Geometric Error Analysis for Shuttle Imaging Spectrometer Experiment

Shyh Jong Wang
Che-Hang Charles Ih

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National Aeronautics and Space Administration
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ABSTRACT

The demand of more powerful tools for remote sensing and management of earth resources has been steadily increasing over the last decade. With the recent advancement of area array detectors, high resolution multichannel imaging spectrometers can be realistically constructed.

This report documents the error analysis study for the Shuttle Imaging Spectrometer Experiment system for the purpose of providing information for design, tradeoff, and performance prediction.

Error sources including the Shuttle attitude determination and control system, instrument pointing and misalignment, disturbances, ephemeris, earth rotation, etc., have been investigated. Geometric error mapping functions were developed, characterized, and illustrated extensively with tables and charts. Selected ground patterns and the corresponding image distortions have been generated for direct visual inspection of how the various error sources affect the appearance of the ground object images.
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I. INTRODUCTION

A. BACKGROUND

Earth resource management and utilization have experienced great success over the last decade through the Landsat programs. In more recent years, both NASA and user communities have envisioned the need for development of better and more powerful instruments for surveying and managing earth resources. The Landsat D's new sensor, Thematic Mapper (TM), the proposed utilization of Tracking and Data Relay Satellite System (TDRSS), and a more advanced ground system represent an advancement in the earth resource satellite development [1].

The Thematic Mapper of the Landsat D (launched in 1982) has seven spectral bands, two more than those of the Multispectral Scanner associated with the earlier Landsats. However, study shows that the reflectance spectrum of earth surface materials contains a significant amount of information which can only be identified with spectral resolution much finer than those of the Thematic Mapper [2]. With the advancement of area array detectors, a push broom imaging spectrometer can be realistically constructed for simultaneous imaging and registration of hundreds of spectral bands. For the case of Shuttle Imaging Spectrometer Experiment, 128 spectral channels have been proposed to cover the spectral range of 0.4 to 1.0 μm for VNIR (visible and near infrared) and 1.0 to 2.5 μm for SWIR (short-wavelength infrared) with instantaneous field of view of 30m. Table 1 shows the required sensor performance [2].

The purpose of this report is to document the error analysis study for the imaging spectrometer experiment. Error analysis is an important aspect of the overall remote sensing system, since errors from many sources, including
the spectrometer itself, the spacecraft that carries the instrument, knowledge limitations on the true spacecraft attitude and locations, earth rotation, curvature, and terrain variations, etc., will all contribute to image distortion, shift, rotation, and misregistration. Error correction or compensation are necessary and are an integral part of the image processing. This work covers the analysis of fundamental and geometric errors and error sensitivities, the development of geometric mapping functions, and the computation of ground

Table 1. Sensor Performance Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
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<tr>
<td>Spectral Coverage</td>
<td>0.4 to 2.5 μm</td>
<td>Although the entire spectrum is probably not required for any one discipline, in the aggregate of all remote sensing disciplines, the entire region is required</td>
</tr>
<tr>
<td>Spectral Sampling Interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VNIR (0.4 to 1.0 μm)</td>
<td>0.01 μm or better</td>
<td>Adequate for most research topics</td>
</tr>
<tr>
<td>SWIR (1.0 to 2.5 μm)</td>
<td>0.02 μm or better</td>
<td></td>
</tr>
<tr>
<td>Instantaneous Field of View</td>
<td>30 m</td>
<td>Adequate for most research topics</td>
</tr>
<tr>
<td>Swath Width</td>
<td>at least 10-12 km</td>
<td>This is adequate for research if pointing capability is provided to assure target access</td>
</tr>
<tr>
<td>Pointing Mirror Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Along track</td>
<td>at least ± 45 deg</td>
<td>Essential for atmospheric and BRDF (Bidirectional Reflectance Distribution Function) Studies</td>
</tr>
<tr>
<td>Cross track</td>
<td>not more than ± 25 deg</td>
<td></td>
</tr>
<tr>
<td>Radiometric Performance (NEdR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VNIR</td>
<td>&lt; 0.5%</td>
<td></td>
</tr>
<tr>
<td>SWIR</td>
<td>&lt; 1.0%</td>
<td></td>
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pattern distortions. The results are translated into many tables, plots, and patterns for visual apprehension. It is believed that the results reported here are important for design, trade-off, and performance prediction.

B. APPROACH

This study has been performed in four progressive stages as shown in block diagram form in Fig. 1. In Stage I, the error sources were identified, dynamic disturbances and the Space Shuttle error dynamics were modeled, and the error power spectral densities for two in-orbit configurations were developed. Stage II of this study concentrated on the development of geometric error mapping functions and error sensitivity analysis. Geometric errors due to ephemeris uncertainties, attitude deviations, earth rotation, etc., were studied. In Stage III, ground pattern image distortions caused by various error effects and forward and side looking angular offsets, altitude change, and effect of earth rotation were generated. Stage IV consists of the analysis of the imaging spectrometer instrument errors. These errors include optical jitter, nonlinearities, processing errors, and repeatability. The study of Stages I, II, and III has been completed and the results are included in this report. The study called for by Stage IV has not been planned. It is emphasized here that the imaging spectrometer error model development is an important step for the overall performance prediction and design of the imaging spectrometer system.

Major findings of this work are summarized in the following subsection. In Section II, the orbital and imaging spectrometer configurations are described. The attitude dynamics and error power spectral densities are documented in Section III; and parametric analysis of geometric errors are treated in Section IV. Section V deals with the ground pattern image distortions. Conclusions are summarized in Section VI.
Figure 1. IS Error Analysis System Block Diagram
C. SUMMARY OF MAJOR FINDINGS

The following is a summary of major findings. The details of these are treated in the sections to follow.

1. The results show that the IS Experiment with image pickup period of 20 seconds at a time is feasible with the shuttle properly phased inside the control deadband. The error PSD (power spectral density) characteristic reveals that the system resonates at very low frequencies (in the $10^{-5}$ to $10^{-2}$ Hz region). Excitations at these frequencies must be avoided through design precautions. The analysis also showed that errors below 0.01 Hz are dominated by the shuttle dynamics reacting to disturbances, whereas those above 0.01 Hz are dominated by the shuttle inertial measurement system uncertainties and its inherent noise. These high frequency errors limit pointing performance and result in a one-sigma ground track error of 54.8 meters per axis. One-sigma rate errors are shown to be less than 4 meters per second per axis in the frequency range of $10^{-5}$ to $4 \times 10^{-2}$ Hz. The image smear is not significant because of the short millisecond-level line time.

2. The effects of earth curvature are very small for the application here (see Fig. 42).

3. Altitude uncertainties cause only moderate geometric errors. The worst 1σ geometric errors are 11.71 m in position and 0.133 m/sec in rate with STDN and large unmodeled perturbations at 200 km orbit. The performance improves with TDRSS. For the 300 km orbit and with small unmodeled perturbations, the 1σ geometric errors will reduce to 0.22 m and 0.0032 m/sec (see Table 11).
4. The effects of other navigation errors are significantly greater. The lo downtrack errors range from 203m (300 km orbit) to 8128m (200 km orbit); and those for the crosstrack are 152m to 508m (see Table 12).

5. The effects of roll and pitch attitude errors are relatively large compared with, for instance, those caused by yaw errors and altitude uncertainties. The error sensitivity is 1.94 m/arc sec or approximately 7000 m/degree. The yaw sensitivity is 0 for 0° view angle and 0.028 m/arc sec for the maximum view angle of ±0.82° (see Table 13).

6. The error sensitivities of attitude errors increase significantly for large attitude offsets. For 20° side looking, the sensitivity increases to 2.28 m/arc sec for roll errors and to 0.75 m/arc sec for yaw errors and the pitch error sensitivity is almost unaffected. For the 45° forward looking case, the sensitivities for the pitch, roll, and yaw errors increase to 2.83, 4.36, and 1.97 m/arc sec, respectively (see Table 13).

7. The performance of the Shuttle Imaging Spectrometer is limited by the Shuttle IMU (Inertial Measuring Unit) accuracy, instrument misalignment, etc., Shuttle RCS (Reaction Control Subsystem) deadband, etc. unless some means of error reduction are employed. For instance, ground control points may be used to reduce navigation prediction errors; and precision point mounts, such as AGS (ASPS* Gimbal System) and IPS (Instrument Pointing System), may be used to reduce the

*Annular Suspension Pointing System
attitude errors.

The single axis geometric errors due to the combined Shuttle/IS misalignment, for instance, for normal nadir pointing, 20° side looking, and 45° forward looking are 169m, 198m, and 379m, respectively (refer to Table 10 for detailed breakdowns).

8. Earth rotation causes shifts of images toward the direction of rotation. The magnitude of this shift depends on the latitude of the object. For instance, at the equator the object moves approximately 462m in one second (for 400 km orbit), and at 60° latitude it moves only 231m in one second.
II. ORBITAL AND IMAGING SPECTROMETER CONFIGURATIONS

A. SHUTTLE NOMINAL FLIGHT CONFIGURATIONS

Two shuttle in-orbit configurations have been considered, the Payload-Bay Nadir and the Nose-Down Nadir, as illustrated in Figures 2 and 3, respectively. It will be shown later that the Nose-Down Configuration is gravity gradient stabilized and the Payload-Bay Nadir Configuration is not. However, the Payload-Bay Nadir Configuration offers simpler instrument mounting and less aerodynamic drag. Besides, for certain experiments that require large forward looking angles, the Nose-Down Configuration will be unsuitable.

A circular orbit of 400 km altitude has been selected for this analysis. This selection is consistent with the SIS-B parameters.*

There are a number of possible instrument mounting options that will affect the pointing and the geometric errors of the instrument. These options include:

a) Direct mount
b) AGS (ASPS Gimbal System) mount
c) IPS (Instrument Pointing System) mount

Since both the AGS and IPS systems are capable of providing precision payload pointing and measurements, the system performance will be improved at the expense of significant extra cost. The direct mount approach is the least complex and most cost effective, provided that the errors are within the tolerance. In this report the direct mount approach is considered. Furthermore, the shuttle IMU

*During the period when this part of the work was performed, SIS-B (Shuttle Imaging Spectrometer-Configuration B) was considered. However, the methods used here are mostly generic, and hence, can be applied to systems of similar configurations.
Figure 2. Payload-Bay Nadir Pointing Configuration (A)

Figure 3. Nose-Down Nadir Pointing Configuration (B)
(Inertial Measurement Unit) and the shuttle state estimator unit are used for obtaining attitude and rate information, without additional instrumentation. Other options may be studied in the future if necessary.

B. IMAGING SPECTROMETER SYSTEM DESCRIPTION

In order to correlate the analysis reported here to the IS applications, it is desirable to understand the basic operating principle of the IS instrument. Figure 4 shows a sketch of the basic elements of the IS, except the memory banks, registers, and the processors. Some of the IS parameters that are relevant to the geometric error analysis, along with definitions of the IS terminologies, are also listed in Fig. 4. It is understood that the sketch and the parameter values used are for illustrative purposes only since the parameters may change as the development of the IS system is finalized.

Referring to Fig. 4, as the reflection from the ground objects passes through a narrow slit, it strikes the incident surface of the prism. The prism separates the incident light into spectral images projected onto an area array of light detectors. The area array consists of 384 linear arrays, corresponding to 384 spectral channels. Each linear array consists of 384 detector elements. Each detector element corresponds to an image area of 30m x 30m on the ground. Hence, each linear array corresponds to an image of a specific spectral channel of the same ground area of 30m (along-track) x 11520m (cross-track). This 11.52 km cross-track measure, referred to as the swath width, defines the IS coverage for each orbit pass. The 30m x 30m area is referred to as the pixel (picture element) which defines the resolution of the image, i.e., within this element no features can be resolved. The IS is operated based on a push broom principle. That is, a specific detector element on the instrument (moving with the spacecraft) collects photons from the 30m x 30m moving window for a specific period.
KEY PARAMETERS
- LINE TIME = 4 ms
- SPECTRUM:
  VISIBLE REGION 0.4 - 1.0 μm
  SHORT WAVELENGTH IR 1.0 - 2.5 μm
- FIELD OF VIEW: ± 0.825°
- SWATH WIDTH: 11.52 km
- POINTING ANGLES (RANGE):
  ± 45° (PITCH)
  ± 20° (ROLL)
- ORBIT: 400 km CIRCULAR

DEFINITIONS
- GIFOV (GROUND INSTANTANEOUS FIELD OF VIEW): PROJECTION ON THE GROUND OF EACH SQUARE DETECTOR
- LINE TIME: TIME TO MOVE ALONG THE GROUND A DISTANCE OF 1 GIFOV
- DN: DATA NUMBER, THE "BRIGHTNESS" OF THE ASSOCIATED PIXEL
- PIXEL: PICTURE ELEMENT (30 m x 30 m HERE, IT DEFINES THE RESOLUTION OF THE IMAGE)
- SWIR: SHORT WAVELENGTH IR
- VIS: VISIBLE WAVELENGTH

Figure 4. Imaging Spectrometer Basic Operating Principles
of time called the line time. The line time in this case is the time required to move 30m along-track, which is determined by the orbit. For a 400 km circular orbit, it is about 4 ms. At the end of each line time, the total number of photons collected by each detector is recorded and processed and the detector/register is reset and a new 4 ms cycle is repeated. For digital processing, the amount of light collected by a collector is assigned a number called DN (data number), which is proportional to the number of photons accumulated. Therefore, the processor has to record and process 384 x 384, or approximately 1.475 x 10^5 DN's every 4 ms.

As the shuttle flies over an area, banks after banks of DN's are collected. By spacing the banks of DN's 30m apart, the features of the ground image emerge. The ratios of the DN's of various channels for the same area are of special interest, as these ratios are closely correlated to geological and ecological states of the earth including mineral deposits, forestry, crops,
disease and insect infestations, land and soil erosion, precipitation in the form of snow and ice, air and water quality, etc.

The Imaging Spectrometer optical system configuration and the arrangement of lenses, mirrors, slit, prisms, focal plane detector, etc. are shown in Fig. 5 [2]. Additional information on the instrument design and requirements can be found in Refs. 2 and 3.
III. ERROR SOURCES AND SHUTTLE ATTITUDE DYNAMICS

A. ERROR SOURCES

There are two types of errors that are important to the imaging spectrometer experiment — the direct errors and the derived errors. The direct errors are those pertaining to the spacecraft and instrument pointing, ephemeris, and instrument errors as shown in Fig. 6. The derived errors are the geometric errors and pattern distortions of ground objects which result from the direct errors and the effects of earth rotation, curvature, oblateness, and local vertical uncertainties. Fig. 1 shows relationships of the error sources and the system dynamics.

- Attitude deviations, rate errors and structural vibration
- Measurement noise and drift
- Misalignment of shuttle imu and attitude reference frame
- Misalignment between shuttle and IS instrument references
- Ephemeris prediction errors
- Earth rotation, curvature, and oblateness
- IS instrument errors including
  - Optical jitter
  - Nonlinearities
  - Processing
  - Repeatability

Figure 6. Error Sources
In this section, the steady state analysis is performed in the frequency domain. The PSD (power spectral density) for the pointing errors and the rate errors were obtained by considering the dynamics of the Space Shuttle Orbiter, the IMU (Inertial Measurement Unit), the attitude control state estimator, the measurement noise, the misalignment of reference frames, and the disturbances including gravity gradient, gyroscopic torques, and aero-dynamic drag torques.

B. SHUTTLE MASS PROPERTY

The shuttle mass properties employed here were obtained from the Shuttle Operational Data Book [4] for OV-102/STS-3. The mass and the c.m. are, respectively:

Shuttle mass: 102,153.73 kg (224,738.21 lbs)

Shuttle c.m.: \( X_o = 1105.5", Y_o = 0", Z_o = 374.3" \)

where the coordinates \( X_o, Y_o, \) and \( Z_o \) are the Orbiter Coordinates [5] defined in Figure 7. The moment of inertia matrix (kg-m^2) is, in the shuttle body frame (refer to Fig. 8),

\[
I_B = \begin{bmatrix}
1.36 \times 10^6 & -4.69 \times 10^3 & -3.49 \times 10^5 \\
-4.69 \times 10^3 & 1.00 \times 10^7 & -3.32 \times 10^3 \\
-3.49 \times 10^5 & -3.32 \times 10^3 & 1.05 \times 10^7 \\
\end{bmatrix}
\]

\[
I_B = \begin{bmatrix}
1.36 \times 10^6 & 0 & -3.49 \times 10^5 \\
0 & 1.00 \times 10^7 & 0 \\
-3.49 \times 10^5 & 0 & 1.05 \times 10^7 \\
\end{bmatrix}
\]  

(i)

The magnitude of the off-diagonal terms of the inertia matrix \( I_B \) suggests strong couplings exist especially between the \( X_o \) and the \( Z_o \)-axis. To simplify the dynamic equations, it is convenient to consider principal-axis
ORBITER COORDINATES

TYPE: Rotating, Orbiter referenced

ORIGIN: Approximately 200 inches (5.1m) ahead of the nose and approximately 400 inches (10.2m) below the centerline of the cargo bay.

ORIENTATION AND LABELING:

The X-axis is parallel to the centerline of the cargo bay, negative in the direction of launch.

The Z-axis is positive upward in landing attitude.

The Y-axis completes the right-handed system.

The standard subscript is 0.

Figure 7. Orbiter Coordinate System
pointing instead of body-axis pointing, e.g., pointing \(-Z_p\) rather than \(-Z_B\) as illustrated in Figure 8.

![Diagram of Shuttle Body and Principal Coordinates](image)

\[
(X_B, Y_B, Z_B) \quad \text{--- Shuttle Body Coordinates}
\]

\[
(X_p, Y_p, Z_p) \quad \text{--- Shuttle Principal Axes}
\]

**Figure 8.** Shuttle Body and Principal Coordinates (Payload-Bay Nadir Pointing Shown)

The orientations of the principal axes can be determined by rotating the body frame an angle \(\alpha\) about the \(Y_B\)-axis, i.e., let \(B: X_B \rightarrow X_p\), then

\[
B = \begin{bmatrix}
\cos\alpha & 0 & -\sin\alpha \\
0 & 1 & 0 \\
\sin\alpha & 0 & \cos\alpha
\end{bmatrix}
\]  \hspace{1cm} (2)

and

\[
I_p = B I_B B^T
\]  \hspace{1cm} (3)

It can be shown that
\[
\alpha = \frac{1}{2} \tan^{-1} \left( \frac{-2 I_{BZX}}{I_{BZZ} - I_{BXX}} \right)
\]  \hspace{1cm} (4)

provided that \( I_{BXY} = I_{BYZ} = 0 \).

For \( I_{BXX} = 1.36 \times 10^6 \text{ kgm}^2 \), \( I_{BZZ} = 1.05 \times 10^7 \text{ kgm}^2 \), and \( I_{BZX} = 3.49 \times 10^5 \text{ kgm}^2 \), the angle \( \alpha = -2.18^\circ \). Therefore, in order to do principal-axis nadir pointing, the shuttle has to rotate 2.18° about the orbit normal (see Figure 8). The moments of inertia about the principal axes are

\[
I_p = \text{diag} \left( 1.38 \times 10^6, 1.00 \times 10^7, 1.05 \times 10^7 \right) \text{ kgm}^2.
\]

C. ASSESSMENT OF DISTURBANCES

The shuttle motion is characterized in part by the environmental disturbances, the major sources of which are the aerodynamic drag, gravity gradient, gyroscopic effect, solar radiation, and on-board causes such as astronaut activities, equipment vibrations, and venting. On-board activities may be partially eliminated or reduced through mission planning and their effects will be assessed in the future. In this subsection, the gyroscopic torques, the gravity gradient torques, and the aerodynamic drag torques are estimated. The solar pressure is at least one order of magnitude less than the aerodynamic drag forces and, hence, it is not included in this analysis.

C.1 The Aerodynamic Drag Torques

To estimate the aerodynamic drag torques, an approach referred to as the three-plate model [6] has been used. Referring to Figure 9, let \( \vec{n}_1, \vec{n}_2, \) and \( \vec{n}_3 \) be the unit normal vectors for the equivalent plates 1, 2, and 3.

where \( \vec{n}_1, \vec{n}_2, \) and \( \vec{n}_3 \) are in the direction of \( X_B, Y_B, \) and \( Z_B \)-axis, respectively.

To express \( \vec{n}_4 \) in body frame,
Let $A_1$, $A_2$, and $A_3$ be the corresponding areas on which the aerodynamic pressure applies, and $\overline{c}_{p1}$, $\overline{c}_{p2}$, and $\overline{c}_{p3}$ the three corresponding centers of pressure, respectively. The model assumes that the aerodynamic force applies to each area in the direction opposite to the vehicle velocity vector and assumes no shading among the plates. It is further assumed that the drag coefficient $C_D$ is constant and the lift coefficient $C_L$ is zero.

Let $\overline{v}_B = (v_{B1}, v_{B2}, v_{B3})^T$ be the inertial velocity vector in the body frame, with magnitude $v$. The force and torque applied on $A_1$ are

$$
\overline{F}_{B1} = -\left(\frac{1}{2} C_D \rho \overline{v}^2 A_1\right) (\overline{n}_1, \overline{u}_B) |\overline{u}_B|
$$

(6)

$$
\overline{r}_{B1} = \overline{F}_{B1} \times \overline{r}_{B1} = -\left(\frac{1}{2} C_D \rho \overline{v}^2 A_1\right) (\overline{n}_1, \overline{u}_B) |\overline{r}_{B1} \times \overline{u}_B|
$$

(7)

where $\rho$ is the atmospheric density at the orbital altitude, $\overline{u}_B = \overline{v}_B/v$ the unit velocity vector, and $r_{B1}$ the vectors of the center of pressure of $A_1$ relative to the vehicle center of mass.
The total aerodynamic forces and torques on the vehicle are

\[
\bar{F}_B = \sum_{i=1}^{3} - \left( \frac{1}{2} C_D \rho v^2 A_i \right) |(\bar{u}_i, \bar{u}_B)| \bar{u}_B \\
\bar{T}_B = \sum_{i=1}^{3} - \left( \frac{1}{2} C_D \rho v^2 A_i \right) |(\bar{u}_i, \bar{u}_B)| \bar{r}_{Bi} \times \bar{u}_B
\]

(8) (9)

The value of \( C_D \) depends on the shape of the vehicle. In Ref. 7, the values of 2.5 to 3.0 were suggested. The value of \( C_D = 2.0 \) is used here as it was used in Ref. 6 for Space Shuttle Simulation.

