{Eq. (2)}$$

where r, p, and y are roll, pitch, and yaw angles expressed in radians, necessarily.

Now, treating vectors $\vec{l}$ and $\vec{b}$ as known quantities, and r, p, and y as unknowns, Eq. (1) can be rewritten as:

$$\begin{bmatrix} -l_3 & 0 & +l_2 \\ 0 & -l_3 & -l_1 \\ l_1 & l_2 & 0 \end{bmatrix} \bullet \begin{bmatrix} r \\ p \\ y \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix}$$

or

$$[m] \cdot \vec{x} = \vec{c} \qquad \text{Eq. (3)}$$

where

$$[m] = \begin{bmatrix} -l_3 & 0 & +l_2 \\ 0 & -l_3 & -l_1 \\ l_1 & l_2 & 0 \end{bmatrix}, \quad \vec{x} = \begin{bmatrix} r \\ p \\ y \end{bmatrix}, \quad and \quad \vec{c} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix}$$

Note that [m] is of rank 2 and det[m] = 0 in which case r, p, and y cannot be solved uniquely using just a single equation. However, using a series of LOS unit vectors during a short observation interval for the case of the beacon or using the star patterns in the case of star observation, the attitude can be solved uniquely. In practice, the LOS vectors are obtained by tracking the beacon source or observing the night sky to collect star patterns.

Let's assume that there are n LOS unit vectors that can be obtained during an observation, Eq. (3) can be written for each LOS unit vector.

We thus have :

$$\begin{aligned} [m]_1 \cdot \vec{x} &= \vec{c}_1 \\ [m]_2 \cdot \vec{x} &= \vec{c}_2 \\ [m]_3 \cdot \vec{x} &= \vec{c}_3 \\ \\ [m]_n \cdot \vec{x} &= \vec{c}_n \end{aligned} \qquad \text{Eq. (4)}$$

Eq. (4) is a system of 3n equations in three unknowns, namely the vector $\vec{x}$. Eq. (4) can be written in a more compact form as:

$$[M] \cdot \vec{x} = \vec{C} \qquad \text{Eq. (5)}$$

where [*M*] is a 3n x 3 augmented matrix and C is a 3n dimensioned vector.

The over-determined system in Eq. (5) can be solved either by the standard least-square method by forming the residual function $\vec{R} = [M] \cdot \vec{x} - \vec{C}$ and minimizing $|\vec{R}|^2$, or by forming the transpose of $[M]$ and solving for $\vec{x}$ directly. The former technique is more general in that it can be applied even when the linearization of the matrix $[A]$ is not invoked. The latter technique is more efficient with the linearized version. In this case, one would form $[M]^T[M] \cdot \vec{x} = [M]^T \cdot \vec{C}$ and $\vec{x} = \{[M]^T[M]\}^{-1}[M]^T \cdot \vec{C}$ where the inverse, $\{[M]^T[M]\}^{-1}$, can easily be determined since it is a 3 x 3 matrix.

Appendix B

Rev #	Frame #	Total Correction roll	pitch	yaw
597	6706	0.65	0.00	-0.97
	10054	0.70	0.00	-1.05
	10510	0.73	0.00	-0.94
1281	3790	0.41	0.00	0.49
1584	3766	0.33	0.00	-0.40
	7738	0.44	0.00	-0.31
1897	4198	0.40	0.00	-0.65
2439	10903	-0.00	0.00	-0.75
2622	9928	1.48	0.00	-0.19
	9994	1.59	0.00	-0.49
2636	3576	0.69	0.00	-0.48
	11947	0.68	0.00	-0.67
2837	3790	0.36	0.00	0.99
3078	7894	0.60	0.00	-0.60
3182	17094	1.33	0.00	-0.05
	4378	1.23	0.00	-0.23
3686	4228	0.75	0.00	0.90
3820	5632	0.35	0.00	1.48
	5650	0.35	0.00	1.48
3835	6196	0.59	0.00	1.23
3866	4564	-0.25	0.00	0.39
4090	11740	-0.52	0.00	0.12
4423	4120	0.80	0.00	0.22
	9339	0.10	0.00	0.40
	13332	1.00	0.00	0.25
4592	9880	-0.76	0.00	-0.57
4621	9583	1.07	0.00	0.78
4669	10426	1.45	0.00	0.17
4983	17896	1.04	0.00	-0.36
5279	7174	-0.38	0.00	0.77
	18244	0.35	0.00	0.86
	18316	0.53	0.00	0.93
5321	3712	1.05	0.00	-0.05
	4588	1.14	0.00	-0.25
	13771	0.72	0.00	-1.64
	13783	0.89	0.00	-1.57
5336	4132	-0.08	0.00	0.88
	4282	-0.08	0.00	0.88
5351	7360	2.01	0.00	0.92
5396	7150	0.85	0.00	0.64
	11601	0.83	0.00	0.35
	22516	0.80	0.00	0.36
5487	6338	0.90	0.00	0.81
	17389	0.17	0.00	2.04
5537	4414	1.54	0.00	-0.45
	4504	1.52	0.00	-0.55
	4942	1.52	0.00	-0.45
5567	6394	2.20	0.00	-0.14
	6412	4.25	0.00	-0.67
5582	4342	-0.30	0.00	-1.43
6411	18121	0.01	0.00	0.19
	25127	0.33	0.00	-0.23
	25288	0.66	0.00	-0.39
6456	3910	1.05	0.00	0.76
6456	4360	0.40	0.00	0.83

Mean	0.74	0.00	0.07
Std. Dev	0.78	0.00	0.80