N90-13414

THE EFFECTS OF SEASONAL AND LATITUDINAL EARTH INFRARED RADIANCE VARIATIONS ON ERBS ATTITUDE CONTROL*

M. Phenneger, J. Dehen, D. Foch, E. Harvie, M. Virdy
Computer Sciences Corporation

ABSTRACT

Analysis performed in the Flight Dynamics Facility by the Earth Radiation Budget Satellite (ERBS) Attitude Determination Support team illustrates the pitch attitude control motion and roll attitude errors induced by Earth infrared (IR) horizon radiance variations. IR scanner and inertial reference unit (IRU) pitch and roll flight data spanning 4 years of the ERBS mission are analyzed to illustrate the changes in the magnitude of the errors on time scales of the orbital period, months, and seasons.

The analysis represents a unique opportunity to compare prelaunch estimates of radiance-induced attitude errors with flight measurements. As a consequence of this work the following additional information is obtained: an assessment of an average model of these errors and its standard deviation, a measurement to determine and verify previously proposed corrections to the current Earth IR radiance data base, and the possibility of a mean motion model derived from flight data in place of IRU data for ERBS fine attitude determination.

* This work was supported by the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC), under Contract NAS 5-31500.

1.0 INTRODUCTION

This paper presents analysis performed in the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) by the Earth Radiation Budget Satellite (ERBS) Attitude Determination Support team. The analysis was performed to measure the ERBS infrared (IR) horizon scanner sensing errors induced by seasonal and latitudinal variations in the Earth's IR horizons. The ERBS mission attitude data offers a unique opportunity to compare prelaunch and early postlaunch estimates of radiance-induced attitude errors with flight measurements of these errors. In addition, this analysis attempts to corroborate the conclusions about the FDD Earth Horizon Radiance Data Base (HRDB) from earlier analysis of data from the Nimbus-7 Limb Infrared Monitor of the Stratosphere (LIMS) experiment. The effects on estimates of these errors, due to adjustments to the radiance data base derived from the earlier LIMS analysis, are evaluated. Radiance errors are derived by a difference between pitch and roll angles obtained from processed IR scanner telemetry and pitch and roll propagations from batch least squares estimates of pitch and roll reference attitudes using the inertial reference unit (IRU). Averages of these differences are used to illustrate the changes in the magnitude of the horizon radiance-induced pitch and roll errors on time scales of the orbital period, a month, and 1 year.

The remaining sections of this paper are as follows. Section 2 is an overview relating this analysis to earlier analysis of IR radiance errors, a description of the ERBS orbit characteristics and attitude system, and a brief description of the ERBS IR scanner sensing geometry and Earth pulse processing. Section 3 describes how the errors are caused by seasonal radiance variations, explains the concept and procedures applied here to extract the errors using the ERBS flight system telemetry data, and presents and describes the flight data errors. Section 4 provides a brief explanation of the IR sensor modeling software system and the result of attempts to model the flight data with this system using two schemes for rescaling the original ERBS radiance profiles. Section 5 is a summary with conclusions about the results and future applications of this analysis.

2.0 OVERVIEW

Analysis performed between 1977 and 1984 evaluated the methods of applying an Earth IR horizon radiance model to correct IR scanner flight data (Ref. 1). Flight data from 12 spacecraft, including early postlaunch data from the ERBS, were used to compare the actual IR scanner response to the modeled response using the Horizon Radiance Modeling Utility (HRMU) (Ref. 2). Differences in the actual Earth horizon radiance pitch and roll errors relative to the model were found to occur due to limitations in the Earth IR model and IR scanner sensitivity to short duration cold cloud effects.

Data from the Nimbus-7 LIMS experiment, which included horizon radiance measurements in two IR spectral passbands similar to those used for IR horizon scanners, were compared with a model of the LIMS data using a data base of Earth IR spectra referred to here as the HRDB (Ref. 3). The HRDB was developed using the LOWTRAN computer program (Ref. 4) and a data base of worldwide balloon and rocketsonde temperature profiles (Ref. 5). The LIMS comparison indicated that the modeled IR horizon intensities for the polar latitudes were underestimated for the summer season and overestimated for the winter season.

An overview of the ERBS attitude system and orbital characteristics is provided in Table 1.