The atmospheric mass density \( \rho \) can be found in a JPL internal memorandum. For 1985 mission time, the peak density is expected to occur in April for the 400 km orbit; the densities are

\[ 2.64 \times 10^{-12} \text{ kg/m}^3 \quad \text{(predicted)} \]

and

\[ 3.77 \times 10^{-12} \text{ kg/m}^3 \quad \text{(97.7 percentile)} \]

The orbital velocity \( v \) for a 400 km circular orbit is computed as

\[ v = 7669.60 \text{ m/sec or } v^2 = 5.882 \times 10^7 \text{ (m/sec)}^2. \]

The plate areas, according to the attachment (SSFS On-Orbit Aero Data, 7/24/80) to Ref. 6, with Cargo Bay doors open, are

\[ A_1 = 119.45 \text{ m}^2 \]
\[ A_2 = 229.92 \text{ m}^2 \]
\[ A_3 = 454.46 \text{ m}^2 \]

(10)

However, a different set of values are given in Ref. 8.

\[ A_1 = 64.1 \text{ m}^2 \]
\[ A_2 = 212.7 \text{ m}^2 \]
\[ A_3 = 367.0 \text{ m}^2 \]

(11)
The values in (10) were used in this work.

The position vectors $\overline{r}_{B1}$ may be obtained using data given in Ref. 4 and Ref. 6. The values are,

\[
\overline{r}_{B1} = \begin{bmatrix} 3.797 \\ 0 \\ -0.231 \end{bmatrix} \text{ m}
\]

\[
\overline{r}_{B2} = \begin{bmatrix} 0.927 \\ 0 \\ -0.742 \end{bmatrix} \text{ m}
\]

\[
\overline{r}_{B3} = \begin{bmatrix} 1.166 \\ 0 \\ -1.074 \end{bmatrix} \text{ m}
\]

The torques $\overline{\tau}_{B1}$ for the predicted density, are

\[
\overline{\tau}_{B1} = -1.855 \times 10^{-2} |u_{B1}| \begin{bmatrix} -r_{B13}u_{B2} + r_{B12}u_{B3} \\ r_{B13}u_{B1} + r_{B11}u_{B3} \\ -r_{B12}u_{B1} + r_{B11}u_{B2} \end{bmatrix}
\]

\[
\overline{\tau}_{B2} = -3.570 \times 10^{-2} |u_{B2}| \begin{bmatrix} -r_{B23}u_{B2} + r_{B22}u_{B3} \\ r_{B23}u_{B1} - r_{B21}u_{B3} \\ -r_{B22}u_{B1} + r_{B21}u_{B2} \end{bmatrix}
\]

\[
\overline{\tau}_{B3} = -7.057 \times 10^{-2} |u_{B3}| \begin{bmatrix} -r_{B33}u_{B2} + r_{B32}u_{B3} \\ r_{B33}u_{B1} - r_{B31}u_{B3} \\ -r_{B32}u_{B1} + r_{B31}u_{B2} \end{bmatrix}
\]
In Eq. (13), the torques are known once the unit velocity vector $\overrightarrow{u}_B$ is specified; $\overrightarrow{u}_B$ varies with the pointing configuration and spacecraft attitude.

C.1.1. Drag Torques for Configuration A

Referring to Fig. 2, since this is "-Zp" pointing, for nominal attitude, the vehicle moves in the Xp direction. Let $\overrightarrow{u}_p$ be the unit velocity vector in the P-frame and let $A_α$ be the rotation matrix due to $α$, then

$$\overrightarrow{u}_B = A_α^T \overrightarrow{u}_p = \begin{bmatrix} \cosα & 0 & \sinα \\ 0 & 1 & 0 \\ -\sinα & 0 & \cosα \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

(14)

Since $α(= -2.18^0 = -0.038 \text{ rad})$ is small,

$$\overrightarrow{u}_B = \begin{bmatrix} 1 \\ 0 \\ -α \end{bmatrix}$$

(15)

Using Eqs. (12), (13), and (15), and

$$\overrightarrow{T}_p = \sum_{i=1}^{3} A_α \overrightarrow{T}_{Bi}$$

(16)

the torques in the P-Frame, for nominal attitude, are

$$\overrightarrow{T}_p = \begin{bmatrix} 0 \\ 9.84 \times 10^{-3} \\ 0 \end{bmatrix} \text{ N-m}$$

(17)

For small attitude errors, $ϕ$, $θ$, and $ψ$, from the rotating orbital frame,

$$\overrightarrow{u}_p = A \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

(18)
where,

\[
A = \begin{bmatrix} 1 & \psi & -\theta \\ -\psi & 1 & \phi \\ \theta & -\phi & 1 \end{bmatrix}
\]

and

\[
\vec{u}_B = A^T \vec{u}_a = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
\]

Using Eqs. (12), (13), and (20), the predicted aerodynamic torques become, by retaining only the first order terms, in N-m,

\[
\vec{T}_p = \sum_{i=1}^{3} A_{\alpha} \vec{T}_{B1}
\]

\[
= \begin{bmatrix} 4.29 \times 10^{-3} \psi \\ 4.29 \times 10^{-3} + 7.04 \times 10^{-2} (\theta - \alpha) + 7.58 \times 10^{-2} |\theta - \alpha| + 2.65 \times 10^{-2} |\psi| \\ 7.04 \times 10^{-2} \psi \end{bmatrix}
\]

C.1.2. Drag Torques for Configuration B

Referring to Figure 3, under this configuration, \( X_p \) is in the Nadir direction and \( Y_p \) is in the direction of motion for nominal attitude. In this case,

\[
\vec{u}_p = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]

\[
\vec{u}_B = A^T \vec{u}_a = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]

and from Eqs. (12), (13), and (23),

\[
\vec{T}_p = \sum_{i=1}^{3} A_{\alpha} \vec{T}_{B1}
\]
In the presence of small attitude errors, $\phi$, $\theta$, and $\psi$, the aero-
dynamic drag torques are

$$\overline{T}_p = \begin{bmatrix}
-3.96 \times 10^{-2} \\
0 \\
-4.53 \times 10^{-2}
\end{bmatrix} \text{ N-m} \quad (24)$$

$$\overline{T}_p = \begin{bmatrix}
-2.45 \times 10^{-2} - 7.58 \times 10^{-2}|\phi| - 4.29 \times 10^{-3}|\phi| + 3.31 \times 10^{-2}a \\
-3.31 \times 10^{-2}\phi + 2.65 \times 10^{-2}\psi \\
-(3.31 \times 10^{-2} + 8.23 \times 10^{-2}|\phi| + 7.04 \times 10^{-2}|\psi| + 2.65 \times 10^{-2}a)
\end{bmatrix} \quad (25)$$

C.1.3. Estimation of Disturbance PSD

Before the PSD’s are estimated, the uncertainty part of the distur-
bance torques has to be determined. The torques of Eqs. (21) and (25) consist
of static parts and the dynamic parts. The dynamic parts are functions of the
attitude errors $\phi$, $\theta$, and $\psi$. The attitude errors are assumed to be random and time-
varying with standard deviation of $1^\circ$ (0.01745 rad.) per axis. Therefore, the
estimated values of the random disturbance torques are, for Configuration A

$$\overline{\sigma}_T = \begin{bmatrix}
7.48 \times 10^{-5} \\
1.86 \times 10^{-3} \\
1.23 \times 10^{-3}
\end{bmatrix} \text{ N-m} \quad (26)$$

and that for Configuration B are,

$$\overline{\sigma}_T = \begin{bmatrix}
1.33 \times 10^{-3} \\
7.40 \times 10^{-4} \\
1.89 \times 10^{-3}
\end{bmatrix} \text{ N-m} \quad (27)$$

and the corresponding PSD’s are obtained by the following approximation with
the correlation time of $T = 180$ seconds,

$$Q_{T_{PA}} = 2T (\overline{\sigma}_T^2)_{T_{PA}}$$
The Gravity Gradient Torques and Gyroscopic Torques

The gravity gradient torques and the gyroscopic torques can be estimated using the following equations, respectively:

\[ \mathbf{T}_{\text{GRP}} = 2T \mathbf{\bar{Q}}_{\text{PB}} \]
\[ \mathbf{\bar{Q}}_{\text{PB}} = \begin{bmatrix} 2.01 \times 10^{-6} \\ 1.25 \times 10^{-3} \\ 5.44 \times 10^{-4} \end{bmatrix} (\text{N-m})^2 \cdot \text{sec} \quad (28) \]
\[ \mathbf{T}_{\text{GEP}} = 3 \mathbf{\omega}^2 \mathbf{u}_{\text{RP}} \mathbf{I}_F \mathbf{\bar{u}}_{\text{RP}} \]
\[ \mathbf{\bar{u}}_{\text{RP}} = \begin{bmatrix} 6.32 \times 10^{-6} \\ 1.97 \times 10^{-6} \\ 1.29 \times 10^{-3} \end{bmatrix} (\text{N-m})^2 \cdot \text{sec} \quad (29) \]

C.2 The Gravity Gradient Torques and Gyroscopic Torques

The gravity gradient torques and the gyroscopic torques can be estimated using the following equations, respectively:

\[ \mathbf{\bar{T}}_{\text{GRP}} = \mathbf{\omega}_{\text{OP}} \times \mathbf{H}_F = \mathbf{\omega}_{\text{OP}} \mathbf{I}_F \mathbf{\omega}_{\text{OP}} \]
\[ \mathbf{\bar{T}}_{\text{GEP}} = 3 \mathbf{\omega}^2 \mathbf{u}_{\text{RP}} \mathbf{I}_F \mathbf{\bar{u}}_{\text{RP}} \]

Where \( \mathbf{\bar{u}}_{\text{RP}} \) and \( \mathbf{\omega}_{\text{OP}} \) are the unit earth vector and the spin velocity vector, respectively, in principal frame, and \( \mathbf{\bar{u}}_{\text{RP}} \) is the skew symmetric matrix of the vector \( \mathbf{\bar{u}}_{\text{RP}} \). For Configuration A,

\[ \mathbf{\bar{u}}_{\text{RP}} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]

and for Configuration B,

\[ \mathbf{\bar{u}}_{\text{RP}} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \]

\[ \mathbf{\omega}_{\text{OP}} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \]

and for Configuration B,
the corresponding torques, to include only the first order effect, are, for

Configuration A

\[
\overrightarrow{\tau}_{gP} = 3 \omega_o^2 \begin{bmatrix}
(I_{PZZ} - I_{PYY}) \phi \\
(I_{PZZ} - I_{PXX}) \theta \\
0
\end{bmatrix} = \begin{bmatrix}
1.92 \phi \\
33.11 \theta \\
0
\end{bmatrix} \text{ N-m} \quad (34a)
\]

\[
\overrightarrow{\tau}_{GRP} = \omega_o^2 \begin{bmatrix}
-(I_{PZZ} - I_{PYY}) \phi \\
0 \\
(I_{PYY} - I_{PXX}) \psi
\end{bmatrix} = \begin{bmatrix}
-.64 \phi \\
0 \\
11.04 \psi
\end{bmatrix} \quad (34b)
\]

and for Configuration B

\[
\overrightarrow{\tau}_{gP} = -3 \omega_o^2 \begin{bmatrix}
0 \\
(I_{PZZ} - I_{PXX}) \theta \\
(I_{PXX} - I_{PYY}) \psi
\end{bmatrix} = \begin{bmatrix}
0 \\
-35.03 \theta \\
43.71 \psi
\end{bmatrix} \quad (35a)
\]

\[
\overrightarrow{\tau}_{GRP} = \omega_o^2 \begin{bmatrix}
-(I_{PZZ} - I_{PYY}) \phi \\
(I_{PZZ} - I_{PXX}) \theta \\
0
\end{bmatrix} = \begin{bmatrix}
-.64 \phi \\
11.68 \theta \\
0
\end{bmatrix} \quad (35b)
\]

Since the gravity gradient torques and gyroscopic torques are proportional to the attitude errors, they may be included in the equations of motion.

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as part of the vehicle dynamics rather than disturbances to the plant.

D. THE MISALIGNMENT AND MEASUREMENT NOISE

In this subsection, the errors that will contribute to pointing uncertainties are estimated. These error sources include the misalignment errors of the IMU and the IS instrument, and the sensor noise.

D.1 The Misalignment Errors

Let $b_{MS}$ be the misalignment between the IMU and the shuttle reference frame; let $b_{SI}$ be the misalignment between the shuttle and the imaging spectrometer reference frame.

Based on the space shuttle performance requirement [5], the IMU $3\sigma$ misalignment uncertainty is $\pm 133^\circ/axis$, hence,

$$\sigma_{b_{MS}} = 0.044^\circ/axis = 159.6 \text{ arc-sec/axis}$$

However, based on a JPL internal memorandum, the shuttle flight test performance is much better,

$$\sigma_{b_{MS}} = 82 \text{ arc-sec/axis}$$

The performance data Eq. (36b) was used in this report.

The misalignment data for the IS instrument is not directly available. Based on Ref. 9, the estimated LANDSAT D initial alignment bias between the sensor optical axis and the vehicle pointing vector was $\pm 200$ arc-sec. The alignment bias can be measured before launch and can be removed from the image data. The variation part that cannot be removed without ground control points was estimated as $\pm 30$ arc-sec. This latter number was used in this work,

$$\sigma_{b_{SI}} = 30 \text{ arc-sec.}$$

Therefore, the total misalignment error becomes

$$\sigma_b = (\sigma_{b_{MS}}^2 + \sigma_{b_{SI}}^2)^{1/2}$$

$$= 87.32 \text{ arc-sec.}$$
D.2 The IMU Model

The sensor dynamics for the shuttle IMU was modeled approximately by the first order low pass filter as shown in Figure 10.

\[
\frac{1}{1 + \tau s}
\]

Figure 10. Simplified IMU Model

Where \( \tau \) is the time constant and \( v \) the white gaussian noise. The time constant was estimated from a DRIRU II Model,

\[
\tau = \frac{1}{\omega_s} = \frac{1}{14\pi} = .023 \text{ sec}
\]  \hspace{1cm} (39)

That is, this measurement is assumed to have a 7 Hz bandwidth.

To determine \( v \), from Ref. 5, the 3\( \sigma \) IMU readout error is \( \pm .073^\circ/\text{axis} \).

Assume that the measurement noise is the readout error, then

\[
\sigma_v = .0243^\circ/\text{axis} = 87.6 \text{ arc-sec/axis}
\]  \hspace{1cm} (40)

However, the actual performance of the shuttle IMU was much better; it has a 1\( \sigma \) gyro resolution error (\( \sigma_{\text{RESO}} \)) of 20 arc-sec/axis. If we assume the random noise has the same amplitude as that of the resolution noise, then

\[
\sigma_v = \sqrt{2} \sigma_{\text{RESO}}
\]  \hspace{1cm} (41)

The corresponding measurement noise PSD, \( R \), is estimated as,

\[
R = \frac{1}{2(14\pi)} \sigma_v^2 = 8.55 \times 10^{-10} \text{ (rad)}^2 \text{ -sec}
\]  \hspace{1cm} (42)
E. SHUTTLE DYNAMICS AND INSTRUMENT POINTING ERRORS

E.1 The Equations of Motion

Consider Configuration A. For simplicity, the subscript P for principal axes is dropped from all equations. Again, let $\phi$, $\theta$, and $\psi$ be the small roll, pitch, and yaw angles, respectively. Let $\vec{\omega} = (\omega_x, \omega_y, \omega_z)^T$ be the angular velocity vector of the shuttle, then for small attitude errors,

$$\begin{align*}
\dot{\omega}_x &= \dot{\phi} + \dot{\psi} \omega_o \\
\dot{\omega}_y &= \dot{\theta} + \omega_o \\
\dot{\omega}_z &= \dot{\psi} + \dot{\phi} \omega_o
\end{align*}$$

(43)

and

$$\begin{align*}
\ddot{\omega}_x &= \ddot{\phi} + \dot{\psi} \omega_o \\
\ddot{\omega}_y &= \ddot{\theta} \\
\ddot{\omega}_z &= \ddot{\psi} + \dot{\phi} \omega_o
\end{align*}$$

(44)

With this simplified relation between the inertial rates and the attitude error rates, one can show that the equations of motion may be summarized as follows, accounting only for first order effects:

$$\begin{bmatrix}
L_x \ddot{\phi} + (I_x - I_y + I_z) \omega_o \dot{\psi} + 4 (I_y - I_z) \omega_o^2 \phi \\
L_y \ddot{\theta} + 3 (I_x - I_z) \omega_o^2 \theta \\
L_z \ddot{\psi} - (I_x - I_y + I_z) \omega_o \dot{\phi} - (I_x - I_y) \omega_o^2 \psi
\end{bmatrix} = \bar{T}_d + \bar{T}_c$$

(45)

The left-hand side of Eq. (45) accounts for the body dynamics and the gravity gradient and the gyroscopic torques; and on the right-hand side of Eq. (45) $\bar{T}_d$ and $\bar{T}_c$ are the disturbance torques and the control torques, respectively.

E.2 The Space Shuttle State Estimator

The Shuttle State Estimator consists of two parallel Kalman-type filters, one for acceleration estimation and one for rate estimation [10]. The attitude estimate is the extrapolation of the measured attitude and the rate estimate may be approximated by using a second order filter with parameters...
determined by the filter gains. With the current baseline filter data, the equivalent damping coefficient and the corner frequency for the rate filter are .8 and .04 Hz (for vernier rate filter), respectively [11].

E.3 The System Pointing Errors

E.3.1. The Pitch Loop (Configuration A)

From Eq. (45) and ignoring the initial conditions, one has the following output function,

\[ \theta(S) = \frac{1}{I_X S^2 + 3\omega_o^2 (I_X - I_Z)} (T_{dY} + T_{cY}) \]  (46)

Figure 11 shows the open-loop block diagram for the dynamics of the instrument pointing error excited by the random disturbances. Included in the diagram are the dynamics of the vehicle, the IMU, and the rate filter. Measurement error and the misalignment error are also included.

E.3.7. The Roll and Yaw Loops (Configuration A)

The output equations for the coupled roll and yaw dynamics are, from Eq. (45)

\[
\begin{bmatrix}
\phi(S) \\
\psi(S)
\end{bmatrix} = \frac{1}{D(S)} \begin{bmatrix}
I_Z S^2 + \omega_o^2 (I_Y - I_X) & -\omega_o (I_X - I_Y + I_Z) S \\
\omega_o (I_X - I_Y + I_Z) S & I_X S^2 + 4\omega_o I_Y - I_Z)
\end{bmatrix} \begin{bmatrix}
T_X \\
T_Z
\end{bmatrix} \]  (47)

where

\[ D(S) = I_X I_Z S^4 + \omega_o^2 (I_X + I_Y^2 + 3 I_Y I_Z - 3 I_Z^2) S^2 + 6\omega_o^4 (I_Y - I_X) (I_Y - I_Z) \]  (48)

and

\[ T_X = T_{cX} + T_{dX} \]  \hspace{1cm} (49a)

\[ T_Z = T_{cZ} + T_{dZ} \]  \hspace{1cm} (49b)

Figure 12 shows the block diagram for the roll and yaw instrument error dynamics. The block diagrams for the pitch and the roll-yaw loops are similar except for
the coupling terms for the roll and yaw axes.

\[
T_{dy} = \frac{1}{I_YS^2 + 3\omega_o^2(I_x - I_z)}
\]

\[
\frac{1}{\tau S + 1}
\]

\[
\frac{S \omega_x^2}{S^2 + 2\tau \omega_x S + \omega_x^2}
\]

\[
\delta_I
\]

Figure 11. Pitch-Axis Block Diagram (Configuration A)

E.4 The Instrument Pointing Error PSD

E.4.1 The Pitch Error PSD (Configuration A)

The PSD's for the pitch-axis instrument pointing error and the rate error are,

\[
P_\theta(\omega) = F_\theta^*(\omega) F_\theta(\omega) Q_Y + R + \sigma_{bo}^2 \delta(\omega)
\]

\[
P_\delta(\omega) = (F_\delta^*(\omega) F_\delta(\omega) Q_Y + R) H_r^*(\omega) H_r(\omega)
\]

where \(Q_Y = Q_{TPA}^Y\) and \(Q_{TPA}^Y\) is the second component of Eq. (28), and where \(R\), and \(\sigma_{bo}\) are defined in preceding sections, and \(\delta(\omega)\) is the Dirac delta function; and where,

\[
F_\theta(\omega) = G_\theta(\omega) H(\omega)
\]

\[
G_\theta(\omega) = \left[ \frac{1}{I_YS^2 + 3\omega_o^2(I_x - I_z)} \right]_{S=j\omega}
\]

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Figure 12. Roll and Yaw Axes Block Diagram. (Configuration A)
The output power spectral density for the system is closely related to the frequency response of the system, which characterizes the steady state dynamics of the system, and, hence, it is meaningful only if the system is stable. Unfortunately, in Eq. (52b), $I_x < I_z$ which implies that the system is unstable. The destabilizing term comes from the gravity gradient because the nadir pointing axis is not the axis of minimum inertia. To proceed, one has to consider the gravity gradient as external disturbance rather than a part of the dynamics. Figure 13 shows the instrument pointing error PSD in (rad)$^2$-sec as a function of frequency in Hz. Figure 14 shows the rate error PSD in (rad/sec)$^2$-sec as a function of frequency.

E.4.2. The Roll and Yaw Error PSD (Configuration A)

The instrument pointing error PSD's for the roll and yaw axes are,

$$P_\phi (\omega) = F_\phi^* (\omega) F_\phi (\omega) Q_\phi + F_\psi^* (\omega) F_\psi (\omega) Q_\psi + R + \sigma_{bo}^2 \delta(\omega)$$  \hspace{2cm} (53a)

$$P_\psi (\omega) = F_\psi^* (\omega) F_\psi (\omega) Q_\psi + F_\phi^* (\omega) F_\phi (\omega) Q_\phi + R + \sigma_{bo}^2 \delta(\omega)$$  \hspace{2cm} (53b)

and the instrument pointing rate error PSD's for the roll and yaw axes are,

$$P_\phi^* (\omega) = [F_\phi^* (\omega) F_\phi (\omega) Q_\phi + F_\psi^* (\omega) F_\psi (\omega) Q_\psi + R] H_\phi^* (\omega) H_\phi (\omega)$$  \hspace{2cm} (54a)
\[ P_x^r(\omega) = [F_{\psi}^*(\omega) F_{\psi}^r(\omega) Q_x^r + F_{\phi \psi}^*(\omega) F_{\psi}^r(\omega) Q_x + R] H_{\psi}^r(\omega) H_x^r(\omega) \] (54b)

Where

\[ F_{\psi}^r(\omega) = G_{\psi}^r(\omega) H(\omega) \] (55a)

\[ G_{\psi}^r(\omega) = \left[ \frac{I_z S^2 + \omega_0^2 (I_y - I_x)}{D(S)} \right] s = j\omega \] (55b)

\[ F_{\phi \psi}^r(\omega) = G_{\phi \psi}^r(\omega) H(\omega) \] (56a)

\[ G_{\phi \psi}^r(\omega) = \left[ \frac{\omega_0 (I_x - I_y + I_z)}{D(S)} \right] s = j\omega \] (56b)

\[ F_{\psi}^r(\omega) = G_{\psi}^r(\omega) H(\omega) \] (57a)

\[ G_{\psi}^r(\omega) = \left[ \frac{I_x S^2 + 4\omega_0^2 (I_y - I_z)}{D(S)} \right] s = j\omega \] (57b)

and \( Q_x \) and \( Q_z \) are the first and the third components of \( \overline{Q}_{TPA} \) in Eq. (28).