Table 1. ERBS Orbit and Attitude Characteristics

Orbit:

Semimajor axis: 6891 km

Inclination: 57 deg

Eccentricity: 0.0014 (near-frozen orbit)

Attitude Parameters:

Angular momentum biased, Earth oriented, 1 revolution per orbit

Nominal geodetic pitch and roll = 0.0 deg

Nominal yaw = 0.0 or 180.0 deg for solar array illumination

Attitude Sensors:

Two Adcole fine Sun sensors 64x64 deg 0.004 deg (l.s.b.)

Two ITHACO Scanwheel IR sensors 0.025 deg (l.s.b.)

One Schoenstedt three-axis fluxgate magnetometer 4.68 mg (l.s.b.)

Two IRUs with three Northrop rate gyros 0.001 deg/sec (l.s.b.)

One gyrocompass onboard analog processor 0.03125 deg (l.s.b.)

Attitude Actuators:

One pitch momentum wheel

Two ITHACO scanwheels

Four orbit adjust and pitch/roll hydrazine thrusters

Two pairs of yaw turn hydrazine thrusters

One roll axis and one yaw axis, 50-ampere turn meter squared (ATm^2) magnetic dipole torque rods for pitch momentum control

Two pitch axis 50 ATm^2 dipole torque rods for roll control

2.1 ERBS IR SCANNER DESCRIPTION

The ITHACO IR scanwheels employ a rotating prism lens and a single-flake thermistor bolometer to sense the Earth with a 1x2-deg field of view (FOV), which sweeps along a 45-deg scan cone at 2000 revolutions per minute (rpm). The IR passband is between 14 and 16.1 microns. The scanner cone axes are on opposite sides of the spacecraft in the pitch-yaw plane and are canted 10 deg down from the pitch axis. Figure 1 illustrates the inflight geometry of the scanner optics for nominal attitude (Ref. 6).

The IR scanner uses normalized threshold locator logic. For this, the Earth IR pulse is averaged between 15 and 20 deg and 20 and 25 deg, respectively, from the inward

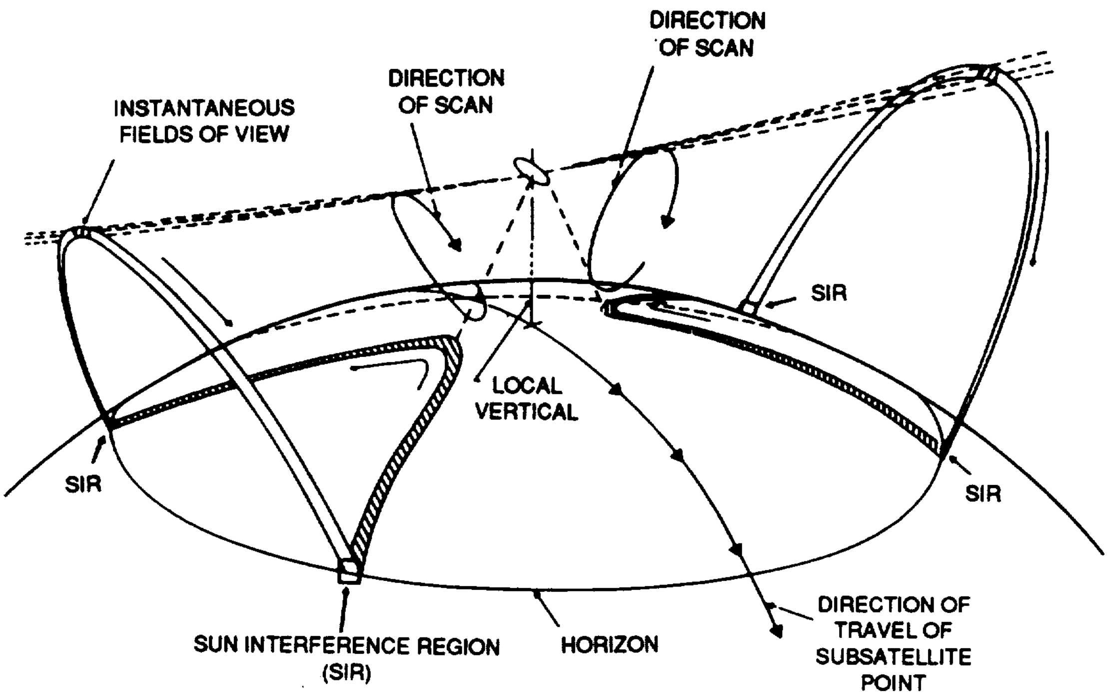

Figure 1. In-Flight Geometry of the ERBS IR Horizon Sensing System for Pitch = 0, Roll = 0, Yaw = 0