For the same reason discussed earlier, the roll and yaw dynamics are also unstable (referring to Eq. (48), \( D(s) \) has roots in the right-half complex plane). The PSD's for this case are obtained again by treating gravity gradient and gyroscopic torques as disturbances. Figures 13 and 14 show the roll and yaw power spectral densities.

E.4.3. The Error PSD's for Configuration B

The stability problem may be resolved by reorienting the shuttle from payload-bay nadir (Configuration A) to nose-down nadir (Configuration B). The advantage of this new configuration is that it is a gravity gradient stabilized system. However, there are drawbacks for this configuration. First, it will require a larger support-tower for the IS instrument, and the second drawback is that the aerodynamic forces and torques have increased significantly over the payload-bay nadir case.
Figure 13. Instrument Pointing Error PSD, (rad)²-sec

Figure 14. Instrument Pointing Rate Error, (rad/sec)²-sec
To obtain the error power spectral density for Configuration B, it is only necessary to replace \( \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_A \) and the corresponding notations of the equations in this section by \( \begin{bmatrix} Y \\ Z \\ -X \end{bmatrix}_B \). That is, for instance, Eq. (52b) becomes,

\[
G_\theta(\omega) = \frac{1}{I_Z S^2 + 3 \omega^2 (I_Y - I_X)} \sin^2 \omega
\]  

(58)

where \( G_\theta(\omega) \) here still represents the pitch dynamics. Since \( I_Y > I_X \), Eq. (58) is stable.

The instrument pointing error PSD's are shown in Figure 15 and the rate error PSD's are illustrated in Figure 16.

The computer programs that are used for generating these results are included in Appendices C and D.

F. SUMMARY OF MAJOR FINDINGS

F.1 The Major Environmental Disturbances

The major disturbance sources that are modeled are the aerodynamic drag torques, the gravity gradient torques, and the gyroscopic torques. The unmodeled disturbances are the solar pressure torques, the on-board equipment vibrations, crew motions, and venting. Table 2 shows the static disturbance torques in N-m and the stochastic torque PSD's in (N-m)^2/sec for both Configurations A and B with a circular orbit of 400 km altitude.

F.2 The Measurement Uncertainties

The modeled measurement uncertainties are summarized in Table 3.

F.3 Ground Track Errors and Navigation Uncertainties

The power spectral densities for the ground track errors and the rate errors due to instrument pointing uncertainties for Configurations A and B are shown in Figure 17. It is important to note that strong resonances occur within
the frequency band of $10^{-5}$ Hz to $10^{-3}$ Hz. The ground track errors at higher frequencies, .01 Hz and above, are dominated by the measurement noise. Recall that the $1\sigma$ measurement noise is 28.28 arc-sec/axis. The corresponding ground track error is 54.84 m/axis or 77.56 m/lateral motion.

The $3\sigma$ ground track errors due to navigational uncertainties are about one order of magnitude greater than the attitude errors with the aid of TDRSS; and the error is greater with STCN as indicated in Table 4 [12]. Note that the values tabulated in Table 3 are the $3\sigma$ rms values.
Figure 15. Instrument Pointing Error PSD, (rad)²/sec

Figure 16. Instrument Pointing Rate Error, (rad/sec)²/sec
### Table 2. Modeled Environmental Disturbances

<table>
<thead>
<tr>
<th>Sources</th>
<th>Static, N-m</th>
<th>Stochastic -- PSD, (N-m)$^2$-sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_p$</td>
<td>$Y_p$</td>
</tr>
<tr>
<td>Aerodynamic Drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drag Torques</td>
<td>Config. A</td>
<td>0</td>
</tr>
<tr>
<td>Config. B</td>
<td>$-2.78 \times 10^{-2}$</td>
<td>0</td>
</tr>
<tr>
<td>Gravity Gradient and Gyroscopic Torques</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 3. Modeled Measurement Uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>Performance (1σ)</th>
<th>Requirement (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU/Shuttle Misalignment</td>
<td>82 arc-sec</td>
<td>160 arc-sec</td>
</tr>
<tr>
<td>IMU Resolution</td>
<td>20 arc-sec</td>
<td>20 arc-sec</td>
</tr>
<tr>
<td>IMU Noise</td>
<td>(20) arc-sec</td>
<td>-</td>
</tr>
<tr>
<td>IMU Derived Rate</td>
<td>-</td>
<td>Dynamic model</td>
</tr>
<tr>
<td>Rate Gyro</td>
<td>-</td>
<td>60 arc-sec/sec</td>
</tr>
<tr>
<td>Shuttle/IS Misalignment (1σ)</td>
<td>30 arc-sec</td>
<td></td>
</tr>
</tbody>
</table>
Figure 17. IS Ground Track Error and Rate Error PSD
Figure 17. (Continued)
Table 4. Expected On-Orbit Navigation Accuracies (30)

<table>
<thead>
<tr>
<th>CASE</th>
<th>NAVIGATION TRACKING SYSTEM</th>
<th>UNMODELED PERTURBATION</th>
<th>MINIMUM PERIGEE n.mi.</th>
<th>POSITION, FEET</th>
<th>VELOCITY, FPS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RADIAL</td>
<td>DOWNTRACK</td>
</tr>
<tr>
<td>1</td>
<td>STDN*</td>
<td>NOMINAL</td>
<td>105</td>
<td>5,000</td>
<td>34,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TDRSS**</td>
<td>105</td>
<td>3,600</td>
<td>18,500</td>
</tr>
<tr>
<td>2</td>
<td>STDN</td>
<td>SMALL</td>
<td>105</td>
<td>3,000</td>
<td>22,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TDRSS</td>
<td>150</td>
<td>1,200</td>
<td>5,500</td>
</tr>
<tr>
<td>3</td>
<td>STDN</td>
<td>LARGE</td>
<td>105</td>
<td>1,800</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TDRSS</td>
<td>150</td>
<td>800</td>
<td>2,000</td>
</tr>
</tbody>
</table>

NOTE:

The correlation between downtrack position and radial velocity is -0.95

The correlation between radial position and downtrack velocity is -0.80

* Spaceflight Tracking and Data Network

** Tracking Data Relay Satellite System
In section III, the steady state error dynamics of the Shuttle Imaging Spectrometer system has been analyzed with the major error sources and disturbance effects estimated. In this section, the emphasis is on the geometric error analysis. Geometric errors are consequences of the more direct errors including attitude and rate errors, ephemeris uncertainties, misalignment errors, earth rotation and curvature, etc. Figure 1 shows how the various errors propagate and how the geometric errors and the ground pattern distortions can be generated through dynamic analysis and simulation. The block that is considered in this section is II. Due to mounting and other practical considerations, only the payload-bay principal-axis nadir pointing configuration is considered (see Fig. 2).

The geometric error mapping functions due to the individual error sources as well as the aggregated errors are derived. The earth curvature effect is incorporated in all of the results. For the purpose of quick reference, the key mapping functions are tabulated in Appendix A. A list of the source code of the computer program that has been used for generating the geometric error characteristic curves is given in Appendix E.

A. COORDINATE CONFIGURATIONS

In Fig. 18, the coordinate frame $(X_p, Y_p, Z_p)$ on the Shuttle c.m. consists of the principal body axes. For the purpose of geometric analysis, another set of coordinates is used, i.e., the $(X, Y, Z)$ frame centered at the nadir point on the ground. This frame is the nadir projection of the orbital rotating frame centered at the Shuttle c.m. Specifically, the $X$-axis is in the direction of the projected motion on the ground, or the along-track direction, the $Z$-axis is in the nadir direction, and the $Y$-axis is in the cross-track direction, so that a right-hand coordinate system is formed.

For the purpose of this report, it is assumed that the Imaging Spectrometer is attached to the payload bay with its optical axis aligned with the body.
Figure 18. Payload-Bay Nadir Pointing Configuration and Coordinates
Z_p-axis. For normal IS operations, this is the desired configuration. However, for some IS experiments, such as those for assessing the atmospheric effects on the images, the IS instrument is required to point up to \( \pm 45^\circ \) about the pitch axis (Y) from nadir (forward and backward looking) or up to \( \pm 20^\circ \) about the roll axis (X) (side looking). For those cases, it is assumed that the instrument is gimbal mounted. However, since the analysis performed here is not primarily concerned with dynamics, no specific details are made at this time regarding mounting configurations.

B. GEOMETRIC ERRORS INDUCED BY EPHEMERIS UNCERTAINTIES

Ephemeris uncertainties include radial, along-track, and cross-track prediction errors. The geometric errors induced by ephemeris uncertainties are discussed in the following subsections.

B.1 Geometric Errors Due to Altitude Uncertainties

When the altitude of the shuttle varies, the ground point will shift in both the X and Y directions accordingly. This can be investigated in the following two ways.

B.1.1 With Fixed Viewing Angles

Referring to Figure 19, when the shuttle flies at nominal altitude \( h \) (position A), a ground point B with coordinates \((X_0, Y_0)\) corresponding to a view angle \( \lambda \) from the shuttle IS is located. After the shuttle elevates \( \Delta h \) to position A', point B' with coordinates \((X_0', Y_0')\) corresponding to the same view angle \( \lambda \) is located. The problem is to determine the shift of image due to the altitude change. Consider that when the altitude increases, the image of ground objects tends to move toward the nadir point, which causes reduction in image size and increase in field of view. Mathematically, the shift of image may be characterized by computing \( \Delta X \) and \( \Delta Y \), where

\[
\Delta X = X_0 - X_0' \\
\Delta Y = Y_0 - Y_0'
\]
Starting by assuming \((X_0, Y_0)\) known, the task is to determine \((X_0', Y_0')\) by first computing the view angle \(\lambda\). Figure 19b is generated by taking a side view from Fig. 19a in the direction perpendicular to Plane \(A'AO_eB'\). Apparently,

\[
\sqrt{X_0^2 + Y_0^2} = R \sin \theta
\]

GROUND AREA COVERED WHEN SHUTTLE IS AT NOMINAL ALTITUDE (POSITION A IN FIGURE 4 (b))

GROUND AREA COVERED WHEN SHUTTLE IS AT HIGHER ALTITUDE (POSITION A' IN FIGURE 4 (b))

LEGEND:

- \(B\) = A GROUND POINT CORRESPONDING TO VIEW ANGLE \(\lambda\) WHEN SHUTTLE IS AT NOMINAL ALTITUDE (POSITION A IN FIG. 4(b))
- \(B'\) = THE GROUND POINT CORRESPONDING TO THE SAME VIEW ANGLE AFTER THE SHUTTLE ELEVATED \(\Delta h\) (POSITION A' IN FIG. 4(b))
- \((X_0, Y_0)\) = COORDINATES OF POINT \(B\)
- \((X_0', Y_0')\) = COORDINATES OF POINT \(B'\)
- \(\Delta X, \Delta Y\) = X AND Y COMPONENTS OF THE POSITION CHANGE

(a) TOP VIEW (LOOKING TOWARD NADIR)

...Figure 19: Ground Point Shift in X and Y Direction due to Altitude Error
LEGEND:

- $h$ = NOMINAL ALTITUDE
- $\Delta h$ = ALTITUDE ERROR
- $\lambda$ = VIEW ANGLE
- $A$ = SHUTTLE'S POSITION AT NOMINAL ALTITUDE
- $A'$ = SHUTTLE'S POSITION AFTER BEING ELEVATED $\Delta h$

Figure 19. (Continued)
or
\[ \beta = \sin^{-1}\left(\frac{\sqrt{X_0^2 + Y_0^2}}{R}\right) \]  

(59)

and
\[ \alpha = 180^\circ - \lambda - \beta \]  

(60)

From triangle ABC, we have
\[ \frac{R}{\sin \lambda} = \frac{R + h}{\sin \alpha} \]  

(61)

Substituting Eqs. (59) and (60) into (61), it becomes
\[ \frac{R}{\sin \lambda} = \frac{R + h}{\sin \left[180^\circ - \lambda - \sin^{-1}\left(\frac{\sqrt{X_0^2 + Y_0^2}}{R}\right)\right]} \]

which leads to
\[ \tan \lambda = \frac{\sqrt{X_0^2 + Y_0^2}}{R + h - \sqrt{R^2 - X_0^2 - Y_0^2}} \]

hence,
\[ \lambda = \tan^{-1}\left(\frac{\sqrt{X_0^2 + Y_0^2}}{R + h - \sqrt{R^2 - X_0^2 - Y_0^2}}\right) \]  

(62)

To determine \( \sqrt{X_0'^2 + Y_0'^2} \), triangle A'B'C is used,
\[ \frac{R}{\sin \lambda} = \frac{R + h + \Delta h}{\sin \alpha'} \]

\[ \therefore \alpha' = \sin^{-1}\left(\left(1 + \frac{h + \Delta h}{R}\right) \sin \lambda\right) \]  

(63)

and
\[ \sqrt{X_0'^2 + Y_0'^2} = R \sin \beta' \]

\[ = R \sin (\lambda + \alpha') \]  

(64)
Substituting Eq. (63) into (64),

$$\sqrt{x_0^2 + y_0^2} = R \sin \left\{ \lambda + \sin^{-1} \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \sin \lambda \right] \right\}$$  \hspace{1cm} (65)

Expanding the right hand side of Eq. (65), and adopting the "-" sign for \( \cos \left\{ \sin^{-1} \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \sin \lambda \right] \right\} \), since \( 90^\circ < \sin^{-1} \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \sin \lambda \right] < 180^\circ \), one has

$$\sqrt{x_0^2 + y_0^2} = R \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h + \Delta h}{R} \right)^2 \sin^2 \lambda} \right] \sin \lambda$$  \hspace{1cm} (66)

Now, referring to Fig. 19(a), since \( B' \) is on the line OB, the angle \( \rho \) is determined by

$$\rho = \sin^{-1} \frac{x_0}{\sqrt{x_0^2 + y_0^2}}$$

$$= \cos^{-1} \frac{y_0}{\sqrt{x_0^2 + y_0^2}}$$  \hspace{1cm} (67)

Hence, from Eqs. (66) and (67),

$$x_0' = \sqrt{x_0^2 + y_0^2} \sin \rho$$

$$= \frac{R x_0 \sin \lambda}{\sqrt{x_0^2 + y_0^2}} \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h + \Delta h}{R} \right)^2 \sin^2 \lambda} \right]$$  \hspace{1cm} (68)

$$y_0' = \sqrt{x_0^2 + y_0^2} \cos \rho$$

$$= \frac{R y_0 \sin \lambda}{\sqrt{x_0^2 + y_0^2}} \left[ \left( 1 + \frac{h + \Delta h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h + \Delta h}{R} \right)^2 \sin^2 \lambda} \right]$$  \hspace{1cm} (69)

where \( \lambda \) is obtained by Eq. (62).

Hence, from Eqs. (68), (69), and (62) the values for \( \Delta x = x_0 - x_0' \) and \( \Delta y = y_0 - y_0' \) can be obtained.
When point $A'$ is below point $A$, the negative value for $\Delta h$ should be used in the above equations.

However, if one starts with given view angle $\lambda$ and $\rho$, the values of $X_0, Y_0, X_0', \text{ and } Y_0'$ can be readily obtained using Eqs. (68) and (69) directly (set $\Delta h$ to 0 for $X_0$ and $Y_0$).

B.1.2 With Fixed Ground Points

Referring to Fig. 20, the view angle for the fixed ground point $B$ will change as the shuttle altitude varies. Follow the same approach of paragraph B.1.1, the view angles $\Omega$ and $\Omega'$ can be found,

$$\Omega = \tan^{-1}\left(\frac{\sqrt{X_0^2 + Y_0^2}}{R + h - \sqrt{R^2 - X_0^2 - Y_0^2}}\right)$$ (70)

and

$$\Omega' = \tan^{-1}\left(\frac{\sqrt{X_0^2 + Y_0^2}}{R + h + \Delta h - \sqrt{R^2 - X_0^2 - Y_0^2}}\right)$$ (71)

Using Eqs. (70) and (71), the value of $\Delta \Omega = \Omega' - \Omega$ can be obtained. Again if point $A'$ is below point $A$, the negative value for $\Delta h$ should be used in the above equations.

B.2. Geometric Errors Due to Intrack and Crosstrack Prediction Errors

The intrack (along X-direction or direction of orbit) and the crosstrack (along Y-direction or "-" orbit normal direction) prediction errors will cause the ground objects to shift along the X and Y directions, respectively, as shown in Fig. 21. To determine the overall geometric errors associated with ephemeris uncertainties, the intrack error $\Delta X^*$ and the crosstrack error $\Delta Y^*$ can be incorporated in $\Delta X$ and $\Delta Y$ found in Section B.1.1, respectively.
LEGEND:

\[ \Omega = \text{VIEW ANGLE FROM SHUTTLE TO POINT B WHEN SHUTTLE IS AT NOMINAL ALTITUDE } h \]

\[ \Omega' = \text{VIEW ANGLE FROM SHUTTLE TO THE SAME POINT B AFTER SHUTTLE ELEVATES } \Delta h \]

Figure 20. Change of View Angle of a Ground Point due to Altitude Error
Figure 21. Geometric Errors Induced by Intrack and Crosstrack Prediction Errors
C. GEOMETRIC ERRORS INDUCED BY ATTITUDE UNCERTAINTIES

Attitude uncertainties refer to the angular errors with respect to the nominal roll ($\phi$), pitch ($\theta$), and yaw ($\psi$) axes. The effects of these errors to the images of ground objects are studied in this subsection first on the individual error basis and then on the aggregated basis. For convenience, in the subsequent discussions, the term nominal flight condition will be used to signify the condition of the shuttle flying in a 400 km circular orbit with the attitude of payload-bay nadir pointing.

C.1 Geometric Errors Induced by Roll Error

Referring to Fig. 22, consider the nominal flight condition with $\phi_0$ offset angle about the roll axis. The IS slit in this case is directed at the Y-axis on the ground. For a given view angle $\lambda$, the image point (or pixel) on the ground is $P_o$ with coordinates $(0, Y^*)$. For the same roll offset and view angle the ground point $P'_o$ is located after a roll error $\phi$ is introduced. The coordinates of $P'_o$ are $(0, Y'^*)$. Equivalently, by rotating the optical instrument to the "left," the image recorded on the film appears to move to the "right." Therefore, the geometric error may be defined as the displacement of the object image after error is introduced relative to the image before the error is introduced. Mathematically, this is $\overrightarrow{P_o} - \overrightarrow{P'_o}$ or $\overrightarrow{P_o} \phi_o \lambda - \overrightarrow{P_o} \phi + \phi, \lambda$. Since, in the case being considered, the image is on the Y-axis, one has

$$\Delta X = 0$$  \hspace{1cm} (72)

$$\Delta Y = Y^* - Y'^*$$  \hspace{1cm} (73)

where $Y^*$ and $Y'^*$ are,

$$Y^* = -R \sin (\lambda + \phi_0) \left[ \left(1 + \frac{h}{R}\right) \cos (\lambda + \phi_0) - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 (\lambda + \phi_0)} \right]$$  \hspace{1cm} (74)
Figure 22. Shift of Ground Point Induced by Roll Error
\[
Y' = -R \sin (\lambda + \phi_0 + \phi) \left[ \left( 1 + \frac{h}{R} \right) \cos (\lambda + \phi_0 + \phi) - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 (\lambda + \phi_0 + \phi)} \right]
\]

(75)

C.2 Geometric Errors Induced by Pitch Error

Consider the case of pitch attitude error. Let \( \theta_0 \) be the offset angle about the pitch axis (desired attitude), and \( \theta \) be the pitch error. Referring to Fig. 23, for a given view angle \( \lambda \), projecting the slit onto the XY-plane forms two line segments: \( \overline{BC} \), corresponding to null pitch error \( \theta = 0 \), and \( \overline{B'C'} \), corresponding to arbitrary pitch error \( \theta \). Projecting along the line of view \( \overline{AC} \) onto the ground, \( P(X*,Y*) \) is obtained; similarly, \( P'(X',Y') \) is obtained, corresponding to line of view \( \overline{AC'} \). The geometric error here is defined the same way as that for the roll case, i.e.,

\[
\Delta X = X* - X' \quad \Delta Y = Y* - Y'
\]

(76)

(77)

The formulae for computing \( X*, Y*, X', \) and \( Y' \) are derived as follows. In Fig. 23, assume that \( h, \theta, \theta_0, \) and \( \lambda \) are known. The lengths of the line segments \( \overline{OB} \) and \( \overline{OB'} \) are

\[
\overline{OB} = h \tan \theta_0
\]

(78a)

and

\[
\overline{OB'} = h \tan (\theta_0 + \theta)
\]

(78b)

and that of \( \overline{AB} \) and \( \overline{AB'} \) are

\[
\overline{AB} = \frac{h}{\cos \theta_0}
\]

(79a)

\[
\overline{AB'} = \frac{h}{\cos (\theta_0 + \theta)}
\]

(79b)
LEGEND:

\( \lambda \) = VIEW ANGLE

\( \theta_0 \) = PITCH OFFSET ANGLE

\( \theta \) = PITCH ERROR

\( P \) = THE GROUND POINT CORRESPONDING TO VIEW ANGLE \( \lambda \) AND PITCH OFFSET \( \theta_0 \)

\( P' \) = THE GROUND POINT CORRESPONDING TO THE SAME \( \lambda \) AND \( \theta_0 \) AFTER PITCH ERROR \( \theta \) IS INTRODUCED