and outward horizons to determine the horizon triggering threshold voltage. A typical Earth pulse is shown in Figure 2. A magnetic pickoff mounted on the sensor body provides a reference pulse from which the acquisition of signal (AOS) and loss of signal (LOS) to index angles are computed (Ω_{in} and Ω_{out} in Figure 2). The pitch angle is computed as

$$P = \pm K_p \left[(\Omega^R_{los} - \Omega^R_{aos}) + (\Omega^L_{los} - \Omega^L_{aos}) \right] \quad (1)$$

where R and L designate the right and left side scanner angles, respectively, and where K_p is a geometry-dependent constant. For ERBS $K_p \approx 0.2462$.

Roll is computed as

$$R = K_r (\Omega^R - \Omega^L)$$

and (2)

$$\Omega^{R,L} = (\Omega^{R,L}_{aos} + \Omega^{R,L}_{los})$$

where $K_r \approx 0.247$.

Figure 3 shows the scanner ground traces at 5-minute intervals for both an equatorial and a polar view of the Earth. It can be seen that the AOS and LOS threshold computation regions (indicated by hashmarks in the figure) are separated by a wide range of latitudes

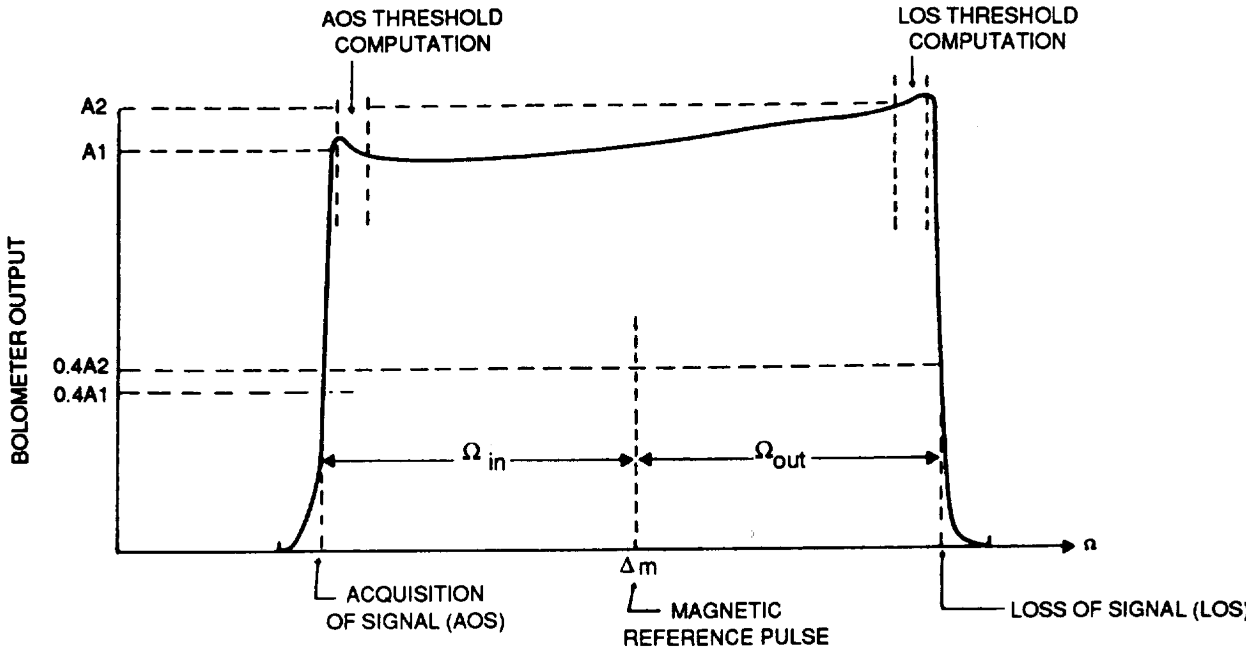

Figure 2. The Horizon Locator Logic and the IR Scanner Earth Pulse

in the equatorial regions, and that the left and right scanners are widely separated at the northern and southern extremes of the orbit.