Figure 23. Shift of Ground Point Induced by Pitch Error
BC and B'C', with respect to Y-axis, can be obtained as

\[
BC = -AB \tan \lambda = -h \tan \frac{\lambda}{\cos \theta_o}
\]  
(80a)

and

\[
B'C' = -AB' \tan \lambda = -h \tan \frac{\lambda}{\cos(\theta_o + \theta)}
\]  
(80b)

implies that the signs of BC and B'C' are opposite to that of \( \lambda \). \( \lambda \) and \( \lambda' \) are, referring to Fig. 23,

\[
\lambda = \sqrt{OB^2 + BC^2} = h \sec \theta_o \sqrt{\sin^2 \theta_o + \tan^2 \lambda}
\]  
(81a)

and

\[
\lambda' = \sqrt{OB'^2 + B'C'^2} = h \sec (\theta_o + \theta) \sqrt{\sin^2 (\theta_o + \theta) + \tan^2 \lambda}
\]  
(81b)

the angles \( \tau \) and \( \xi \) (see Fig. 23) can then be determined,

\[
\tau = \tan^{-1} \left( \frac{\xi}{h} \right) = \tan^{-1} \left( \sec \theta_o \sqrt{\sin^2 \theta_o + \tan^2 \lambda} \right)
\]  
(92a)

and

\[
\xi' = \tan^{-1} \left( \frac{\xi'}{h} \right) = \tan^{-1} \left[ \sec (\theta_o + \theta) \sqrt{\sin^2 (\theta_o + \theta) + \tan^2 \lambda} \right]
\]  
(92b)

Finally,

\[
X* = \sqrt{X^2 + Y^2} \cdot \frac{OB}{R}
\]

\[
= R \left[ \left( 1 + \frac{h}{R} \right) \cos \tau - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \tau} \right] \frac{\sin \tau \sin \theta_o}{\sqrt{\sin^2 \theta_o + \tan^2 \lambda}}
\]  
(83a)

\[
Y* = \sqrt{X^2 + Y^2} \cdot \frac{BC}{R}
\]

\[
= -R \left[ \left( 1 + \frac{h}{R} \right) \cos \tau - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \tau} \right] \frac{\sin \tau \tan \lambda}{\sqrt{\sin^2 \theta_o + \tan^2 \lambda}}
\]  
(83b)
\[ X^* = \sqrt{X^*'^2 + Y^*'^2} \]

\[ = R \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi} \right] \frac{\sin \xi \sin (\theta_o + \theta)}{\sqrt{\sin^2 (\theta_o + \theta) + \tan^2 \lambda}} \]

\[ Y^* = \sqrt{X^*'^2 + Y^*'^2} \frac{B'C'}{L'} \]

\[ = -R \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi} \right] \frac{\sin \xi \tan \lambda}{\sqrt{\sin^2 (\theta_o + \theta) + \tan^2 \lambda}} \]

However, if one starts with \((X^*, Y^*)\) given, then \(\lambda\) and \(\theta_o\) would have to be computed. In that case,

\[ \lambda = -\tan^{-1} \left( \frac{Y^*}{(R + h - \sqrt{R^2 - X^*^2 - Y^*^2}) \sqrt{1 + \left(\frac{X^*}{R + h - \sqrt{R^2 - X^*^2 - Y^*^2}}\right)^2}} \right) \]

(84a)

and

\[ \theta_o = \tan^{-1} \left( \frac{X^*}{R + h - \sqrt{R^2 - X^*^2 - Y^*^2}} \right) \]

(84b)

Once \(\lambda\) and \(\theta_o\) are determined, \(\tau\) and \(\xi\) can be computed using (82), and \(X^*\)

and \(Y^*\) are determined using (83).

C.3 Geometric Errors Induced by Yaw Error

For a given yaw offset angle, \(\psi_o\), and the view angle, \(\lambda\), the ground point \(P(X^*, Y^*)\) is located. A new point \(P'(X^*', Y^*)\) is found as yaw attitude error, \(\psi\), is introduced (see Fig.24). The values for \(X^*, Y^*, X^*\), and \(Y^*\) can be computed as follows:

\[ X^* = \left(1 + \frac{h}{R}\right) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \]

\[ R \sin \lambda \sin \psi_o \]

(85a)
LEGEND:

$\psi_0$ = YAW OFFSET ANGLE  
$\psi$ = YAW ERROR  
P = THE GROUND POINT CORRESPONDING TO VIEW ANGLE $\lambda$ AND YAW OFFSET $\psi_0$  
P' = THE GROUND POINT CORRESPONDING TO THE SAME $\lambda$ AND $\psi_0$ AFTER YAW ERROR $\psi$ IS INTRODUCED

Figure 24. Shift of Ground Point Induced by Yaw Error

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\[
Y^* = - \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right] R \sin \lambda \cos \psi_o
\tag{85b}
\]
\[
X'^* = \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right] R \sin \lambda \sin (\psi_o + \psi)
\tag{86a}
\]
and
\[
Y'^* = - \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right] R \sin \lambda \cos (\psi_o + \psi)
\tag{86b}
\]

From Eqs. (85) and (86), we can obtain
\[
\Delta X = X^* - X'^*
\]
\[
\Delta Y = Y^* - Y'^*
\]

C.4 Geometric Errors Induced by Roll, Pitch, and Yaw Attitude Errors

C.4.1. The Shift of IS Line-of-Sight due to Attitude Error

Referring to Fig. 25, the shuttle is flying at an arbitrary attitude \((\phi, \theta, \psi)\). Consider the 3-2-1 sequence, i.e., the yaw, pitch, and roll rotation sequence. After yaw and pitch rotations, the Imaging Spectrometer line-of-sight will shift to \(AB\), where \(B(X_1, Y_1)\) is its intersection with the XY-plane. The \((X_1, Y_1)\) coordinates are determined as follows:
\[
X_1 = X_o + h \tan \phi \cos \psi
\tag{87a}
\]
\[
Y_1 = Y_o + h \tan \phi \sin \psi
\tag{87b}
\]

Through a roll angle rotation, point B will move to \(C(X_2, Y_2)\) on the XY-plane, where
\[
X_2 = X_o + h \tan \phi \cos \psi + \frac{h}{\cos \theta} \tan \phi \sin \psi
\tag{88a}
\]
\[
Y_2 = Y_o + h \tan \phi \sin \psi - \frac{h}{\cos \theta} \tan \phi \cos \psi
\tag{88b}
\]

60
Figure 25. The Shift of Ground Projection of the IS Line-of-Sight due to Attitude Error
The interest here is to determine the coordinates of $O'(X,Y)$ corresponding to the final line-of-sight projected onto the ground. By taking a view normal to the ACO-plane, Figure 26 is obtained. The quantities $\varepsilon$, $\lambda$, and $\rho$ are obtained as follows,

\[ \varepsilon = \tan^{-1} \left( \frac{\sqrt{X_2^2 + Y_2^2}}{h} \right) \]  
\[ \lambda = R \sin \varepsilon \left[ (1 + \frac{h}{R}) \cos \varepsilon - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \varepsilon} \right] \]  

and

\[ \rho = \sin^{-1} \left( \frac{Y_2}{\sqrt{X_2^2 + Y_2^2}} \right) = \cos^{-1} \left( \frac{X_2}{\sqrt{X_2^2 + Y_2^2}} \right) \]

Hence, the coordinates of $X$ and $Y$ are,

\[ X = \lambda \cos \rho = R \sin \varepsilon \left[ (1 + \frac{h}{R}) \cos \varepsilon - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \varepsilon} \right] \frac{X_2}{\sqrt{X_2^2 + Y_2^2}} \]  
\[ Y = \lambda \sin \rho = R \sin \varepsilon \left[ (1 + \frac{h}{R}) \cos \varepsilon - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \varepsilon} \right] \frac{Y_2}{\sqrt{X_2^2 + Y_2^2}} \]

where $X_2$ and $Y_2$ are given in Eq. (88).

Note that this derivation is general enough so that the formulae are valid if one replaces the attitude errors with errors plus offsets, i.e., replacing $\phi$, $\theta$, and $\psi$ by $\phi_0 + \phi$, $\theta_0 + \theta$, and $\psi_0 + \psi$, respectively.
Figure 26. Side View of Figure 25
C.4.2. The Shift of Ground Image Due to Attitude Error

For simplicity, $\phi$, $\theta$, and $\psi$ are used to represent the attitude angles as sums of attitude offsets and attitude errors. To fix the derivation, the yaw ($\psi$), pitch ($\theta$), and roll ($\phi$) Euler sequence is assumed.

In this subsection, the results of subsection C.4.1 are extended to cover the entire field of view of the IS slit. First consider the case of a nominal flight with zero attitude offset. Referring to Fig. 27, let $O$ be the nadir point which is the origin of the XY-Frame and the $X'Y'$-Frame. The $X'Y'$-Frame is formed by rotating the XY-Frame through an angle $\psi$ about the yaw axis. Let $P$ be a point corresponding to a view angle $\lambda$ (negative value shown in Fig. 27) on the Y-axis before any rotation occurs. After a $\psi$ rotation, for the same view angle, the IS is sighting point $P_1$. Similarly, after a pitch ($\theta$) and then roll ($\phi$) rotation, the points $P_2$ and then $P_3$ are sighted, respectively.

The coordinates of $P_2$ in the $X'Y'$-Frame are, from the results of subsections C.1 and C.2 and Fig. 23,

\[
X'_2 = \frac{R \sin \theta \sin \xi_2 \left[ \left(1 + \frac{h}{R}\right) \cos \xi_2 - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi_2} \right]}{\sqrt{\sin^2 \theta + \tan^2 \lambda}} \quad (91a)
\]

\[
Y'_2 = \frac{-R \tan \theta \sin \xi_2 \left[ \left(1 + \frac{h}{R}\right) \cos \xi_2 - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi_2} \right]}{\sqrt{\sin^2 \theta + \tan^2 \lambda}} \quad (91b)
\]

where the angle $\xi_2$ is the angle $\xi$ defined in Fig. 23 corresponding to point $P_2$ here, and

\[
\xi_2 = \tan^{-1} \left( \frac{\sec \theta}{\sqrt{\sin^2 \theta + \tan^2 \lambda}} \right) \quad (91c)
\]
Figure 27. Shift of Ground Point Induced by Attitude Errors.
The coordinates of \( P_3 \) in the \( X'Y' \)-Frame are

\[
X'_3 = \frac{R \sin \theta \sin \xi_3 \left[ \left( 1 + \frac{h}{R} \right) \cos \xi_3 - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi_3} \right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}}
\]

(92a)

\[
Y'_3 = -\frac{R \tan (\lambda + \phi) \sin \xi_3 \left[ \left( 1 + \frac{h}{R} \right) \cos \xi_3 - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi_3} \right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}}
\]

(92b)

where \( \xi_3 \) is similarly defined as \( \xi_2 \) and

\[
\xi_3 = \tan^{-1} \left( \sec \theta \sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)} \right)
\]

(92c)

or, finally, in the \( XY \)-Frame

\[
X_3 = X'_3 \cos \psi - Y'_3 \sin \psi
\]

(93a)

\[
Y_3 = X'_3 \sin \psi + Y'_3 \cos \psi
\]

(93b)

where \( X'_3 \) and \( Y'_3 \) are given in (92).

The geometric error caused by the attitude errors is therefore,

\[
\Delta X = X - X_3
\]

(94a)

\[
\Delta Y = Y - Y_3
\]

(94b)

where

\[
X = 0
\]

\[
Y = -R \sin \lambda \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right]
\]

Now, consider the case of the shuttle (or the IS) flying at a nominal attitude

\((\phi_o, \theta_o, \psi_o)\) with attitude uncertainties of \((\phi, \theta, \psi)\). Let \( P_o(X_o, Y_o) \) be a ground point that is sighted by the IS with a view angle \( \lambda \) and attitude \((\phi_o, \theta_o, \psi_o)\).

After \((\phi, \theta, \psi)\) attitude rotations from the nominal, the ground point \( P_3(X_3, Y_3) \) is sighted with the same view angle. In this case, the geometric error is
\[ \Delta X = X_0 - X_3 \]  
\[ \Delta Y = Y_0 - Y_3 \]  

where

\[ X_0 = X_o' \cos \psi - Y_o' \sin \psi \]  
\[ Y_0 = X_o' \sin \psi + Y_o' \cos \psi \]  
\[ X_3 = X_3' \cos (\psi + \phi) - Y_3' \sin (\psi + \phi) \]  
\[ Y_3 = X_3' \sin (\psi + \phi) + Y_3' \cos (\psi + \phi) \]

and

\[ X'_o = \frac{R \sin \theta \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi}\right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}} \]  
\[ Y'_o = \frac{R \tan (\lambda + \phi) \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi}\right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}} \]  

where

\[ \xi = \tan^{-1} \left( \sec \theta \sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)} \right) \]  

and

\[ X'_3 = \frac{R \sin (\theta + \phi) \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi}\right]}{\sqrt{\sin^2 (\theta + \phi) + \tan^2 (\lambda + \phi)}} \]  
\[ Y'_3 = \frac{R \tan (\lambda + \phi + \phi) \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi}\right]}{\sqrt{\sin^2 (\theta + \phi) + \tan^2 (\lambda + \phi)}} \]

and where

\[ \xi = \tan^{-1} \left[ \frac{\sec (\theta + \phi) \sqrt{\sin^2 (\theta + \phi) + \tan^2 (\lambda + \phi)}}{\sqrt{\sin^2 (\theta + \phi) + \tan^2 (\lambda + \phi)}} \right] \]
To include errors caused by altitude uncertainties, one can replace $h$ by $h_0$ in Eq. (97), and $h$ by $h_0 + \Delta h$ in Eq. (98), where $h_0$ is the nominal or estimated altitude and $h_0 + \Delta h$ is the actual altitude.

D. GEOMETRIC ERRORS INDUCED BY ATTITUDE RATE ERRORS

Attitude rates cause attitude angle changes which in turn cause geometric errors. To account for attitude rates, one integrates the rates to obtain the attitude angles, and then uses the formulae derived to obtain the corresponding time-varying geometric errors. The instantaneous attitude angles are:

\[
\begin{align*}
\phi' &= \phi_0 + \int_{t_0}^{t} \dot{\phi} \, dt \\ 
\theta' &= \theta_0 + \int_{t_0}^{t} \dot{\theta} \, dt \\
\psi' &= \psi_0 + \int_{t_0}^{t} \dot{\psi} \, dt
\end{align*}
\] (99)

E. GEOMETRIC ERRORS INDUCED BY MISALIGNMENT ERRORS

The misalignment errors can be incorporated in the attitude errors. Let $(\gamma_b', \beta_b', \psi_b')$ be the attitude bias or misalignment, then the effective IS attitude angles will be

\[
\begin{align*}
\gamma' &= \gamma_0 + \gamma_b + \gamma' \\
\beta' &= \beta_0 + \beta_b + \beta' \\
\psi' &= \psi_0 + \psi_b + \psi'
\end{align*}
\] (100)
The corresponding geometric errors can be determined using the formulae derived in subsection C.

F. GEOMETRIC ERRORS INDUCED BY EARTH ROTATION

The effect of earth rotation on images varies with the position of the Shuttle relative to the earth and the Shuttle orbital elements. In general, ground images become skewed as a result of earth rotation.

Referring to Fig. 28. Let \( \theta \) be the nadir point at which the latitude is \( \zeta \).

Let \( \omega_e \) be the spin rate of the earth, where \( \omega_e = \frac{2\pi}{86400} = 7.2722 \times 10^{-5} \) rad/sec.

Let \( V_e \) be the linear velocity of the earth at \( \theta \),

\[
V_e = \omega_e R \cos \zeta \quad (101)
\]

Let \( \Gamma \) be the orbital inclination at the equator, and let \( \Lambda \) be the orbital inclination to the local meridian at \( \theta \). From Fig. 29 and Appendix B, one has the following spherical geometrical relation,

\[
\cos \Gamma = \cos \zeta \sin \Lambda
or
\sin \Lambda = \frac{\cos \Gamma}{\cos \zeta} \quad (102a)
\]

and

\[
\cos \Lambda = \sqrt{1 - \sin^2 \Lambda} = \sqrt{1 - \left(\frac{\cos \Gamma}{\cos \zeta}\right)^2} \quad (102b)
\]

From Fig. 29 again, \( \Lambda \) is also the angle between the linear velocity vector \( V_e \) and the \( Y \)-axis. Hence, velocity components \( V_{eX} \) and \( V_{eY} \) are, using (102),

\[
V_{eX} = V_e \sin \Lambda = \frac{V_e \cos \Gamma}{\cos \zeta} \quad (103a)
\]

and

\[
V_{eY} = V_e \cos \Lambda = V_e \sqrt{1 - \left(\frac{\cos \Gamma}{\cos \zeta}\right)^2} \quad (103b)
\]
LEGEND:
\( \omega_e \) = ANGULAR VELOCITY OF EARTH SPIN
\( \zeta \) = LATITUDE AT POINT O
\( v_e \) = LINEAR VELOCITY OF THE EARTH AT POINT O

Figure 28. Linear Velocity of the Earth at the Nadir Point
(a) INTRACK AND CROSSTRAK COMPONENTS OF EARTH LINEAR VELOCITY VECTOR AT THE NADIR POINT

(b) ORBIT INCLINATION TO THE LOCAL MERIDIAN (A), degrees

<table>
<thead>
<tr>
<th>ORBITAL INCLINATION (degrees)</th>
<th>NORTH LATITUDE, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18.5</td>
<td>90</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 29. Earth Spherical Geometry
During the time interval from \( t_1 \) to \( t_2 \), the ground point has moved from \( P(X, Y) \) to \( P'(X', Y') \), the corresponding position changes are,

\[
\Delta X = \int_{t_1}^{t_2} v_{eX} \, dt = \int_{t_1}^{t_2} \frac{v_e \cos \Gamma}{\cos \zeta} \, dt \quad (104a)
\]

\[
\Delta Y = \int_{t_1}^{t_2} v_{eY} \, dt = \int_{t_1}^{t_2} v_e \sqrt{1 - \left(\frac{\cos \Gamma}{\cos \zeta}\right)^2} \, dt \quad (104b)
\]

Note that for small time intervals, \( \zeta \) may be considered constant and (104) may be approximated as

\[
\Delta X = \frac{\cos \Gamma}{\cos \zeta} v_e (t_2 - t_1) \quad (105a)
\]

\[
\Delta Y = \sqrt{1 - \left(\frac{\cos \Gamma}{\cos \zeta}\right)^2} v_e (t_2 - t_1) \quad (105b)
\]

and

\[
X' = X + \Delta X \quad (106a)
\]

\[
Y' = Y + \Delta Y \quad (106b)
\]

G. NUMERICAL RESULTS: GEOMETRIC ERRORS AND ERROR SENSITIVITIES

Numerical results of error sensitivities and geometric errors due to various direct errors have been generated. These data are summarized in Tables 5-10 and discussed in the following subsections.

G.1 Geometric Errors Due to Altitude Uncertainties

Table 5 shows the geometric error for a 1 km altitude change and error sensitivity caused by altitude uncertainty. The nominal altitude of 400 km was used to generate these data. This result is also plotted in Fig. 30 as a function of view angles for altitude changes ranging from 1 km to 4 km. As indicated in this figure, the geometric errors are quite linear with the view angles and the altitude errors for the range shown.

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For the Imaging Spectrometer illustrated in Fig. 4, the view angles are limited by the field of view of ±825°. Using the various expected on-orbit navigation accuracies shown in Table 4, and the sensitivity data of Table 5, the corresponding geometric error can be determined. For instance, from Table 4, the 3σ altitude uncertainty, with TDRSS in the tracking system for the 150 nmi orbit, if the small unmodeled perturbation is used, is 800 feet (or ~244 m) and with the STDN system and large unmodeled perturbation and 105 nmi orbit, the 3σ altitude uncertainty is 8000 feet (or ~2440 m). From Table 5, the corresponding 3σ geometric errors for the largest view angle (825°) are 3.51 m and 35.1 m, respectively. Note that the nominal pixel size is 30 m.

G.2 Geometric Errors Due to Roll Uncertainties

The geometric errors for view angles ranging from −9° to +9° due to a roll error of 1° are tabulated in Table 6. The error sensitivity at the nominal attitude is also tabulated in Table 6. By comparing the errors for 1° and the sensitivity for the same view angle, it is found that the differences are 2% or less. That is, for small angles, the error sensitivity data can be used to compute errors. Fig. 31 shows the plots of geometric errors for roll errors of up to 5°. Unlike the errors corresponding to altitude uncertainties, these curves are relatively flat. The geometric error is about 7 km per 1° of roll error.

It is noted from Fig. 31, that for small roll errors, the geometric errors are nearly symmetrical with the view angles. For larger roll angles, the geometric errors are greater for view angles that have the same sign of φ. This is more visible from Fig. 32 which shows the plots of geometric errors corresponding to roll errors of 1° and 2° from a roll offset of 20°.
G.3 Geometric Errors Due to Pitch Uncertainties

Table 7 shows the error sensitivity and the geometric errors corresponding to the 1° pitch error for the view angles of up to ±9°. The geometric errors caused by pitch errors are about the same in amplitude as those caused by roll errors. Fig. 33 shows that pitch curves are rather flat, unlike the corresponding roll curves. Figs. 34 and 35 show the 1° and 2° pitch uncertainty induced geometric error curves with 22.5° and 45° pitch offsets, respectively. These curves, especially those in Fig. 35, are more similar to the roll curves in shape.

G.4 Geometric Errors Due to Yaw Uncertainties

Geometric errors due to rotations about the yaw or the local vertical axis (assuming zero offsets) are tabulated in Table 8 for 1° and plotted in Fig. 36 for up to 5°. Linearity applies for both the view angles and the yaw angles for the ranges covered here. Unlike roll and pitch errors, yaw errors induce much smaller geometric errors.

G.5 Geometric Errors Due to Attitude Uncertainties

Table 9 shows the geometric errors due to 1° error in each of the roll, pitch, and yaw axes. The error magnitude for a given view angle is approximately the vector sum of the roll and pitch induced errors.

Fig. 37 shows the plots of geometric errors caused by up to 5° roll, pitch, and yaw errors. Fig. 38 shows two curves, one corresponding to 1° pitch error and the other, 1° yaw error, with the roll offset of 20°.

Comparing pitch curve with that of Fig. 33, the 20° roll offset has no noticeable effects on the geometric errors. On the other hand, the effects on the yaw curve are quite pronounced, as a large bias of approximately 2.5 km results due to the 20° roll.
Fig. 39 shows the $1^\circ$ roll and $1^\circ$ yaw curves for a pitch offset of $22.5^\circ$. Fig. 40 shows the same curves for $45^\circ$ pitch offset.

With the large angular pitch offsets, the yaw curves appear quite different from those without pitch offset, as noted in Figs. 36, 39, and 40. With these offsets, yaw-induced error curves look quite similar to those induced by roll errors in shape. By offsetting the pitch angle to $45^\circ$, the yaw-induced geometric errors increase to about sevenfold from zero pitch offset, and more than twofold over the $22.5^\circ$ pitch offset.

The roll-induced geometric errors were less drastically affected by pitch angular offsets. For instance, for $22.5^\circ$ pitch offset, the error has increased about 7% from that with zero offset, and about 46% for $45^\circ$ pitch offset.

G. 6 Ground Point Shift Due to Shuttle Motion and Earth Rotation

The earth rotation effect on the shift of the ground image varies with the latitude of the shuttle, and the combined effects of the earth rotation and shuttle motion vary with the orbital inclination in addition to the latitude. Table 10 shows the tabulation with latitude ranging from $0^\circ$ to $80^\circ$. The largest earth rotation effect occurs at the equator, .46 km in one second, and diminishes to .08 km in one second at the latitude of $80^\circ$ as shown in Fig. 41.

The combined effects are dominated by the motion of the shuttle since at 400 km altitude the projected ground speed is much greater than the earth rotation speed. In a one-second period, the image will shift more than 7 km for any latitude.
Table 5. Geometric Errors and Error Sensitivity Due to Altitude Uncertainties

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Altitude = 400 km

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric Error Induced by 1 km Altitude Error, km</td>
<td>0.01746</td>
<td>0.03492</td>
<td>0.05242</td>
<td>0.06995</td>
<td>0.08753</td>
<td>0.1052</td>
<td>0.1229</td>
<td>0.1407</td>
<td>0.1586</td>
<td></td>
</tr>
<tr>
<td>Geometric Error Sensitivity, km/km</td>
<td>0.01746</td>
<td>0.03492</td>
<td>0.05242</td>
<td>0.06995</td>
<td>0.08753</td>
<td>0.1052</td>
<td>0.1229</td>
<td>0.1407</td>
<td>0.1586</td>
<td></td>
</tr>
</tbody>
</table>
Figure 30. Geometric Error due to Altitude Uncertainties ($\Delta h$)
Table 6. Geometric Errors and Error Sensitivity Due to Roll Attitude Error

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Altitude = 400 km

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>-9</th>
<th>-8</th>
<th>-7</th>
<th>-6</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric Error Induced by +1° Roll Error, km</td>
<td>6.987</td>
<td>6.996</td>
<td>7.010</td>
<td>7.029</td>
<td>7.052</td>
<td>7.081</td>
<td>7.114</td>
<td>7.153</td>
<td>7.196</td>
</tr>
</tbody>
</table>
Figure 31. Geometric Error due to Roll Attitude Error (\(\phi\))
Figure 32. Geometric Error due to Roll Uncertainty ($\phi$) About $20^\circ$ Roll Offset
Table 7. Geometric Errors and Error Sensitivity Due to Pitch Attitude Error

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Altitude = 400 km

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>-9</th>
<th>-8</th>
<th>-7</th>
<th>-6</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
</table>
Figure 33. Geometric Error due to Pitch Attitude Error ($\theta$)
Figure 34. Geometric Error due to Pitch Uncertainty ($\theta$) About 22.5° Pitch Offset
Figure 35. Geometric Error due to Pitch Uncertainty (θ) About 45° Pitch Offset
Table 8. Geometric Error and Error Sensitivity Due to Yaw Attitude Error

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Altitude = 400 km

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric Error Induced by 1 Yaw Error, km</td>
<td>0</td>
<td>0.1219</td>
<td>0.2438</td>
<td>0.3659</td>
<td>0.4883</td>
<td>0.6109</td>
<td>0.7340</td>
<td>0.8576</td>
<td>0.9818</td>
<td>1.107</td>
</tr>
<tr>
<td>Geometric Error Sensitivity, km/deg.</td>
<td>0</td>
<td>0.1219</td>
<td>0.2438</td>
<td>0.3659</td>
<td>0.4883</td>
<td>0.6109</td>
<td>0.7340</td>
<td>0.8576</td>
<td>0.9818</td>
<td>1.107</td>
</tr>
</tbody>
</table>
Figure 36. Geometric Error due to Yaw Attitude Error ($\psi$)
Table 9. Geometric Errors Induced by Yaw, Pitch, and Roll Errors

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Altitude = 400 km
- Yaw Error = +1°
- Pitch Error = +1°
- Roll Error = +1°

<table>
<thead>
<tr>
<th>View Angle, deg.</th>
<th>-9</th>
<th>-8</th>
<th>-7</th>
<th>-6</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>View Angle, deg.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Error, km</td>
<td>9.966</td>
<td>10.06</td>
<td>10.16</td>
<td>10.27</td>
<td>10.37</td>
<td>10.48</td>
<td>10.60</td>
<td>10.72</td>
<td>10.85</td>
<td></td>
</tr>
</tbody>
</table>
Figure 37. Geometric Error due to Roll ($\phi$), Pitch ($\theta$), and Yaw ($\psi$) Errors
Figure 38. Geometric Error due to Pitch ($\theta$) and Yaw ($\psi$) Uncertainties About 20° Roll Offset
Figure 39. Geometric Error due to Roll ($\phi$) and Yaw ($\psi$) Uncertainties About 22.5° Pitch Offset
Figure 40. Geometric Error due to Roll ($\phi$) and Yaw ($\psi$) Uncertainties About 45° Pitch Offset
Table 10. Ground Point Shift Induced by Shuttle Motion and Earth Rotation

- Nominal Earth Radius = 6356.785 km (Polar)
- Nominal Orbit Inclination = 85°
- Nominal Shuttle Ground Speed = 7.202 km/sec

<table>
<thead>
<tr>
<th>Latitude, deg.</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Point Shift Velocity due to Earth Rotation, km/sec</td>
<td>0.4623</td>
<td>0.4344</td>
<td>0.3541</td>
<td>0.2311</td>
<td>0.08027</td>
</tr>
<tr>
<td>Ground Point Shift Velocity Relative to Nadir Point, km/sec</td>
<td>7.177</td>
<td>7.175</td>
<td>7.171</td>
<td>7.166</td>
<td>7.162</td>
</tr>
<tr>
<td>Angle of Velocity Vector with Y-axis, deg.</td>
<td>-86.32</td>
<td>-86.54</td>
<td>-87.19</td>
<td>-88.18</td>
<td>-89.44</td>
</tr>
<tr>
<td>Shift in 0.1 sec, km</td>
<td>0.7177</td>
<td>0.7175</td>
<td>0.7171</td>
<td>0.7166</td>
<td>0.7162</td>
</tr>
</tbody>
</table>
Figure 41. Geometric Error Caused by Earth Rotation for the Time Period of 1 Second
In this section geometric errors caused by the "direct error sources" are analyzed. Equations that map the direct errors onto the geometric errors are derived in Subsections B through G. Extensive illustrations of geometry are used to assist the derivations. Direct error effects included here are those of pointing errors and angular rates, ephemeris prediction errors including altitude, intrack, and crosstrack uncertainties, earth rotation and curvature, and shuttle and instrument misalignment. For quick reference the key error mapping functions are listed in Appendix A. A program list is given in Appendix E.

The numerical results for both the geometric errors and error sensitivities are tabulated in Tables 5 through 10 and also plotted in Figs. 30 through 41. To illustrate the effects of view angles and linearity, an extended range of $45^\circ$ is used. For the push broom imaging spectrometer studied here, the field of view is limited by $\pm 8.25^\circ$ (see Fig. 4). The following are the specific findings resulting from further analysis:

1. The effects of earth curvature are very small for the applications here. For instance, the linear displacement of a 10 km arc is 9.9999... km. Fig. 42 illustrates several cases of earth curvature effects.

![Figure 42. Effects of Earth Curvature](image)
2. Altitude uncertainties cause only moderate geometric errors. Table 11 shows that the worst 1σ geometric error is 11.71 m and the corresponding rate is .133 m/sec. The worst case associates with the STDN system and large unmodeled perturbation and 200 km orbit. The least 1σ errors are .22 m and .0032 m/sec corresponding to the TDRSS system and small unmodeled perturbation and 300 km orbit. The effects of other navigation uncertainties such as downtrack and crosstrack position errors are not small, however. Table 12 shows the 3σ uncertainties in feet. Downtrack and crosstrack position errors are mapped directly to the geometric errors.

3. Geometric errors caused by altitude uncertainties are, within the range of interest here, proportional to the view angle and altitude error (see Table 5 and Fig. 30).

4. The effects of roll and pitch attitude errors are relatively large compared with those of altitude errors and yaw attitude errors. Table 13 shows that, for nominal flight conditions, the error sensitivity is approximately 1.94 m/arc sec, or ~7000 m/degree. The yaw sensitivity is very small, from 0 for 0° view angle to .0279 m/arc sec for maximum IS view angle ±.825°.

The effects of attitude errors increase significantly for large attitude offsets. For instance, for 20° roll offset (side looking), the roll sensitivity increases to 2.28 m/arc sec from 1.94 and yaw sensitivity increases to .75 m/arc sec from .0279. The pitch sensitivity, in this case, is nearly unaffected. By offsetting the pitch angle to 45° (forward looking), the roll sensitivity increases to 2.83 m/arc sec, the pitch to 4.36 m/arc sec, and the yaw to 1.97 m/arc sec. Table 13 shows the error sensitivities and 1° geometric errors for many combinations of interest.
5. Without attitude offsets and within the IS field of view, the geometric errors are almost proportional to roll errors (Fig. 31), pitch errors (Fig. 33), and yaw errors (Fig. 36), and are independent of the view angle except for the yaw cases (for which the error is proportional to the view angle). For the cases of large roll or pitch angular offset, most of the properties change only slightly (see Figs. 32, 34, 35, 38, 39, and 40).

6. The performance of the Imaging Spectrometer is limited by the shuttle Inertial Measuring Unit accuracy, the shuttle reference misalignment, and the misalignment between the shuttle and the Imaging Spectrometer, unless means of error reduction, such as using ground control points and a precision point mount between the shuttle and the IS instruments, are employed.

On top of these uncertainties, the shuttle deadband is another source of error that can cause gross geometric errors. This problem, of course, can be resolved by using a precision point mount.

Table 14 shows geometric errors caused by the IMU/shuttle misalignment, IMU resolution, IMU noise, rate gyro drift, and combined shuttle/IS misalignment, for nominal attitude and attitude offsets. Single axis geometric errors corresponding to the combined shuttle/IS misalignment are 169 m, 198 m, and 379 m, respectively, for nominal, 20° roll offset, and 45° pitch offset, for instance. Other cases are shown in detail in Table 14.

7. Earth rotation causes images to shift toward the direction of rotation. The magnitude of this shift depends on the latitude of the object (see Fig. 41). For instance, at the equator, the object moves approximately 462 m in 1 second, while at 60° latitude, it moves only 231 m in one second.
Table 11. Geometric Errors Due to Expected On-orbit Navigation Uncertainty

<table>
<thead>
<tr>
<th>Navigation Tracking System</th>
<th>Unmodeled Perturbation</th>
<th>Minimum Altitude, km</th>
<th>1σ Altitude Error, m</th>
<th>Max. Geom. Error in FOV, m</th>
<th>1σ Radial Velocity, m/s</th>
<th>Max. Geom. Error in FOV, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDN</td>
<td>Nominal</td>
<td>200</td>
<td>508</td>
<td>7.32</td>
<td>3.87</td>
<td>.056</td>
</tr>
<tr>
<td>TDRSS</td>
<td></td>
<td>200</td>
<td>366</td>
<td>5.27</td>
<td>2.25</td>
<td>.032</td>
</tr>
<tr>
<td>STDN</td>
<td>Small</td>
<td>200</td>
<td>305</td>
<td>4.39</td>
<td>2.50</td>
<td>.036</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>122</td>
<td>1.76</td>
<td>.59</td>
<td>.0085</td>
</tr>
<tr>
<td>TDRSS</td>
<td></td>
<td>200</td>
<td>183</td>
<td>2.63</td>
<td>1.12</td>
<td>.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>81</td>
<td>1.17</td>
<td>.22</td>
<td>.0032</td>
</tr>
<tr>
<td>STDN</td>
<td>Large</td>
<td>200</td>
<td>813</td>
<td>11.71</td>
<td>9.27</td>
<td>.133</td>
</tr>
<tr>
<td>TDRSS</td>
<td></td>
<td>200</td>
<td>610</td>
<td>8.78</td>
<td>5.69</td>
<td>.082</td>
</tr>
</tbody>
</table>

STDN — Spaceflight Tracking and Data Network
TDRSS — Tracking Data Relay Satellite System
Table 12. Expected On-Orbit Navigation Accuracies (Ref. 12)

<table>
<thead>
<tr>
<th>Navigation Tracking System</th>
<th>Unmodeled Perturbation</th>
<th>Minimum Perigee, n.mi.</th>
<th>3σ Position, Feet</th>
<th>3σ Velocity, FPS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Radial</td>
<td>Down Track</td>
</tr>
<tr>
<td>STDN</td>
<td>Nominal</td>
<td>105</td>
<td>5,000</td>
<td>34,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
<td>3,600</td>
<td>18,500</td>
</tr>
<tr>
<td>STDN</td>
<td>Small</td>
<td>105</td>
<td>3,000</td>
<td>22,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>1,200</td>
<td>5,500</td>
</tr>
<tr>
<td>TDRSS</td>
<td></td>
<td>105</td>
<td>1,800</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>800</td>
<td>2,000</td>
</tr>
<tr>
<td>STDN</td>
<td>Large</td>
<td>105</td>
<td>8,000</td>
<td>80,000</td>
</tr>
<tr>
<td>STDN</td>
<td>Large</td>
<td>105</td>
<td>6,000</td>
<td>50,000</td>
</tr>
</tbody>
</table>

NOTE:
The correlation between downtrack position and radial velocity is -0.95.
The correlation between radial position and downtrack velocity is -0.80.

STDN - Spaceflight Tracking and Data Network
TDRSS - Tracking Data Relay Satellite System
Table 13. Geometric Error Sensitivity

Nominal Orbit: 400 km Circular

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Attitude Offset</th>
<th>Error Sensitivity, m/arc sec</th>
<th>Geometric Error for 1° Angular Error, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>For View Angle = 0°</td>
<td>For View Angle = ±.825°</td>
</tr>
<tr>
<td>Roll angle</td>
<td>No offset</td>
<td>1.939</td>
<td>1.940</td>
</tr>
<tr>
<td>Pitch angle</td>
<td></td>
<td>1.939</td>
<td>1.939</td>
</tr>
<tr>
<td>Yaw angle</td>
<td></td>
<td>0</td>
<td>.0279</td>
</tr>
<tr>
<td>Roll angle</td>
<td>20° roll offset</td>
<td>2.25</td>
<td>2.28</td>
</tr>
<tr>
<td>Pitch angle</td>
<td></td>
<td>1.94</td>
<td>1.94</td>
</tr>
<tr>
<td>Yaw angle</td>
<td></td>
<td>.72</td>
<td>.75</td>
</tr>
<tr>
<td>Roll angle</td>
<td>22.5° pitch offset</td>
<td>2.11</td>
<td>2.11</td>
</tr>
<tr>
<td>Pitch angle</td>
<td></td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>Yaw angle</td>
<td></td>
<td>.83</td>
<td>.83</td>
</tr>
<tr>
<td>Roll angle</td>
<td>45° pitch offset</td>
<td>2.82</td>
<td>2.93</td>
</tr>
<tr>
<td>Pitch angle</td>
<td></td>
<td>4.33</td>
<td>4.36</td>
</tr>
<tr>
<td>Yaw angle</td>
<td></td>
<td>1.94</td>
<td>1.97</td>
</tr>
<tr>
<td>Altitude uncertainty</td>
<td></td>
<td>0</td>
<td>.0144 m/m</td>
</tr>
</tbody>
</table>
Table 14. Geometric Error Induced by Shuttle and Imaging Spectrometer Measurement Uncertainties

Nominal Orbit: 400 km Circular

<table>
<thead>
<tr>
<th>Source</th>
<th>Attitude Offset</th>
<th>Per Axis, arc · sec</th>
<th>Per Axis Geometric Error, m</th>
<th>2 Axes, Geometric Error, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU/Shuttle Misalignment</td>
<td>No Offset</td>
<td>82</td>
<td>159</td>
<td>225</td>
</tr>
<tr>
<td>IMU Resolution ²</td>
<td></td>
<td>20</td>
<td>39</td>
<td>55</td>
</tr>
<tr>
<td>IMU Noise</td>
<td></td>
<td>20</td>
<td>39</td>
<td>55</td>
</tr>
<tr>
<td>Rate Gyro</td>
<td></td>
<td>60 arc sec/sec</td>
<td>116 m/s</td>
<td>165 m/s</td>
</tr>
<tr>
<td>Combined Shuttle/IS Misalignment</td>
<td></td>
<td>87</td>
<td>169</td>
<td>239</td>
</tr>
<tr>
<td>IMU/Shuttle Misalignment</td>
<td>20° Roll Offset</td>
<td>82</td>
<td>187</td>
<td>245</td>
</tr>
<tr>
<td>IMU Resolution ²</td>
<td></td>
<td>20</td>
<td>46</td>
<td>60</td>
</tr>
<tr>
<td>IMU Noise</td>
<td></td>
<td>20</td>
<td>46</td>
<td>60</td>
</tr>
<tr>
<td>Rate Gyro</td>
<td></td>
<td>60 arc sec/sec</td>
<td>137 m/s</td>
<td>180 m/s</td>
</tr>
<tr>
<td>Combined Shuttle/IS Misalignment</td>
<td></td>
<td>87</td>
<td>198</td>
<td>260</td>
</tr>
<tr>
<td>IMU/Shuttle Misalignment</td>
<td>45° Pitch Offset</td>
<td>82</td>
<td>358</td>
<td>426</td>
</tr>
<tr>
<td>IMU Resolution ²</td>
<td></td>
<td>20</td>
<td>87</td>
<td>104</td>
</tr>
<tr>
<td>IMU Noise</td>
<td></td>
<td>20</td>
<td>87</td>
<td>104</td>
</tr>
<tr>
<td>Rate Gyro</td>
<td></td>
<td>60 arc sec/sec</td>
<td>262 m/s</td>
<td>312 m/s</td>
</tr>
<tr>
<td>Combined Shuttle/IS Misalignment</td>
<td></td>
<td>87</td>
<td>379</td>
<td>452</td>
</tr>
</tbody>
</table>

² Combined roll and pitch axes.
V. GROUND PATTERNS AND IMAGE DISTORTIONS

The extent that direct errors and earth geometric properties affect the performance of the Shuttle Imaging Spectrometer are analyzed and extensively illustrated with charts and tables in section IV. The advantages of tables and charts are that they carry precise and specific information which is invaluable for design and performance prediction. However, it is difficult to relate this information directly to images of ground objects by human brains. To compensate for this and to make direct observation of how errors in the system affect ground images, selected ground patterns as seen through this optical system are studied here.

The patterns that are readily generated and, most importantly, suitable for exhibiting imaging distortions are square grid patterns.

To cover a large ground that is comparable to the field of view of the imaging spectrometer, a 10 km field is selected and the field is evenly divided into 10 segments of 1 km each. Since the imaging spectrometer employs a push broom principle, each field is then 10 km wide (cross track) and 30 m "long" (along track). However, to see a large ground area, a 10 km x 10 km field is employed with the along track grids tagged with time. Considering a perfectly spherical earth, an imaginary 10 x 10 grid is painted on the ground. As the satellite flies through this region, in the direction from the bottom to the top of the paper, a push broom camera should see a pattern just like that of Fig. 43(a). This pattern is referred to as the nominal ground pattern.

Fig. 43 shows how the ground pattern changes when simple attitude error occurs without considering the effect of Earth rotation. To show the effect of errors, the solid pattern (actual) is overlayed with the "+" pattern (the undistorted nominal pattern). Fig. 43(b) shows that when a 0.1° roll attitude error occurs, the IS instrument points 0.1° left of the object field and the image on
Fig. 43. Ground Pattern Distortions With No Earth Rotation Effect
the "film" has shifted to the right; therefore, the solid pattern has shifted to the right of the "+" pattern. The same explanation applies also to the 0.1° pitch error as shown in Fig. 43(d), except that, for pitch, the pattern image has shifted to the "-"-along track" direction. A 5° yaw error (clockwise rotation) will make the pattern appear skewed as shown in Fig. 43(c).

Fig. 44 shows the effects of simple attitude errors with 20° roll offset. With the large roll angle, the nominal pattern itself has suffered cross track distortions, i.e., the pattern image appears shrunk cross-trackwise as shown in Fig. 44(a). In Fig. 44(b), (c), and (d), the "+" patterns represent the distorted nominal patterns due to roll offset alone and the solid patterns represent those due to attitude errors on top of roll offset. The distortions are similar to those found in Fig. 43 except that with the 20° roll offset the images appear narrower.

The effects of simple attitude errors with 45° pitch offset are shown in Fig. 45. The effect of pitch offset is similar to roll offset, i.e., the nominal pattern image has shrunk cross-trackwise. One might expect also along-track shrinkage. The reason that there is no along-track shrinkage is because of the push-broom effect. Shrinkage will occur for a frame camera, however. It is noted that the pattern images associated with the 45° pitch offset are narrower than those of the 20° roll offset. This is due to the fact that 20° is a lot less than 45°.

The effects of constant attitude rate errors are shown in Fig. 46. Rate errors cause accumulation of attitude errors, i.e., the attitude errors grow with time t. Take the 0.1 deg/sec rate error for the roll axis for instance, the roll error is 0.1 t; whereas, the 0.1° roll error (Fig. 43(b)) at t = 0 is 0; therefore, the "+" pattern image coincides with the solid one at a very
(a) NOMINAL GROUND PATTERN

(b) WITH 0.05° ROLL ERROR

(c) WITH 5° YAW ERROR

(d) WITH 0.1° PITCH ERROR

Fig. 44. Ground Pattern Distortions With 20° Roll Offset and No Earth Rotation Effect
Fig. 45. Ground Pattern Distortions With 45° Pitch Offset and No Earth Rotation Effect
Fig. 46. Ground Pattern Distortions With Constant Rotation Rate and No Earth Rotation Effect
small t. Shown in Fig. 46(b) is the solid pattern shift to the right at a constant slope with time, which is quite different from Fig. 43(b). Similar comment applies to Fig. 46(c) and (d).