3.0 HORIZON RADIANCE ERRORS FROM FLIGHT DATA

The horizon radiance-induced pitch and roll errors in the IR scanner input to the ERBS magnetic control system (MCS) control loop are caused by radiance gradients along the scan ground traces. The gradients are most severe in the winter and summer seasons between the polar latitudes and the temperate latitudes. The gradient causes the threshold normalization region intensity and the rising edge of the Earth pulse intensity to vary relatively. A brightening at the horizon causes an increased Earth width for a given threshold voltage. Likewise, a diminished radiance at the horizon will decrease the sensed Earth width. When the ERBS is on the Equator, a minimal north-south gradient occurs for any month and pitch errors are near zero. Roll errors at this location are dependent on east-west gradients that on the average will be zero. At the midlatitudes, near 40 deg, the AOS and LOS horizons for either scanner are at maximum latitudinal separation and include the latitude regions where the stratosphere experiences the greatest seasonal radiance variation. These are latitudes between 40 deg and the poles. Thus, the pitch errors will be maximum. At the highest and lowest latitudes, the left and right scanner traces are at north and south extremes, where differences between the 80 deg and 40 deg radiance intensities will determine the peak roll errors. At these points the latitudes of the AOS and LOS horizon points are the same for each scanner and pitch errors are expected to be near zero.