The effects of sinusoidal attitude rates on the pattern images are shown in Fig. 47. For instance, the sinusoidal rate causing a 0.2 sin (4.51378t) degree roll error will make the image appear as the shape "S", as shown in Fig. 47(b). The same function applied to the pitch axis will cause along-track distortions with densely packed grid lines followed by loosely packed ones, etc., as illustrated in Fig. 47(d).

Altitude change causes images to vary in size. Again, it affects the cross-track much more than the along-track due to the push-broom principle. As shown in Fig. 48, the solid image has shrunk cross-trackwise but expanded along-trackwise. The former is due to the altitude increase of 40 km which has no amplification effect on push-broom camera; the latter is due to the fact that, at higher altitude, the orbital rate is decreased, i.e., it will take a longer period of time to fly through the same ground area.

Finally, the effects of earth rotation are shown in Fig. 49. Earth rotation will cause the image to skew toward the direction of earth rotation. As discussed in section IV, the effect of the image shift is most pronounced when the satellite flies through the equator, and reduces as the latitude increases. Earth rotation will not cause along-track distortions.

Computer programs that are used to generate these patterns and distortions are listed in Appendix F.
Fig. 47. Ground Pattern Distortions With Sinusoidal Rotation Rate and No Earth Rotation Effect
Fig. 48. Ground Pattern Distortions With Effect of Altitude Change (increase) of 40 km and No Earth Rotation Effect.
Fig. 49. Ground Pattern Distortions With Effect of Earth Rotation for 40° Latitude and Orbit Inclination of 85°
VI. CONCLUSIONS

1. The effects of earth curvature are very small for the application here (see Fig. 42).

2. Altitude uncertainties cause only moderate geometric errors. The worst 1σ geometric errors are 11.71 m in position and 0.133 m/sec in rate with STDN and large unmodeled perturbations at 200 km orbit. The performance improves with TDRSS. For the 300 km orbit and with small unmodeled perturbations, the 1σ geometric errors will reduce to 0.22 m and 0.0032 m/sec (see Table 11).

3. The effects of other navigation errors are significantly greater. The 1σ downtrack errors range from 203 m (300 km orbit) to 8128 m (200 km orbit); and those for the cross track are 152 m to 508 m (see Table 12).

4. The effects of roll and pitch attitude errors are relatively large compared with, for instance, those caused by yaw errors and altitude uncertainties. The error sensitivity is 1.94 m/arc sec or approximately 7000 m/degree. The yaw sensitivity is 0 for a 0° view angle and 0.028 m/arc sec for the maximum view angle of ±0.825° (see Table 12).

5. The error sensitivities of attitude errors increase significantly for large attitude offsets. For 20° side looking, the sensitivity increases to 2.28 m/arc sec for roll errors and to 0.75 m/arc sec for yaw errors, and the pitch error sensitivity is almost unaffected. For the 45° forward looking case, the sensitivities for the pitch, roll, and yaw errors increase to 2.83, 4.36, and 1.97 m/arc sec, respectively (see Table 13).

6. The performance of the Shuttle Imaging Spectrometer is limited by the Shuttle IMU (Inertial Measuring Unit) accuracy, instrument misalignment, Shuttle RCS (Reaction Control Subsystem) deadband, etc. unless some means of error reduc-
tion are employed. For instance, ground control points may be used to reduce navigation prediction errors; and precision point mounts, such as AGS (ASPS+) Gimbal System) and IPS (Instrument Pointing System), may be used to reduce the attitude errors. The single axis geometric errors due to the combined Shuttle/IS misalignment, for instance, for normal nadir pointing, 20° side looking, and 45° forward looking are 169 m, 198 m, and 379 m, respectively (refer to Table 14).

7. Earth rotation causes shifts of images toward the direction of rotation. The magnitude of these shifts depends on the latitude of the object. For instance, at the equator the object moves approximately 462 m in one second (for 400 km orbit), and at 60° latitude it moves only 231 m in one second.

8. Distorted images for selected ground patterns provide revealing information of the effects of system errors to the images of ground objects.

+ Annular Suspension Pointing System
REFERENCES


APPENDICES
APPENDIX A
GEOMETRIC ERROR MAPPING FUNCTION TABLE

Part A: Given the attitude offsets and a view angle, find the coordinates of the corresponding ground points before and after the errors are introduced.

<table>
<thead>
<tr>
<th>Error Sources</th>
<th>Geometric Error Mapping Function</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Altitude Error, \( \Delta h \) | At nominal altitude \( h \), a view angle \( \lambda \) is given which sights a ground point \( P(O, Y_0) \). After elevating \( \Delta h \), the same view angle will sight another ground point \( P'(0, Y'_0) \). The following equations are for obtaining \( Y_0 \) and \( Y'_0 \):
| | \[
Y_0 = -R \sin \lambda \left[ (1 + \frac{h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \right]
\]
| | \[
Y'_0 = -R \sin \lambda \left[ (1 + \frac{h + \Delta h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h + \Delta h}{R}\right)^2 \sin^2 \lambda} \right]
\] | \( R = \) Earth Radius |
| Yaw Error, \( \psi \) | Given a yaw offset \( \psi \) and a view angle \( \lambda \) which sights a ground point \( P(X^*, Y^*) \). The same view angle will sight another ground point \( P'(X'^*, Y'^*) \) after yaw error \( \psi \) is introduced. The following equations are for obtaining \( X^*, Y^*, X'^* \), and \( Y'^* \):
| | \[
X^* = \left[ (1 + \frac{h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \right] R \sin \lambda \sin \psi
\]
| | \[
Y^* = -\left[ (1 + \frac{h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \right] R \sin \lambda \cos \psi
\] | \( R = \) Earth Radius \( h = \) Nominal Altitude |
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</table>
| Roll Error, $\phi$ | $X^* = \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right] R \sin \lambda \sin (\psi_o + \psi)$ | $R = \text{Earth Radius}$  
$h = \text{Nominal Altitude}$ |
|                | $Y^* = \left[ \left( 1 + \frac{h}{R} \right) \cos \lambda - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \lambda} \right] R \sin \lambda \cos (\psi_o + \psi)$ |          |
| Pitch Error, $\theta$ | $Y^* = -R \sin (\lambda + \phi_o) \left[ \left( 1 + \frac{h}{R} \right) \cos (\lambda + \phi_o) - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 (\lambda + \phi_o)} \right]$ | $R = \text{Earth Radius}$  
$h = \text{Nominal Altitude}$  
For $\tau$ and $\xi$, refer to Fig. 23. |
<p>|                | $Y^* = -R \sin (\lambda + \phi_o + \phi) \left[ \left( 1 + \frac{h}{R} \right) \cos (\lambda + \phi_o + \phi) - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 (\lambda + \phi_o + \phi)} \right]$ |          |
|                | $X^* = R \left[ \left( 1 + \frac{h}{R} \right) \cos \tau - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \tau} \right] \frac{\sin \tau \sin \theta_o}{\sqrt{\sin^2 \theta_o + \tan^2 \lambda}}$ |          |
|                | $Y^* = -R \left[ \left( 1 + \frac{h}{R} \right) \cos \tau - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \tau} \right] \frac{\sin \tau \tan \lambda}{\sqrt{\sin^2 \theta_o + \tan^2 \lambda}}$ |          |</p>
<table>
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<tbody>
<tr>
<td></td>
<td>[ X' = R \left[ \left( 1 + \frac{h}{R} \right) \cos \xi - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi} \right] \frac{\sin \xi \sin (\theta_o + \theta)}{\sin^2 (\theta_o + \theta) + \tan^2 \lambda} ]</td>
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<tr>
<td></td>
<td>[ Y' = -R \left[ \left( 1 + \frac{h}{R} \right) \cos \xi - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi} \right] \frac{\sin \xi \tan \lambda}{\sin^2 (\theta_o + \theta) + \tan^2 \lambda} ]</td>
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<tr>
<td></td>
<td>[ \xi = \tan^{-1} \left( \sec (\theta_o + \theta) \sqrt{\sin^2 (\theta_o + \theta) + \tan^2 \lambda} \right) ]</td>
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<tr>
<td></td>
<td>[ \tau = \tan^{-1} \left( \sec \theta_o \sqrt{\sin^2 \theta_o + \tan^2 \lambda} \right) ]</td>
<td></td>
</tr>
<tr>
<td>Yaw Error ( \psi ), Followed by pitch error ( \theta ), then roll error ( \phi )</td>
<td>Given a yaw offset ( \psi_0 ), followed by a pitch offset ( \theta_0 ), then a roll offset ( \phi ). A view angle ( \lambda ) is also given which sights a ground point ( P_0(X_0, Y_0) ). After the errors ( \psi ), ( \theta ), and ( \phi ) are introduced, the same view angle will sight another ground point ( P_3(X_3, Y_3) ). The following equations are for obtaining ( X_0', Y_0', X_3, ) and ( Y_3 ): [ X_0' = \frac{R \sin \theta \sin \xi_o \left[ \left( 1 + \frac{h}{R} \right) \cos \xi_o - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi_o} \right]}{\sqrt{\sin^2 \theta_o + \tan^2 (\lambda + \phi)}} ]</td>
<td>R = Earth Radius, ( h = \text{Nominal Altitude} ) For ( \xi_0 ) and ( \xi_3 ), refer to Fig. 23.</td>
</tr>
<tr>
<td></td>
<td>[ Y_0' = -\frac{R \tan (\lambda + \phi) \sin \xi_o \left[ \left( 1 + \frac{h}{R} \right) \cos \xi_o - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi_o} \right]}{\sqrt{\sin^2 \theta_o + \tan^2 (\lambda + \phi)}} ]</td>
<td></td>
</tr>
<tr>
<td>Error Sources</td>
<td>Geometric Error Mapping Function</td>
<td>Comments</td>
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<tr>
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</tr>
<tr>
<td>$X'_3 = \frac{R \sin (\theta_0 + \theta) \sin \xi_3 \left[ (1 + \frac{b}{R}) \cos \xi_3 - \sqrt{1 - \left(1 + \frac{b}{R}\right)^2 \sin^2 \xi_3} \right]}{\sqrt{\sin^2 (\theta_0 + \theta) + \tan^2 (\lambda + \phi_0 + \phi)}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y'_3 = -\frac{R \tan (\lambda + \phi_0 + \psi) \sin \xi_3 \left[ (1 + \frac{b}{R}) \cos \xi_3 - \sqrt{1 - \left(1 + \frac{b}{R}\right)^2 \sin^2 \xi_3} \right]}{\sqrt{\sin^2 (\theta_0 + \theta) + \tan^2 (\lambda + \phi_0 + \psi)}}$</td>
<td></td>
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</tr>
<tr>
<td>$\xi_0 = \tan^{-1} \left( \sec \theta_0 \sqrt{\sin^2 \theta_0 + \tan^2 (\lambda + \phi_0)} \right)$</td>
<td></td>
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<tr>
<td>$\xi_3 = \tan^{-1} \left[ \sec (\theta_0 + \theta) \sqrt{\sin^2 (\theta_0 + \theta) + \tan^2 (\lambda + \phi_0 + \psi)} \right]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_0 = X'_0 \cos \phi_0 - Y'_0 \sin \phi_0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_0 = X'_0 \sin \phi_0 + Y'_0 \cos \phi_0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_3 = X'_3 \cos (\psi_0 + \psi) - Y'_3 \sin (\psi_0 + \psi)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_3 = X'_3 \sin (\psi_0 + \psi) + Y'_3 \cos (\psi_0 + \psi)$</td>
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</tbody>
</table>
Part B: Given the coordinates of a ground point, find the attitude offsets, the corresponding view angle and the coordinates of the point with the same view angle after the errors are introduced.

<table>
<thead>
<tr>
<th>Error Sources</th>
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</thead>
<tbody>
<tr>
<td>Altitude Error, $\Delta h$</td>
<td>At nominal altitude $h$, a ground point $P(X_o, Y_o)$ corresponding to view angle $\lambda$ is given. After elevating $\Delta h$, the same view angle $\lambda$ will aim at another ground point $P'(X'_o, Y'_o)$. The following equations are for obtaining $X'_o$ and $Y'_o$:</td>
<td></td>
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<tr>
<td></td>
<td>$\lambda = \tan^{-1} \left( \frac{\sqrt{X_o^2 + Y_o^2}}{R + h - \sqrt{R^2 - X_o^2 - Y_o^2}} \right)$</td>
<td>R = Earth Radius</td>
</tr>
<tr>
<td></td>
<td>$X'_o = \frac{RX_o \sin \lambda}{\sqrt{X_o^2 + Y_o^2}} \left[ (1 + \frac{h + \Delta h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h + \Delta h}{R}\right)^2 \sin^2 \lambda} \right]$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y'_o = \frac{RY_o \sin \lambda}{\sqrt{X_o^2 + Y_o^2}} \left[ (1 + \frac{h + \Delta h}{R}) \cos \lambda - \sqrt{1 - \left(1 + \frac{h + \Delta h}{R}\right)^2 \sin^2 \lambda} \right]$</td>
<td></td>
</tr>
</tbody>
</table>
A ground point $P(0, y^*)$ corresponding to roll offset $\phi_o$ and view angle $\lambda$ is given. After roll error $\phi$ is introduced, the same view angle $\lambda$ will aim at another ground point $P'(0, y^*)$. The following equations are for obtaining $y^*$:

\[
\lambda + \phi_o = -\text{sgn}(y^*) \tan^{-1} \left( \frac{|y^*|}{R + h - \sqrt{R^2 - y^*^2}} \right)
\]

\[
y^* = -R \sin'(\lambda + \phi_o) \left[ \left(1 + \frac{h}{R}\right) \cos(\lambda + \phi_o) \phi \right]
\]

\[
-\sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2(\lambda + \phi_o) \phi}
\]

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Roll Error, $\phi$</td>
<td>$\lambda + \phi_o = -\text{sgn}(y^*) \tan^{-1} \left( \frac{</td>
<td>y^*</td>
</tr>
<tr>
<td></td>
<td>$y^* = -R \sin'(\lambda + \phi_o) \left[ \left(1 + \frac{h}{R}\right) \cos(\lambda + \phi_o) \phi \right]$</td>
<td>$h = \text{Nominal Altitude}$</td>
</tr>
<tr>
<td></td>
<td>$-\sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2(\lambda + \phi_o) \phi}$</td>
<td></td>
</tr>
<tr>
<td>Error Sources</td>
<td>Geometric Error Mapping Function</td>
<td>Comments</td>
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<tr>
<td>------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Pitch Error, θ         | A ground point \( P(X^*, Y^*) \) corresponding to pitch offset \( \theta_0 \) and view angle \( \lambda \) is given. After pitch error \( \theta \) is introduced, the same view angle \( \lambda \) will aim at another ground point \( P'(X'^*, Y'^*) \). The following equations are for obtaining \( X'^* \) and \( Y'^* \): | \( R = \) Earth Radius
\( h = \) Nominal Altitude
For \( \xi \), refer to Fig.23. |

\[
\lambda = \tan^{-1} \left( \frac{Y^*}{R + h - \sqrt{R^2 - X^*^2 - Y^*^2}} \left( 1 + \left( \frac{X^*}{R + h - \sqrt{R^2 - X^*^2 - Y^*^2}} \right)^2 \right) \right)
\]

\[
\theta_0 = \tan^{-1} \left( \frac{X^*}{R + h - \sqrt{R^2 - X^*^2 - Y^*^2}} \right)
\]

\[
\xi = \tan^{-1} \left( \frac{\sec (\theta_0 + \theta) \sqrt{\sin^2(\theta_0 + \theta) + \tan^2 \lambda}}{\sec (\theta_0 + \theta) \sqrt{\sin^2(\theta_0 + \theta) + \tan^2 \lambda}} \right)
\]

\[
X'^* = \frac{R \sin (\theta_0 + \theta) \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi} \right]}{\sqrt{\sin^2(\theta_0 + \theta) + \tan^2 \lambda}}
\]

\[
Y'^* = \frac{-R \tan \lambda \sin \xi \left[ (1 + \frac{h}{R}) \cos \xi - \sqrt{1 - \left( 1 + \frac{h}{R} \right)^2 \sin^2 \xi} \right]}{\sqrt{\sin^2(\theta_0 + \theta) + \tan^2 \lambda}}
\]
### Geometric Error Mapping Function

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<tbody>
<tr>
<td>Yaw Error, $\psi$</td>
<td>A ground point $P(X*,Y*)$ corresponding to yaw offset $\psi_o$ and a certain view angle is given. After yaw error $\psi$ is introduced, the same view angle will aim at another ground point $P'(X'^<em>,Y'^</em>)$. The following equations are for obtaining $X'^<em>$ and $Y'^</em>$:</td>
<td></td>
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<tr>
<td></td>
<td>$\psi_o = -\tan^{-1} \left( \frac{X*}{Y*} \right)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\lambda = -\text{sgn}(Y*) \tan^{-1} \left( \frac{\sqrt{X^2 + Y^2}}{R + h - \sqrt{R^2 - X^2 - Y^2}} \right)$</td>
<td></td>
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<tr>
<td></td>
<td>$X'^* = \left[ \left(1 + \frac{h}{R}\right) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \right] R \sin \lambda \sin (\psi_o + \psi)$</td>
<td></td>
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<tr>
<td></td>
<td>$Y'^* = -\left[ \left(1 + \frac{h}{R}\right) \cos \lambda - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \lambda} \right] R \sin \lambda \cos (\psi_o + \psi)$</td>
<td></td>
</tr>
<tr>
<td>Earth Rotation</td>
<td>Let $\Gamma$ be the shuttle orbital inclination at the equator, and $\zeta$ be the latitude of the nadir point. A given point $P(X,Y)$, after time period $\Delta t$, will move to $P'(X',Y')$. The following equations are for obtaining $X'$ and $Y'$:</td>
<td></td>
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<tr>
<td></td>
<td>$V_e = \omega R \cos \zeta$</td>
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<tr>
<td></td>
<td>$\omega = \frac{2\pi}{86,400}$ radians/sec</td>
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</tr>
<tr>
<td></td>
<td>$X' = X + \frac{\cos \Gamma}{\cos \zeta} V_e \Delta t$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y' = Y + \sqrt{1 - \left(\frac{\cos \Gamma}{\cos \zeta}\right)^2} V_e \Delta t$</td>
<td></td>
</tr>
</tbody>
</table>

- $R$ = Earth Radius
- $h$ = Nominal Altitude
- $V_e$ = Linear Velocity of Ground Point at Latitude $\zeta$
- $\omega$ = Angular Velocity of Earth Rotation
- $\Delta t$ is assumed small.
<table>
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</thead>
<tbody>
<tr>
<td>Yaw Error $\psi$ followed by Pitch Error $\theta$ then Roll Error $\phi$</td>
<td>A ground point $P(0,Y^<em>)$ corresponding to view angle $\lambda$ (with no attitude offset) is given. A yaw error $\psi$ is introduced first, then a pitch error $\theta$, finally a roll error $\phi$. The same view angle $\lambda$ will then aim at another ground point $P'(X',Y'^</em>)$. The following equations are for obtaining $X'$ and $Y'$:</td>
<td>$R = \text{Earth Radius}$ $h = \text{Nominal Altitude}$ For $\xi$, refer to Fig. 23.</td>
</tr>
</tbody>
</table>

$$\lambda = - \text{sgn}(Y^*) \tan^{-1} \left( \frac{|Y^*|}{R + h - \sqrt{R^2 - Y^*^2}} \right)$$

$$\xi = \tan^{-1} \left[ \sec \theta \sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)} \right]$$

$$X = \frac{R \sin \theta \sin \xi \left[ \left(1 + \frac{h}{R}\right) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi} \right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}}$$

$$Y = \frac{-R \tan (\lambda + \theta) \sin \xi \left[ \left(1 + \frac{h}{R}\right) \cos \xi - \sqrt{1 - \left(1 + \frac{h}{R}\right)^2 \sin^2 \xi} \right]}{\sqrt{\sin^2 \theta + \tan^2 (\lambda + \phi)}}$$

$$X' = X \cos \phi - Y \sin \phi$$

$$Y' = X \sin \phi + Y \cos \phi$$
APPENDIX B

NAPIER'S RULES FOR RIGHT SPHERICAL TRIANGLES*

A right spherical triangle has five variable parts. If these components and their complements (complement of \( \Gamma = 90^\circ - \Gamma \)) are arranged in a circle, as illustrated below:

Then, the following relationships hold between the five components in the circle:

The sine of any component equals the product of either:

1. The tangents of the adjacent components, or
2. The cosines of the opposite components

For our case, from 2:

\[
\sin (90^\circ - \Gamma) = \cos \zeta \cos (90^\circ - A)
\]

i.e.,

\[
\cos \Gamma = \cos \zeta \sin A
\]

*See Ref. 13
APPENDIX C

COMPUTER PROGRAM FOR SHUTTLE IMAGING SPECTROMETER POINTING ERROR

POWER SPECTRAL DENSITIES FOR CONFIGURATION A — PAYLOAD-BAY NADIR POINTING

ELT $\text{MED-10/28-10:22:28-152,}$
12537IS(1), SWAP=PRIS(12)
1 PROGRAM IMAGING SPECTROMETER SHUTTLE RIGID MOUNT — A
2: INITIAL
3: VARIABLE T=0.0
4: INTEGER FMUM,NPOINT
5:
6:
7: COMMENT INITIALIZE SOME PARAMETERS
8: CONSTANT NPOINT=641
9: CONSTANT FMUM=39
10: CALL FOPEN(FMUM)
11: TFNAM=1.0*NPOINT-1.0
12: CONSTANT FACTOR=0.0
13: CONSTANT SCFAC=1.0E+5
14: SCFAC2=SCFAC*SCFAC
15: SCF2DB=1.0*LLOG10(SCFAC2)
16:
17: COMMENT SET VARIOUS MATHEMATICAL CONSTANTS
18: PI=3.14159265
19: RSRC=PI/1180.0*3600.0
20: RSRC2=1.0E12.0*PI
21:
22: COMMENT DEFINE MOMENTS OF INERTIA
23: CONSTANT IX=1.3BE+6
24: CONSTANT IY=1.0E+7
25: CONSTANT IZ=1.0E+7
26: IXZ=IX*IY
27: IYZ=IY*IY
28: IZZ=IZ*IZ
29: IXYZ=IX+IY+IZ
30: IXZ2=IXZ*IXZ
31:
32: COMMENT DEFINE W0
33: CONSTANT W0=0.0011315
34: W04=W0*W0
35: W05=W0*W0
36:
37: COMMENT DEFINE INITIAL ANGLES AND RATES
38: CONSTANT TH0=0.0
39: CONSTANT PHIO=0.0
40: CONSTANT PSI0=0.0
41: CONSTANT TH0D=0.0
42: CONSTANT PHID=0.0
43: CONSTANT PSID=0.0
44: TH02=TH0*TH0
45: PHIO2=PHIO*PHIO
46: PHID2=PHID*PHID
47: PSI02=PSI0*PSI0
48: PSI0D=PSI0D
49: PSI02=PSI0D
50:
51: COMMENT DEFINE G'S
52: CONSTANT GX=2.014E-6
53: CONSTANT GY=1.251E-3
54: CONSTANT GZ=5.438E-4
55:
56: COMMENT DEFINE RATE FILTER PARAMETERS
57: CONSTANT WD=0.2513
58: CONSTANT ZET0=0.0
59: WD4=WD*WD
60: WD5=WD*WD
61: ZET02=ZET0*ZET0
62:
63: COMMENT DEFINE VARIOUS CONSTANTS
64: CONSTANT R=0.35E-10

125
65: CONSTANT SIGBO=87.22
66: SIGBO=SIGBO*SIGBO*SIGBO
67: SIGBO=SIGBO*SIGBO
68: CONSTANT TAU=0.023
69: TAU=TAU*TAU
70: DELW=1.0
71: 72: COMMENT DEFINE W CONSTANTS AND INITIALIZE W
73: CONSTANT WL=6.2631853167
74: CONSTANT WFACT=1.029200527
75: W=WL/WFACT
76:
77: END
78: DYNAMIC
79: INTERVAL CI=1.0
80: 81: COMMENT COMPUTE W
82: W=WFACT
83: PROCEDURE(DELW=W)
84: DELW=0.0
85: IF(W.LE.0.) DELW=1.0
86: END
87: W=W+2*WCC
88: FZERO=RLG101(WH)
89: W2=W4
90:
91: 92: COMMENT COMPUTE M42 AND DM2
93: M42=1.0/(TAU2+W2-1.0)
94: DM2=W4+M42/(1-W2+W2)*2+4.0*W2+W2*M42
95: DM2=W4*M42+M42*(1-W2+3.0*W2+W2)***M42
96: COMMENT DM2=M42+W4+W2*(1-Y+1-Y)*W2
97: DM2=DM2/(SCRFRC)
98: DM2=DM2+W2
99:
100: COMMENT COMPUTE F'S
101: COMMENT FTHW2=M42*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
102: COMMENT FNU2=(1-Z+W2-W2*1-Y)*W2
103: COMMENT FTHW2=W4*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
104: FTHW2=NU2*W4*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
105: FTHW2=NU2*W4*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
106: FTHW2=NU2*W4*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
107: FTHW2=NU2*W4*SCRFRC/(1-W2+3.0*W2+1-Y)*W2
108: 
109: COMMENT COMPUTE PSD'S
110: 
111: COMMENT PITCH PSD COMPUTATIONS
112: PPW1=FTHW2*Y2*TH0Z
113: PPW2=FTHW2*Y2*TH0Z
114: PPW3=FTHW2*Y2*TH0Z
115: PPW4=FTHW2*Y2*TH0Z
116: PPW5=PPW1+PPW2+PPW3+PPW4+PPW5
117: PPW6=PPW1+PPW2+PPW3+PPW4+PPW5
118: COMMENT ROLL PSD COMPUTATIONS
119: PRW1=FTHW2*X2*PHI0Z
120: PRW2=FTHW2*X2*PHI0Z
121: PRW3=FTHW2*X2*PHI0Z
122: PRW4=FTHW2*X2*PHI0Z
123: PRW5=FTHW2*X2*PHI0Z
124: PRW6=FTHW2*X2*PHI0Z
125: PRW7=FTHW2*X2*PHI0Z
126: PRW8=FTHW2*X2*PHI0Z
127: PRW9=SIGBO2+DELW
128: PRW10=(PRW1+PRW2+PRW3+PRW4+PRW5+PRW6+PRW7+PRW8+PRW9+PRW10)/SCRFRC2
129: PRW11=PRW1+PRW2

126
131: COMMENT YFW PSD COMPUTATIONS
132:  PYW1+PYM2*IXZ*PSI02
133:  PYW2+PYM2*IXZ*PSI02*IXZ
134:  PYW3+PYM2*IXZ*IXYZZ*PSI02
135:  PYM4+PYM2*IXZ
136:  PYM5+PYM2*IXZ*PSI02
137:  PYM6+PYM2*IXZ*PSI02*IXZ
138:  PYM7+PYM2*IXZ*IXYZZ*PSI02
139:  PYM8+PYM2*IXZ*IX
140:  PYM9+PYM2+PYM3+PYM4+PYM5+PYM6+PYM7+PYM8)}/SCFAC2
141:  PYM0+PYM2/H02
142:  
143:  
144: COMMENT PREPARE VARIABLES FOR OUTPUT
145:  RSIG=P+SIGB02*DELW
146:  RS10DB=10.0*ALOG10(RSIG)+FACTOR
147:  PPW3DB=10.0*ALOG10(PPW3)+SCFDB+FACTOR
148:  PPW4DB=10.0*ALOG10(PPW4)+SCFDB+FACTOR
149:  PRW5DB=10.0*ALOG10(PRW4)+SCFDB+FACTOR
150:  PRW6DB=10.0*ALOG10(PRW4)+SCFDB+FACTOR
151:  PRW7DB=10.0*ALOG10(PRW4)+FACTOR
152:  PRW8DB=10.0*ALOG10(PRW4)+SCFDB+FACTOR
153:  PRW8DB=10.0*ALOG10(PRW4)+SCFDB+FACTOR
154:  PRW9DB=10.0*ALOG10(PRW4)+FACTOR
155:  
156:  PPWODB=10.0*ALOG10(PPW4)+FACTOR
157:  PRW6DB=10.0*ALOG10(PRW4)+FACTOR
158:  PRW9DB=10.0*ALOG10(PRW4)+FACTOR
159:  
160: COMMENT SAVE NUMBERS IN FILE
161:  CALL FSAVE(FREQ,PPWDB,PRWDB,PRWDB,FNUM)
162:  
163:  
164:  TERMT(,GE,FINAL)
165:  DERIVATIVE
166: ALGORITHM ALG-3
167:  GO=INTEG(1,0,0,0)
168: END
169: END
170: TERMINAL
171: 
172: COMMENT CLOSE FILE
173: CALL FCLOSE(FNUM)
174: END
175: END

EOF:175
0:10 WED-10/20/82-10:30:02-(3,)
12537*IS(1),SSAV,FSUBS(3)
1:0FOR,IS FF,FOPEN
2: SUBROUTINE FOPEN(N)
3: Rewind N
4: RETURN
5: CIC
6:0FOR,IS FF,FSAVE
7: SUBROUTINE FSAVE(N,P1,P2,P3,N)
8: WRITE(N,100)N,P1,P2,P3
9: 100 FORMAT(4G14.8)
10: RETURN
11: END
12:0FOR,IS FF,FCLOSE
13: SUBROUTINE FCLOSE(N)
14: ENDFILE N
15: RETURN
16: END
EDF:16

128
APPENDIX D

COMPUTER PROGRAM FOR SHUTTLE IMAGING SPECTROMETER POINTING ERROR

POWER SPECTRAL DENSITIES FOR CONFIGURATION B — NOSE-DOWN NADIR POINTING

```
ELT  WED-10/20/82-10:36:41-(14,)
12337/15(1).ERHB/PROG(14)
1:PROGRAM IMAGING SPECTROMETER SHUTTLE RIGID MOUNT - B
2:INITIAL
3:VARIABLE T=0.0
4:  INTEGER NPREP,NPOINT
5:
6:7:COMMENT INITIALIZE SOME PARAMETERS
8:  CONSTANT NPREP=641
9:  CONSTANT NPREP=39
10: CALL FORNT(NPREP)
11:  TEMP=1.0/NPREP-1.0
12:  CONSTANT FACTOR=0.0
13:  CONSTANT SCFAC=1.0E+10
14:  SCFAC2=SCFAC+SCFAC
15:  SCF2DB=10.0*LOG10(SCFAC2)
16:
17:COMMENT SET VARIOUS MATHEMATICAL CONSTANTS
18:  PI=3.14159265
19:  ASRCC=PI/180.0*3.0
20:  ASR2CC=1.0/12.0*PI
21:
22:COMMENT DEFINE MOMENTS OF INERTIA
23:  CONSTANT IX=1.0E+7
24:  CONSTANT IY=1.0E+7
25:  CONSTANT IZ=1.0E+7
26:  IX2=IX*IX
27:  IY2=IX*IX
28:  IZ2=IX*IX
29:  IX2=IX*IX
30:  IXY2=IXY2
31:
32:COMMENT DEFINE W0
33:  CONSTANT W0=0.0011315
34:  W02=W0*W0
35:  W04=W0*W0*W0
36:
37:COMMENT DEFINE INITIAL ANGLES AND RATES
38:  CONSTANT TH0=0.0
39:  CONSTANT PHI0=0.0
40:  CONSTANT PSI0=0.0
41:  CONSTANT THD=0.0
42:  CONSTANT PHI0=0.0
43:  CONSTANT PSI0=0.0
44:  TH02=TH0*TH0
45:  PHI02=PHI0*PHI0
46:  PSI02=PSI0*PSI0
47:  PHI02=PHI0*PHI0
48:  PSI02=PSI0*PSI0
49:
50:
51:COMMENT DEFINE O'S
52:  CONSTANT OX=1.5707E+4
53:  CONSTANT OY=1.28E+0
54:  CONSTANT OZ=6.32E+0
55:
56:COMMENT DEFINE RATE FILTER PARAMETERS
57:  CONSTANT MD=0.2513
58:  CONSTANT ZETD=0.8
59:  MZ=MD*MD
60:  MD2=MD*MD
61:  ZETD2=ZETD*ZETD
62:
63:COMMENT DEFINE VARIOUS CONSTANTS
64:  CONSTANT R=8.555E+10
```
CONSTANT SIGBO=87.32
SIGBO=SIGBO+SIGBOCC
SIGBO2=SIGBO+SIGBO
CONSTANT TAU=0.023
TAU=TAU*TAU
DELW=1.0

COMMENT DEFINE W CONSTANTS AND INITIALIZE W
CONSTANT MLO=6.28318531E-7
CONSTANT NFACT=1.029200527
W=MLO*NFACT

END

DYNAMIC
CINTERVAL CI=1.0

COMMENT COMPUTE W
W=W*NFACT
W=W*WFACT
END

PROCEDURE DELW=W
DELW=0.0
IF(W.LE.0.) DELW=0.0
ELSE
WHZ=W+SIGBOCC
REAL=ALOG10(WHZ)
W=W*WFACT
HWZ=W+WHZ
HWZ=(HWZ+1.0)
HWZ=W*WFACT
HWZ=HWZ/W
HWZ=HWZ/WHZ
THWZ=HW2*SCFACZ*CIIY.WZ+3.0.WOZ.fIZ-IX» ...)
FRWZ=(WZ-IXZ)*THODZ
PRWZ=WZ.IXZ*THIOZ+WZ
PRW3=WZ+SIGBOZ+DELW+(PPW1+PPW2+PPW3+PPW4+PRW1+PRW2+PRW3+PRW4)/SCFACZ
PRW0=PRW-DELW
PRW1=FYWZ-IZZ*PSIOZ

COMPUTE PSD'S

COMPUTE PITCH PSD COMPUTATIONS
PPW1=FTWZ+IX2*PHIOZ
PPW2=FTWZ+IX2*PHIOZ
PPW3=FTWZ+IX2*PHIOZ
PPW4=SIGBOZ+DELW+(PPW1+PPW2+PPW3+PPW4)/SCFACZ

COMPUTE ROLL PSD COMPUTATIONS
PRW1=FRWZ+IX2*PHIOZ
PRW2=FRWZ+IX2*PHIOZ
PRW3=FRWZ+IX2*PHIOZ
PRW4=FRWZ+IX2*PHIOZ
PRW5=FRWZ+IX2*PHIOZ
PRW6=FRWZ+IX2*PHIOZ
PRW7=FRWZ+IX2*PHIOZ
PRW8=FRWZ+IX2
PRW9=FRWZ+IX2
PPW1=PRW1+PRW2+PRW3+PRW4+PRW5+PRW6+PRW7+PRW8+PRW9)/SCFACZ
PRW0=PRW-DELW

COMPUTE YAW PSD COMPUTATIONS
FYWZ-IZZ*PSIOZ

130
131: PYW1+PYW2+PYW3+PYW4+PYW5+PYW6+PYW7+PYW8)/SCFAC2
132: PYWD·PYWI-IDWZ
133: COMMEHT PPEPRRE
134: VRRIRB~ES
135: FOR OUTPUT
136: RSIG·R+SIGBOZ*DE~W
137: R5IGDS.'0.0*P~OG10(RSIGJ+FACTOR
138: PPW3DB.'0.0*R~OG10(PPW3J-SCFZDS+FACTOR
139: PPWDS·'0.0*A~OG10(PPW)+FACTOR
140: PRW4DS-l0.0*ALOG10(PRW4J-SCFZDB+FACTOR
141: PRWDB-l0.0*R~OG10(PRWDJ+FACTOR
142: RSIGR+SIGBOZ*DELW
143: RSIGR+SIGBOZ*DELW
144: PPW3DB·l0.0*ALOG10(PPW3J-SCFZDB+FACTOR
145: PPWDB·l0.0*ALOG10(PPW)+FACTOR
146: PRW4DB·l0.0*ALOG10(PRW4J-SCFZDB+FACTOR
147: PRWDB·l0.0*ALOG10(PRWDJ+FACTOR
148: PRW4DS-l0.0*ALOG10(PRW4J-SCFZDB+FACTOR
149: PRWDB-l0.0*R~OG10(PRWDJ+FACTOR
150: Comment Save Numbers In File
151: CALL FSAVE(FREQ,PPWDB,PRWDB,PYWDS,FNUM)
152: TERM(T.GE.TFINXAL)
153: DERIVATIVE
154: ALGCRITHM 3
155: QO·INTEGR(1.0,0.0)
156: END
157: END
158: TERMINAL
159: COMMENT CLOSE FILE
160: CALL FCLOSE(FNUM)
161: END
162: END
163: EOF: 172
ELT MED-10/20-82-10:50:42-(G,) 12337#19(1),SRMB/FSUBO
1: IFOR,IS FF.FOPEN
2: SUBROUTINE FOPEN(N)
3: REWIND N
4: RETURN
5: END
6: IFOR,IS FF.FSAVE
7: SUBROUTINE FSAVE(w,p1,p2,p3)
8: WRITE(N,100)w,p1,p2,p3
9: 100 FORMAT(4I4,8)
10: RETURN
11: END
12: IFOR,IS FF.FCLOSE
13: SUBROUTINE FCLOSE(N)
14: ENDFILE N
15: RETURN
16: END

END:16
APPENDIX E

GEOMETRIC ERROR ANALYSIS PROGRAM LISTINGS

100 0 004552 DOLTA 0000 0 00263 DPTCH 0000 0 00156 DBA 0000 0 00067 C
100 0 00664 DBS12 0000 0 00262 DROL 0000 0 00262 DXY 0000 0 000170 C
100 0 00125 DTETA1 0000 0 000130 DTE2A 0000 0 00213 DTHETA 0000 0 003216 C
100 0 00214 DY 0000 0 00225 DYN 0000 0 02676 ERR 0000 0 023102 C
100 0 01582 FI 0000 0 00352 FI1 0000 0 00360 F12 0000 0 00000 C
100 0 03071 J 0000 0 03076 K 0000 0 00502 LAMDA 0000 0 000624 C
100 0 01535 PDY 0000 0 01540 PDI 0000 0 030710 PI 0000 0 01716 C
100 0 04272 P11 0000 0 00176 P12 0000 0 03264 PXY 0000 0 00742 C
100 0 02452 RA 0000 0 00520 RHI 0000 0 010254 RHO1 0000 0 01043 C
100 0 02512 RD1 0000 0 00252 RD2 0000 0 006047 SDH 0000 0 013350 C
100 0 01886 S1V1 0000 0 01502 S1V2 0000 0 005562 S1V3 0000 0 00066 C
100 0 022759 VP 0000 0 02275 VPS 0000 0 02273 V8 0000 0 022556 C
100 0 01756 X1 0000 0 00507 X2 0000 0 00316 X3 0000 0 00133 C
100 0 01276 X2 0000 0 01530 X2 0000 0 01720 X3 0000 0 00676 C
100 0 01013 Y1 0000 0 05062 Y2 0000 0 023140 Y3 0000 0 01136 C
100 0 01172 Y2 0000 0 02612 Y3

1) C THIS PROGRAM COMPUTES THE ERROR SENSITIVITIES AND GEOMETRIC
2) C ERRORS OF GROUND POINTS INDUCED BY ALTITUDE, ROLL, YAW AND
3) C PITCH ERRORS AS WELL AS EARTH ROTATION AND SHUTTLE MOTION
4)
5)
6)
7)
8)
9)
10) 8343.0 DOLTA(E10) = 100
11) 8343.0 DOLTA(E10) = 200
12) 8343.0 DOLTA(E10) = 300
13) 8343.0 DOLTA(E10) = 400
14) 8343.0 DOLTA(E10) = 500
15) 8343.0 DOLTA(E10) = 600
16) 8343.0 DOLTA(E10) = 700
17) 8343.0 DOLTA(E10) = 800
18) 8343.0 DOLTA(E10) = 900
19) 8343.0 DOLTA(E10) = 1000
20) 8343.0 DOLTA(E10) = 1100
21) 8343.0 DOLTA(E10) = 1200
22) 8343.0 DOLTA(E10) = 1300
23) 8343.0 DOLTA(E10) = 1400
24) 8343.0 DOLTA(E10) = 1500
25) 8343.0 DOLTA(E10) = 1600
26) 8343.0 DOLTA(E10) = 1700
27) 8343.0 DOLTA(E10) = 1800
28) 8343.0 DOLTA(E10) = 1900
29) 8343.0 DOLTA(E10) = 2000
30) 8343.0 DOLTA(E10) = 2100
31) 8343.0 DOLTA(E10) = 2200
32) 8343.0 DOLTA(E10) = 2300
33) 8343.0 DOLTA(E10) = 2400

133
101 CONTINUE
102 CONTINUE

DO 103 J=1,NLAMDA
LAMDA(J)=DLAMDA(J)*PI/180.
103 CONTINUE

DO 111 K=1,NDFI
F1(K)=DF1(K)*PI/180.
111 CONTINUE

DO 110 J=1,NLAMDA
LAMDA(J)=DLAMDA(J)*PI/180.
110 CONTINUE

DO 109 K=1,NDFI
F1(K)=DF1(K)*PI/180.
109 CONTINUE

135 CONTINUE
139 CONTINUE

130 CONTINUE

130 CONTINUE

130 CONTINUE
DO 132 K=I+DPSIA
   DSF(A(K))=DSF(A(K)) #(1+DPSIA(K))/#(2+DPA(K))/#(P/2)
   DSF(A(K))=DSF(A(K))/#(1+DPSIA(K))/#(P/2)
   DO 133 J=I+LAMDA
   R(A(K),J)=(1+1/H)*DCOS(LAMDA(J)) # DSRT((1+1/H)*#(1+1/H))/#(1+1/H))/#(1+1/H)
   DO 131 J=I+LAMDA
   OULY(K+J)=(RA(A(K),J))/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   CONTINUE
   131 CONTINUE
   132 CONTINUE

DO 136 I=1+P#I
   OUII(K)=DSF(K)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   OUII(K)=DSF(K)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   DO 135 J=I+LAMDA
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   YO(J)=Y(0(J)+1/H)*DCOS(LAMDA(J)) # DSRT((1+1/H)*#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   S(LAMDA(J),J)=DSRT((1+1/H))/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   DO 130 J=I+LAMDA
   CONTINUE
   130 CONTINUE
   135 CONTINUE

DO 206 K=I+DPSIA
   TETRA(K)=TETRA(K)/#(1+DPSIA(K))/#(P/2)
   TETRA(K)=TETRA(K)/#(1+DPSIA(K))/#(P/2)
   DO 205 J=I+LAMDA
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   TII(J)=TII(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   TII(J)=TII(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   DEL1(J)+=DSRT(TII(K=I+1))/+TII(K=I+1))/+TII(K=I+1))/+TII(K=I+1))/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   CONTINUE
   205 CONTINUE
   206 CONTINUE

DO 208 K=I+1/H)
   TETRA(K)=TETRA(K)/#(1+1/H))/#(P/2)
   TETRA(K)=TETRA(K)/#(1+1/H))/#(P/2)
   DO 207 J=I+LAMDA
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   LAMDA(J)=LAMDA(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   TII(J)=TII(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   TII(J)=TII(J)/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   DEL1(J)+=DSRT(TII(K=I+1))/+TII(K=I+1))/+TII(K=I+1))/+TII(K=I+1))/#(1+1/H))/#(1+1/H))/#(1+1/H))/#(P/2)
   CONTINUE
   207 CONTINUE
   208 CONTINUE

136
2620  \[V_3 = 2.6 \times 10^{-5} \times 10^4 \times 10^6 \]
2630  \[\text{TAUNDAUPE}/S/1000 \]
2640  \[\text{OMEGA}_2 = 2.0 \times 10^4 \times 10^6 \]
2650  \[DO 222 \text{KM} = \text{OMEGA} \]
2660  \[ETA(K) = \text{OMEGA}(K) = \text{ETA}(K) \]
2670  \[\text{SLUNDA(K)} = \text{OCCOB} \times \text{ETA}(K) \times \text{ETA}(K) \]
2680  \[CLUNDA(K) = \text{SORT}([\text{SLUNDA(K)}] + \text{SLUNDA(K)}) \]
2690  \[V(K) = V(K) + \text{SLUNDA(K)} \]
2700  \[V(K) = \text{SLUNDA(K)} \]
2710  \[\text{VX(K)} = \text{VY(K)} \times \text{SLUNDA(K)} \]
2720  \[\text{VX(K)} = \text{VY(K)} \times \text{VY(K)} \]
2730  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2740  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2750  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2760  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2770  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2780  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2790  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2800  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2810  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2820  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2830  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2840  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2850  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2860  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2870  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2880  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2890  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2900  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2910  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2920  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2930  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2940  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2950  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2960  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2970  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2980  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
2990  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3000  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3010  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3020  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3030  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3040  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3050  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3060  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3070  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3080  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3090  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3100  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3110  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3120  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3130  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3140  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3150  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3160  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3170  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]
3180  \[\text{ERROR} = \text{ERROR} \times \text{DELY(K,J)} \]

138
240 FORMAT(1H1, '****GEOMETRIC ERROR SENSITIVITY****',/)
241 $1 WITH RESPECT TO ALTITUDE ERROR
242 $1 ALTITUDE M = $1 F4.1 $1 km
243 $1 ALITUDE ERROR 2 TOMA = $1 F5.2 $1 km
244 $1 VIEW = 5X$1 ANGLE = $1 D1
245 $1 $2 (km) $1 10011.4 $1 $1 D1
246 $1 ERROR 2 (km) $1 10011.4 $1 $1 D1
247 $1 ERROR 1 (km) $1 10011.4
248 $1 SENSITIVITY (km/km) $1 10
249 $1 10
250 $1 10
251 $1 10
...
240 FORMAT(1H1, '****GEOMETRIC ERROR SENSITIVITY****',/)
241 $1 WITH RESPECT TO ALTITUDE ERROR
242 $1 ALTITUDE M = $1 F4.1 $1 km
243 $1 ALITUDE ERROR 2 TOMA = $1 F5.2 $1 km
244 $1 VIEW = 5X$1 ANGLE = $1 D1
245 $1 $2 (km) $1 10011.4 $1 $1 D1
246 $1 ERROR 2 (km) $1 10011.4 $1 $1 D1
247 $1 ERROR 1 (km) $1 10011.4
248 $1 SENSITIVITY (km/km) $1 10
249 $1 10
250 $1 10
...