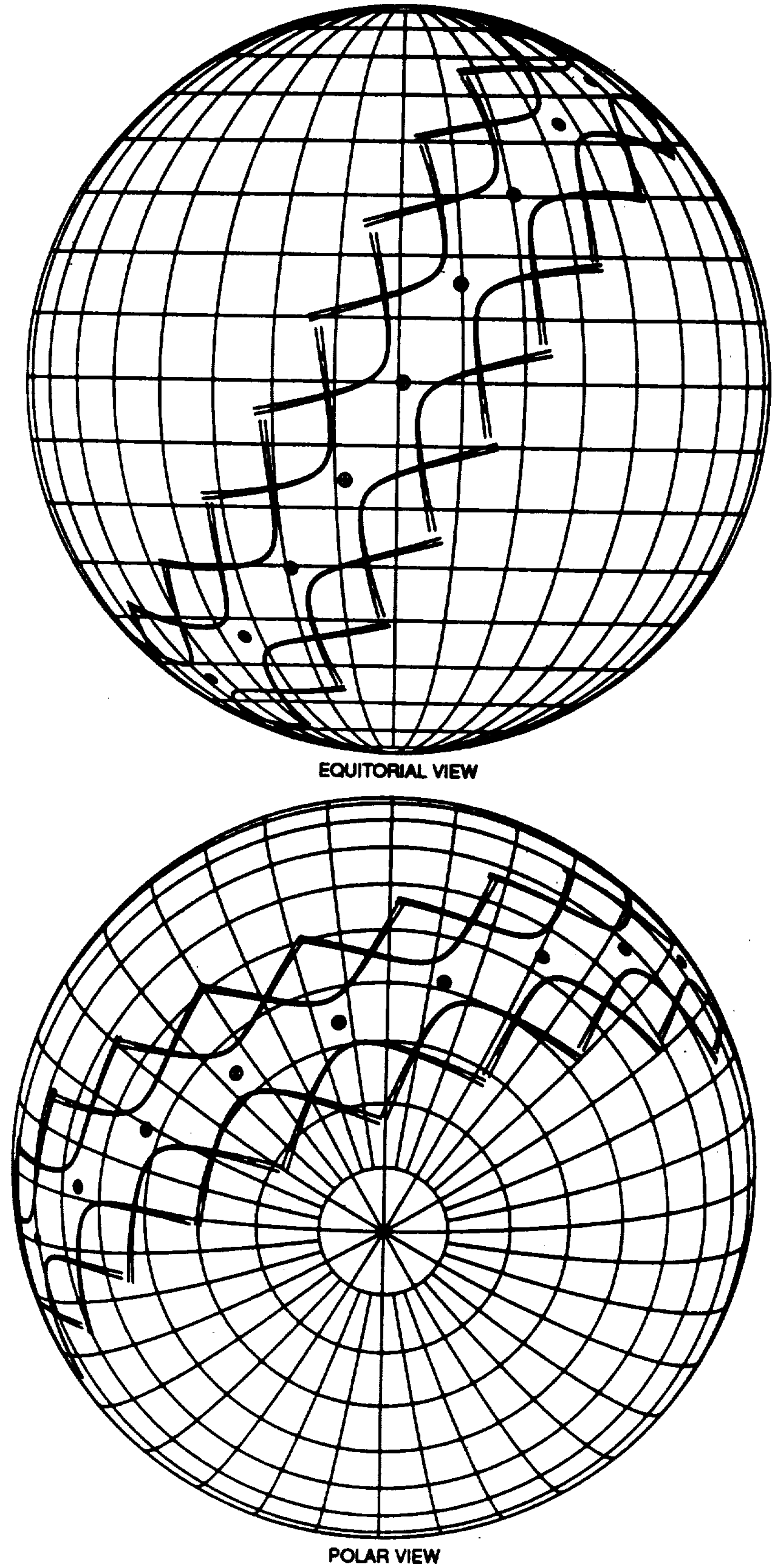

Figure 3. ERBS IR Horizon Scanner Ground Tracks on the Earth at 5-Minute Intervals

3.1 ERROR COMPUTATION CONCEPTS

The flight system horizon radiance-induced errors are computed by subtracting IRU-based pitch and roll determined by the ERBS Attitude Ground Support System (AGSS) (Ref. 6) Fine Attitude Determination Subsystem (FADS) from the IR scanner pitch and roll. The IR scanner pitch error is the error input to the ERBS pitch control loop. Horizon radiance-induced pitch errors from the IR scanner thus cause pitch motion to null the IR scanner error signal that is received in the downlink telemetry. However, this motion is sensed by the pitch IRU. The difference, IR scanner pitch minus FADS-IRU pitch, is approximately equal to the radiance-induced pitch error in IR scanner output.

The IR scanner roll error signal is not used for continuous roll control, but for intermittent activation of the magnetic dipoles for nutation and precession control. These torques cause the spacecraft pitch axis to precess along the 33-deg latitude line at a daily average rate of 4-deg per day, which is the ascending node rate. IR scanner roll minus FADS-IRU roll is approximately equal to the radiance-induced roll error in IR scanner output.

In summary, the IR scanner pitch error is continuously nulled by the reaction wheels, and therefore does not unambiguously indicate attitude motion. The IR scanner roll error signal should vary with the radiance induced error, with periodic steps to a null roll caused by magnetic dipole precession activity. The subtraction of IRU pitch and roll attitude data from IR scanner pitch and roll thus isolates IR horizon radiance errors. Since true spacecraft motion caused by control system and environmental torques is registered by both the IR scanners and the IRUs, this motion will not contribute to the difference. Similarly, the pitch rotation that occurs in response to the high-gain antenna transponder activation for Tracking and Data Relay Satellite (TDRS) contacts, will not appear in the data.

3.2 ERROR COMPUTATION PROCEDURE

The analysis procedure begins by processing selected orbits of ERBS attitude telemetry from archived data spanning 4 years of mission operations, between 1984 and 1988. The Data Adjuster subsystem of the AGSS is used to write processed IR scanner pitch and roll data to the Processed Engineering data set. After further processing, the IRU pitch and roll solutions are derived in the FADS and written to the Attitude History File (AHF). A FORTRAN utility program, written for this analysis, then subtracts the IRU pitch and roll angles from the IR scanner pitch and roll angles to produce the IR scanner horizon radiance-induced errors. These errors are averaged over 1-deg latitude bins on the northward and southward sides of each orbit to statistically improve the accuracy and reduce the data volume. To remove the effect of IR scanner and AGSS processing biases, the monthly averaged error representations are shifted to be zero at 0-deg latitude, where these errors are expected to be zero due to orbital geometry and radiance profile symmetry. The bias values were determined by the averaged pitch and roll errors between −5 and +5 deg latitude. The one-orbit representations of the latitude averaged errors were again averaged with three to five orbits for each month in each of the 4 years to form an overall average for each month.

3.3 FLIGHT DATA ANALYSIS RESULTS

The pitch and roll errors obtained from flight data analysis for each month of the year are plotted versus subsatellite latitude in Figures 4a and 4b. The standard deviations from the mean and the northward (N) and southward (S) direction of flight are indicated by the size and type of the plot symbols. The number of orbits averaged is noted to the right of each plot. The tick marks on the ordinate at 0 deg latitude are at intervals of 0.1 deg.

The following characteristics should be noted. For most of the months the pattern of the IR radiance-induced pitch and roll errors is as expected. December and February pitch errors are unusual when compared with adjacent months. The magnitude of the pitch and roll errors in the winter and summer seasons is two to five times higher than the pre-launch analysis predicted. The Southern Hemisphere summer and winter errors are significantly different from their Northern Hemisphere counterparts. The effects of the gradual change in the radiance with season is clearly evident in this 4 year averaged data that indicates a high level of annual similarity in the stratosphere. Finally for June and July, the months when the errors are the largest, the standard deviations do not exceed the error amplitude. The next section describes the results of analysis to simulate these data using the HRMU.

4.0 MODELING THE FLIGHT DATA WITH THE HORIZON RADIANCE MODELING UTILITY

The horizon radiance errors modeled by the HRMU are derived from a detailed computation using an Earth IR model and an IR scanner model composed of the orbital geometry, the IR scanner optics, and the signal processing electronics. The input characteristics of the IR scanner electronics include threshold normalization parameters and time constants, scanner mounting tilt angles and FOV, and orbital radius and inclination. HRMU input is the IR horizon profile of brightness versus FOV tangent height and angle of incidence to the Earth data. These data are in a set of nine profiles for each month in 20-deg latitude bins between -90 and +90 deg latitude. This horizon profile data set is derived from the HRDB by integrating the HRDB Earth IR spectra over the optical IR passband for each of the 51 viewing angles represented in the profile. The HRMU computes sensor response to the Earth radiance by integrating the IR radiance, from a latitude interpolated function of the profiles, incident on the scanner optics. As the scanner FOV sweeps across the Earth, a model of the bolometer energy pulse is computed. The scanner step response function is convolved with the pulsed input radiance signal to compute the electronics output Earth pulse signal. The horizon crossing angle is determined from this output pulse as is done onboard the spacecraft in the actual IR scanner electronics. The pitch and roll error signals expected over one orbit for a specific month of the year are computed using the horizon crossing angles according to Equations (1) and (2). The HRMU model of the ERBS IR scanner is not precise, and experience has shown that the following approximations made do not significantly alter the results:

- Two components of the electronics transfer functions are not included
- Nonlinear components in the electronics are not modeled; these are voltage limiting components