DO 240 K1=1,10
WRITE(6,250) RM,DFI(K),OLOMA(J),JM1,10,JY(J),JM1,10)
255 $1 JM1,10)
256 $1 JM1,10)
257 $1 JM1,10)
258 $1 JM1,10)
259 $1 JM1,10)
260 $1 JM1,10)
261 $1 JM1,10)
262 $1 JM1,10)
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264 $1 JM1,10)
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266 $1 JM1,10)
267 $1 JM1,10)
268 $1 JM1,10)
269 $1 JM1,10)
270 $1 JM1,10)
271 $1 JM1,10)
272 $1 JM1,10)
273 $1 JM1,10)
274 $1 JM1,10)
275 $1 JM1,10)
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277 $1 JM1,10)
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279 $1 JM1,10)
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281 $1 JM1,10)
282 $1 JM1,10)
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288 $1 JM1,10)
289 $1 JM1,10)
290 $1 JM1,10)
291 $1 JM1,10)
292 $1 JM1,10)
293 $1 JM1,10)
294 $1 JM1,10)
295 $1 JM1,10)
296 $1 JM1,10)
297 $1 JM1,10)
298 $1 JM1,10)
299 $1 JM1,10)
300 $1 JM1,10)

300 CONTINUE

DO 300 K1=1,10
WRITE(6,259) RM,DF1(K),DF2(K),OLOMA(J),JM1,10,JY(J),JM1,10)
355 $1 JM1,10)
356 $1 JM1,10)
357 $1 JM1,10)
358 $1 JM1,10)
359 $1 JM1,10)
360 $1 JM1,10)
361 $1 JM1,10)
362 $1 JM1,10)
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364 $1 JM1,10)
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366 $1 JM1,10)
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368 $1 JM1,10)
369 $1 JM1,10)
370 $1 JM1,10)
371 $1 JM1,10)
372 $1 JM1,10)
373 $1 JM1,10)
374 $1 JM1,10)
375 $1 JM1,10)

300 CONTINUE
ORIGINALLY FOR POOR QUALITY
$1$ Y DIRECTION (KM) $1$ 3X.3015.4$///$ TOTAL SHIFT
$2$ (KM) $1$ 3X.3015.4$///$ TOTAL SHIFT

DO 707 KM1+NDETA

WRITE(6,70b) R+DTAU+DETA(K),Y(K),VS+VP(K),DANGL(K),D(T,C,)

$2$=1+NDT)+(DELX(K,J)+J$1$+NDT)+DELX(K,J)+J$1$+NDT)+(ERR0(K,J),

$2$=1+NDT)

700 FORMAT(1HN,1x,15H GROUND POINT SHIFT INDUCED:

5000 $1$ BY SHUTTLE MOTION AND EARTH ROTATION

5010 $1$ EARTH RADIUS $1$=FQ.6$1$KM///$1$ ORBIT

5020 $1$ INCLINATION $1$=FQ.0$1$DEGREE///$1$ LATITUDE $1$=FQ.0$1$

5030 $1$ DEGREE///$1$ GROUND POINT SHIFT VELOCITY DUE TO EARTH

5040 $1$ ROTATION $1$=DI0$1$.81KM/SEC///$1$ SHUTTLE GROUND SPEED $1$

5050 $1$ DIO$1$.81KM/SEC///$1$ GROUND POINT SHIFT VELOCITY RELATIVE

5060 $1$ TO RADIR POINT $1$=DIO$1$.81

5070 $1$ KM/SEC///$1$ ANGLE OF VELOCITY VECTOR WITH Y=AXIS $1$

5080 $1$ DIO$1$.81DEGREE///$1$ TIME INTERVAL (SEC)$1$3P15.2///$1$

5090 $1$ SHIFT IN///$1$ X DIRECTION (KM)$1$ 3X.3015.4$///$1$

5100 $1$ SHIFT IN///$1$ Y DIRECTION (KM)$1$ 3X.3015.4$///$1$

5110 $1$ TOTAL SHIFT (KM)$1$ 3X.3015.4$///$1$

707 CONTINUE

5120 STOP

5130 END

41 CTP$1$35 888$1$10.769

* A SMUTEX, IMAGE/ABB
25$1$JB 04/27/83 0113121

2 SUP+$736 CPU=900 IO=302 GC=ERR=433

142
### Geometric Error Induced by Altitude Error

**Earth Radius** $R = 6356.789$ km

**Nominal Altitude** $H = 3500$ km

**Altitude Error 1** $DH_1 = 0.01$ km

**Altitude Error 2** $DH_2 = 0.02$ km

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<tr>
<th>View Angle (degrees)</th>
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<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td>Nominal Location (km)</td>
<td>0.000</td>
<td>0.0002+0.01</td>
<td>0.0007+0.02</td>
<td>0.0009+0.02</td>
<td>0.0007+0.02</td>
<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
<td>0.0003+0.02</td>
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<td>Shifted Location (km)</td>
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<td>0.0007+0.02</td>
<td>0.0009+0.02</td>
<td>0.0007+0.02</td>
<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
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<td>Error (km)</td>
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<td>0.0009+0.02</td>
<td>0.0007+0.02</td>
<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
<td>0.0003+0.02</td>
<td>0.0002+0.02</td>
</tr>
<tr>
<td>Error Sensitivity (km/km)</td>
<td>0.000</td>
<td>0.0007+0.02</td>
<td>0.0009+0.02</td>
<td>0.0007+0.02</td>
<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
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<td>0.0003+0.02</td>
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### Geometric Error Sensitivity with Respect to Altitude Error

**Earth Radius** $R = 6356.789$ km

**Nominal Altitude** $H = 3500$ km

**Altitude Error 1** $DH_1 = 0.01$ km

**Altitude Error 2** $DH_2 = 0.02$ km

<table>
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<tr>
<th>View Angle (degrees)</th>
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<th>5</th>
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<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
<td>0.0003+0.02</td>
<td>0.0002+0.02</td>
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<td>Shifted Location Due to Error 2 (km)</td>
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<td>0.0007+0.02</td>
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<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
<td>0.0003+0.02</td>
<td>0.0002+0.02</td>
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<td>Difference (km)</td>
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<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
<td>0.0004+0.02</td>
<td>0.0003+0.02</td>
<td>0.0002+0.02</td>
</tr>
<tr>
<td>Error Sensitivity (km/km)</td>
<td>0.000</td>
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<td>0.0006+0.02</td>
<td>0.0005+0.02</td>
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**Geometric Error Sensitivity**

**Original Page is of Poor Quality**
### Geometric Error Sensitivity

**Earth Radius**: 6356.750km

**Nominal Altitude**: 480km

#### View Angle

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<thead>
<tr>
<th>View Angle (Degrees)</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<th>6</th>
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<tbody>
<tr>
<td><strong>Error (km)</strong></td>
<td>0.000</td>
<td>0.019</td>
<td>0.038</td>
<td>0.057</td>
<td>0.076</td>
<td>0.095</td>
<td>0.114</td>
<td>0.133</td>
<td>0.152</td>
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#### Geometric Error Sensitivity with Respect to Tan Error

**Earth Radius**: 6356.750km

**Nominal Altitude**: 480km

#### View Angle

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<th>View Angle (Degrees)</th>
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<tr>
<td><strong>Total Shift (km)</strong></td>
<td>0</td>
<td>0.019</td>
<td>0.038</td>
<td>0.057</td>
<td>0.076</td>
<td>0.095</td>
<td>0.114</td>
<td>0.133</td>
<td>0.152</td>
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<td><strong>Error Sensitivity (km/deg)</strong></td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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146
EARTH RADIUS = 6354.755 KM

ORBIT INCLINATION = 85.0 DEGREE

LATITUDE = 28.0 DEGREE

GROUND POINT SHIFT VELOCITY DUE TO EARTH ROTATION = 0.434488 KM/SEC

SHUTTLE GROUND SPEED = 7.292286 KM/SEC

GROUND POINT SHIFT VELOCITY RELATIVE TO NADO IN POINT = 0.7175401 KM/SEC

ANGLE OF VELOCITY VECTOR WITH T-AXIS = 0.658492 DEGREE

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<td>SHIFT IN X DIRECTION (KM)</td>
<td>0.7102001</td>
<td>0.7102000</td>
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<td>SHIFT IN Y DIRECTION (KM)</td>
<td>0.6382000</td>
<td>0.6382000</td>
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<tr>
<td>TOTAL SHIFT (KM)</td>
<td>0.7174001</td>
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EARTH RADIUS = 6354.755 KM

ORBIT INCLINATION = 85.0 DEGREE

LATITUDE = 28.0 DEGREE

GROUND POINT SHIFT VELOCITY DUE TO EARTH ROTATION = 0.3581400 KM/SEC

SHUTTLE GROUND SPEED = 7.292286 KM/SEC

GROUND POINT SHIFT VELOCITY RELATIVE TO NADO IN POINT = 0.7171401 KM/SEC

ANGLE OF VELOCITY VECTOR WITH T-AXIS = 0.871092 DEGREE

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<tr>
<td>SHIFT IN X DIRECTION (KM)</td>
<td>0.7102001</td>
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<td>SHIFT IN Y DIRECTION (KM)</td>
<td>0.3516000</td>
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<td>TOTAL SHIFT (KM)</td>
<td>0.7171001</td>
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14b
Earth radius = 6356.780 km

Orbit inclination = 69.5 degrees

Latitude = 69.5 degrees

Ground point shift velocity due to Earth rotation = 0.8510 km/sec

Shuttle ground speed = 0.7822 km/sec

Ground point shift velocity relative to Nadir point = 0.7192 km/sec

Angle of velocity vector with Nadir = 30 degrees

<table>
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<tr>
<th>Time interval (sec)</th>
<th>1.0</th>
<th>0.1</th>
<th>0.01</th>
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<tr>
<td>Shift in X direction (km)</td>
<td>0.7162 x 0.01</td>
<td>0.7162 x 0.1</td>
<td>0.7162 x 1.0</td>
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<tr>
<td>Shift in Y direction (km)</td>
<td>0.2275 x 0.01</td>
<td>0.2275 x 0.1</td>
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<tr>
<td>Total shift (km)</td>
<td>0.7164 x 0.01</td>
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## APPENDIX F

### GROUND PATTERN AND IMAGING

#### DISTORTIONS GENERATION PROGRAM LISTINGS

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100 1* 1 C DECLARE PARAMETERS
101 2* PARAMETER N LINES = 11* N DT = 100* N LAMBDA = 440* N LMPDA = 310*
101 3* N LNA = 50* N LAMDA = 440*
101 4* 5* REAL LMPDA + N LNPDA + N LMPDA + N LAMDA
101 6* n INTGER FLAG = AFLAG
101 7* C 8* C DIMENSION OF VARIABLES
101 9* C 9* DIMENSION OF VARIABLES
102 10* C 10* DIMENSION OF VARIABLES
102 11* C 11* DIMENSION OF VARIABLES
102 12* C 12* DIMENSION OF VARIABLES
102 13* C 13* DIMENSION OF VARIABLES
102 14* C 14* DIMENSION OF VARIABLES
102 15* C 15* DIMENSION OF VARIABLES
102 16* C 16* DIMENSION OF VARIABLES
102 17* C 17* DIMENSION OF VARIABLES
```

150
C 0150 30  C INITIALIZE THE PLOTTER
    C 0150 31  CALL EGPLT
    C 0151 32  C CENTER PLOT
    C 0151 33  XCENT=5.0
    C 0152 35  YCENT=1.0
    C 0153 36  CALL ORIGIN(XCENT,YCENT)
    C 0154 37  C DEFINE THE FORM OF THE PLOT
    C 0154 38  PTYPE=LIN
    C 0155 40  XLEN=F
    C 0156 41  YLEN=F
    C 0157 42  CALL PLOMRG(PTYPE,XLEN,YLEN)
    C 0160 43  C SCALE THE PLOT
    C 0160 44  AX(11)=2
    C 0161 46  YX(21)=8
    C 0162 47  YY(11)=8
    C 0163 48  YY(23)=8
    C 0164 49  MXX=2
    C 0165 50  MYY=2
    C 0166 51  NGC=1
    C 0166 52  NGT=1
    C 0167 52  CALL PLSCFL(XXX,NXX,NGC,YY,NGT)
    C 0170 55  C TO START PLOTTING
    C 0171 55  CALL PLGRAF
    C 0172 57  C DEFINE GRID LIMITS
    C 0172 59  XLEFT=5
    C 0173 63  XRIGHT=5
    C 0174 61  CEL=RIGHT-XLEFT+(NLLINES-1)
    C 0175 62  YBOT=-5
    C 0176 63  YTOP=5
    C 0177 64  YDEL=(YTOP-YBOT)/(NLLINES-1)
    C 0200 65  C CONSTRUCT DATA
    C 0200 66  YCF=YTOP
    C 0200 67  DO 150 IKOR=1,NLLINES
    C 0200 67  XCNLEFT
    C 0200 70  DO 100 IPT=1,NLLINES
    C 0210 71  C X=IKOR*XCNMS+I
    C 0210 72  C Y=IKOR*XCNMS+Y
    C 0211 74

151
0212  75*    X=INOR1PFI=KOM
0213  76*    Y=INOR1PFI=KOM
0214  77*    X=CC+YDEL
0215  78*  100 CONTINUE
0217  79*    YG=YEL
0219  80*  150 CONTINUE
0220  81*    IF(FLAG.GE.9) GO TO 200
0221  82*    IF(FLAG.EQ.2) GO TO 208
0222  83*    IF(FLAG.EQ.3) GO TO 231
0223  84*    IF(FLAG.EQ.4) GO TO 251
0224  85*    GO TO 261
0225  86*  230 CONTINUE
0226  87*    DO 202 J=1,MLINES
0227  88*    DO 201 JR=1,MLINES
0228  89*    MFLAG(I,J)=0
0229  90*  201 CONTINUE
0230  91*  262 CONTINUE
0231  92*    YXYSTAR
0232  93*    DO 206 L=1,NRT
0233  94*    SLAMDA=DS
0234  95*    DO 205 K=1,MLAMDA
0235  96*    LAMDA=DLAMDA+PSI390
0236  97*    X(R)=X(R)+COS(LAMDA)-SORT(1-4I+N/R)+N1*N/R*
0237  98*    SS(LAMDA)=SIN(LAMDA)+SIN(LAMDA)
0238  99*    DO 50 I=1,MLINES
0239  100*    DO 70 J=1,MLINES
0240  101*    Z(W)=W-X(I,J)
0241  102*    YZ3=O-Y(I,J)
0242  103*    I=I
0243  104*    JR=I
0244  105*    JR=J
0245  106*    IF(ABS(Y3).LE.EPSIL0.AND.ABS(Y3).LE.EPSIL0) GO TO 204
0246  107*  70 CONTINUE
0247  108*  80 CONTINUE
0248  109*    GO TO 99
0249  110*  204 MFLAG(IR,JR)=1
0250  111*    XFI1R,JR)=D=(-TAN(LAMDA))
0251  112*    YFI1R,JR)=YXYSTAR+EL-1)-0228
0252  113*    WRITE(6,99) IR,(Y5+JR)+(X5+JR)+(X5+JR)+BLAMDA,XF1R,JR)+YF1R,JR)
0253  114*    98 FORCA17/1S2F10.5S2163S10.53
0254  115*    99 DLAMDA=SLAMDA-99
0255  116*  205 CONTINUE
0256  117*  206 CONTINUE
0257  118*    YXYSTAR+L=D=VS
0258  119*    GO TO 299
0259  120*  302 CONTINUE
0260  121*    DO 2 I=1,MLINES
0261  122*    DO 1 J=1,MLINES
0262  123*    MFLAG(I,J)=0
0263  124*    1 CONTINUE
0264  125*    2 CONTINUE
0265  126*    DTHETA=2C
0266  127*    3 CONTINUE
0267  128*    YAYSAP
0268  129*    DO 217 L=1,NRT
0269  130*    THETA=DTHETA+PSI100.
0270  131*    9LPMDA=PS

152
ORIGINAL PAGE IS
OF POOR QUALITY
0763    301  DL=MDA+RS
0764    302  DO 255 K=1,MLMDA
0765    303  LRMDA=DLMDA+PI/180.
0770    305  S=S+1(1+D/R)+COS(LMMD)+ROLL+ER=SQRT((1+D/R)*2+1+D/R)
0771    306  CK1=D151+XSTAO
0772    307  DO 99 J=1,NLINES
0775    309  00 77 J=1,NLINES
1000    310  IF=XK1-YTL1)J
1001    311  YTL1=YX1-YTL1J
1002    312  J=1
1003    313  1F6ASX1L1)LE.EPSI.ANSYLY1.LE.EPSI. GO TO 252
1006    314  77 CONTINUE
1010    315  99 CONTINUE
1012    316  GO TO 254
1013    317  252 LFLAG=(PI+JM11)*
1014    318  (M1+M1-J+12-TAN(MLMDA))
1015    319  YM1(1+J+12+YBT+J+12)-.0288
1016    320  dNTE(6,255) YK1+YKL1+J+1+JMDA*XMI+1+JMJ1
1016    321  SYM1(J+1+JMJ1
1027    322  253 FORMAT(2F10.5,3F10.5)
1030    323  254 DLMDA=ULMDA=RD
1031    324  255 CONTINUE
1033    325  YK1=YSTAC(.L.+0298
1034    326  DER=0.2* SinH(PIJ/174.)
1035    327  260 CONTINUE
1037    328  GO TO 299
1040    329  261 CONTINUE
1041    330  DO 263 J=1,NLINES
1044    332  DO 262 J=1,NLINES
1047    333  AFLAG=(1+1)*
1050    334  262 CONTINUE
1052    335  263 CONTINUE
1054    336  TAU=DTAU+FI/160.
1055    337  OMEGA=2.*FI/6400.
1056    338  ETA=DELTA+PI/180.
1057    339  V=OMEGA+D*COS(ETA)
1060    340  SLMDA=CSKTAU/COS(ETA)
1061    341  CLUMDA=5R(I-SLMDA-SLMDA)
1062    342  VX=V+CLUMDA
1063    343  VY=V+SLMDA
1064    344  VTV=-VX
1065    345  VTV=VS-VY
1066    346  XAA+YSTA
1067    347  YAA+YSTA
1070    348  DO 270 L=1,NDT
1073    349  270 L=1,NDT
1074    350  DLMDA=V45
1077    351  LMDA=DLMDA+PI/180.
1100    352  dAA=K+(1+D/R)+COS(LMMDA)=SQRT((1+D/R)*(1+D/R))
1100    353  SLMDA=Sin(LMMDA) Sin(LMMDA) Sin(LYMDA)
1101    354  C=SLMDA+AA
1102    355  YDA+YAA
1103    356  DO 265 J=1,NLINES
1166    357  DO 264 J=1,NLINES
C PLOT HORIZONTAL LINES

C PLOT VERTICAL LINES

C PLOT HORIZONTAL LINES
C  PLOT VERTICAL LINES
  DO 907 IVERT=1,NLINES
  CALL PLCURVE(X1,IVERT),YM(1,IVERT),NLINES,NTIC3,TIC3)
  CONTINUE
  GO TO 999
  C  PLOT HORIZONTAL LINES
  CALL PLCURVE(XP4,YP4,NLINES,NTIC4,TIC4)
  CONTINUE
  C  PLOT VERTICAL LINES
  DO 913 IVERT=1,NLINES
  CALL PLCURVE(XM1,IVERT),YM(1,IVERT),NLINES,NTIC4,TIC4)
  CONTINUE
  C  PLOT HORIZONTAL LINES
  DO 917 IPT=1,NLINES
  CALL PLCURVE(XM2,IVERT),YM(1,IVERT),NLINES,NTIC5,TIC5)
  CONTINUE
  C  PLOT VERTICAL LINES
  DO 921 IPT=1,NLINES
  CALL PLCURVE(XM1,IVERT),YM(1,IVERT),NLINES,NTIC7,TIC7)
  CONTINUE
  C  PLOT HORIZONTAL LINES
  DO 923 IPT=1,NLINES
  CALL PLCURVE(XM2,IVERT),YM(1,IVERT),NLINES,NTIC5,TIC5)
  CONTINUE
  C  PLOT VERTICAL LINES
  DO 925 IPT=1,NLINES
  CALL PLCURVE(XP5,YP5,NLINES,NTIC5,TIC5)
  CONTINUE
1447 527- C PLOT VERTICAL LINES
1447 529- DO 924 IVERT=1:NLINES
1452 530- CALL PLOUAW(YDD(1:IVERT)*YDD(1:IVERT)*NLINES*IVERT)*
1453 531- 924 CONTINUE
1455 532- 933- C TO FINISH PLOTTING
1455 534- 999 CALL ENDPLT
1456 535- 999 CALL ENDPLT
1456 536- ** STOP
1457 537- END

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