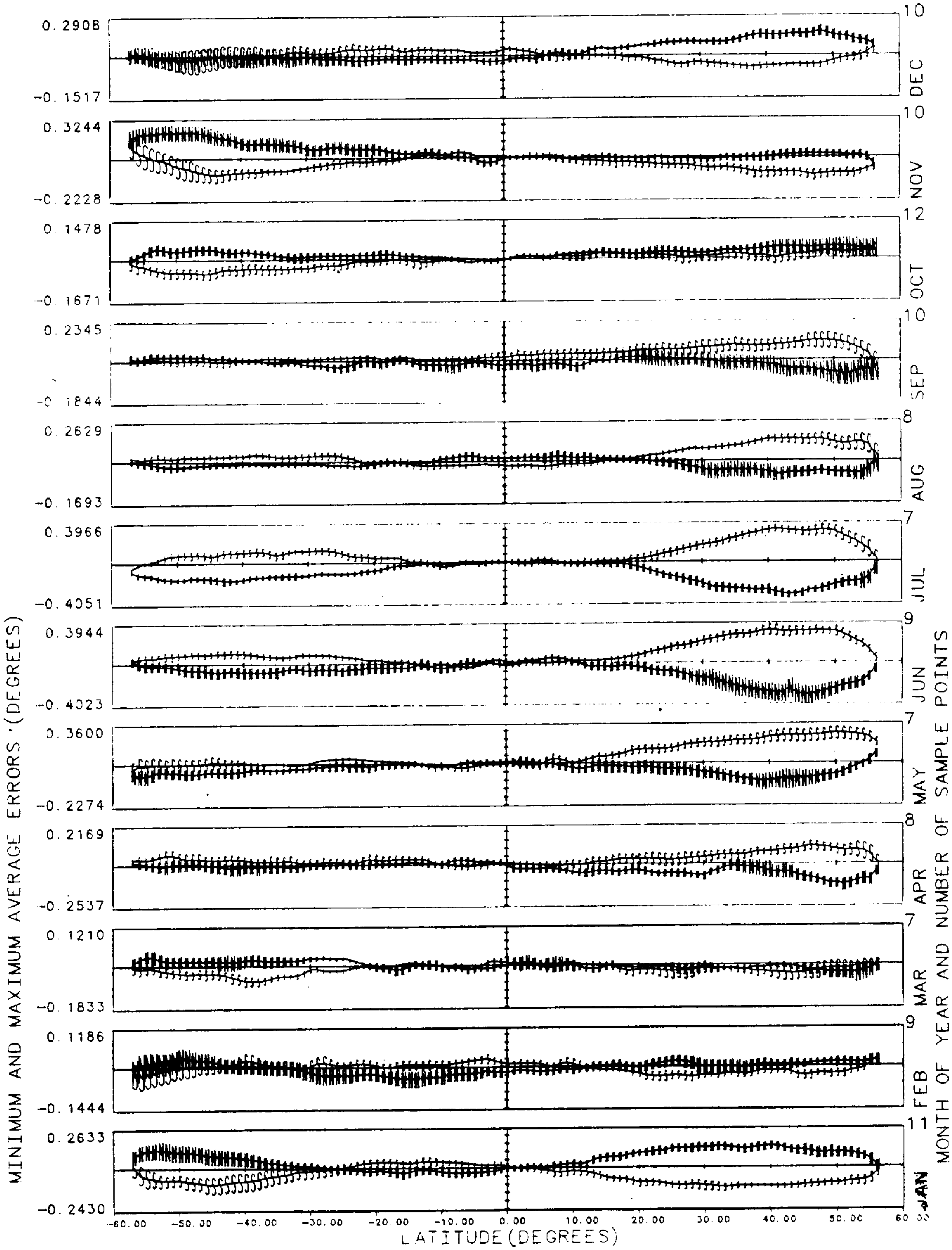

Figure 4a. Flight Data Pitch Errors Versus Latitude and Month (With Standard Deviations)

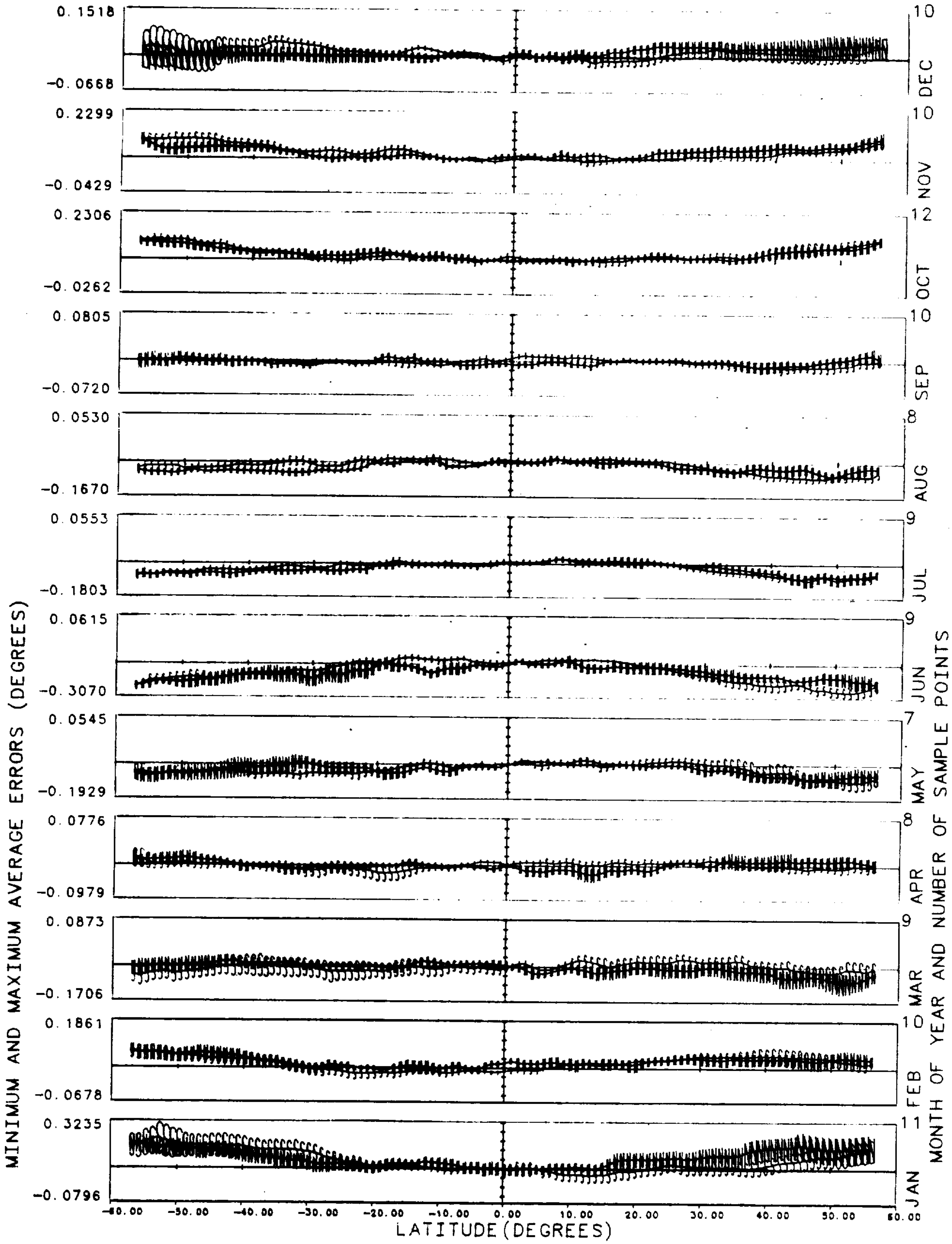

Figure 4b. Flight Data Roll Errors Versus Latitude and Month (With Standard Deviations)

- The Earth pulse processing branch of the actual ERBS IR horizon scanner circuit for threshold normalization is not modeled. Instead, the Earth detection pulse processing transfer function is also used for threshold computation.
- The optics are modeled by a square FOV without distortion due to the prism-lens optics.

The pitch and roll errors expected for ERBS as a result of prelaunch analysis using the HRMU and HRDB are illustrated in Figures 5a and 5b. The HRMU was also run on the radiance profile data adjusted using two schemes. The first uses LIMS analysis results; the second adjusts the profiles until a reasonable match to the flight data is obtained.

4.1 HORIZON RADIANCE ANALYSIS USING LIMS DATA

Analysis of the HRDB, in comparison with Nimbus/LIMS Earth radiance data, indicated that the (HRDB) model underestimates horizon radiance errors in the summer latitudes and overestimates the errors in the winter latitudes, causing the HRMU to underestimate the corresponding pitch and roll errors. This result is also verified by the comparison of the roll and pitch errors measured in this work with errors predicted by the HRMU using original horizon radiance profile data as input. To investigate the cause of the difference between the prelaunch predictions and the flight measurements of the errors, modifications were made to the HRMU input radiance profiles.

Profile adjustment scale factors were determined from plots of 0-kilometer tangent height radiance intensities from LIMS and HRDB models of LIMS profiles, illustrated in Figure 6 from Reference 3. For the months in which LIMS data were not available, the radiance profiles in the Northern and Southern Hemispheres were assumed to be seasonally symmetric. The pitch and roll errors resulting from this rescaled profile data are illustrated in Figures 7a and 7b. Improved agreement between predicted and measured pitch and roll errors for ERBS is demonstrated; however, the differences in the error magnitudes of 0.2 deg still remained. Because of this the second adjustment scheme was tried.

4.2 ADJUSTING THE RADIANCE PROFILES TO MATCH THE FLIGHT DATA ERRORS

The monthly errors from this process are illustrated in Figures 8a and 8b. The match is approximate; in most cases the model agrees with the average flight errors within the standard deviation of the flight data. During this exercise the following understanding was obtained. Efforts to raise the pitch errors relative to the LIMS profile renormalization scheme by raising and lowering the 60 and 80 deg latitude radiance profile intensities caused roll errors to exceed 0.5 deg. Thus it was determined that the pitch error in the model is controlled by changing the radiance gradient between 20, 40, and 60 deg latitudes and that to avoid excessive roll errors the gradient between 40, 60, and 80 deg latitudes must be moderated. For the summer months the radiance increases at 80 deg latitude appear to lag behind those at 60 deg latitude, as these latitudes receive increasing amounts of sunlight with the approaching solstice. Similarly, the winter 80-deg profiles are near and not much dimmer than the 60-deg profiles. Thus, roll errors were moderated

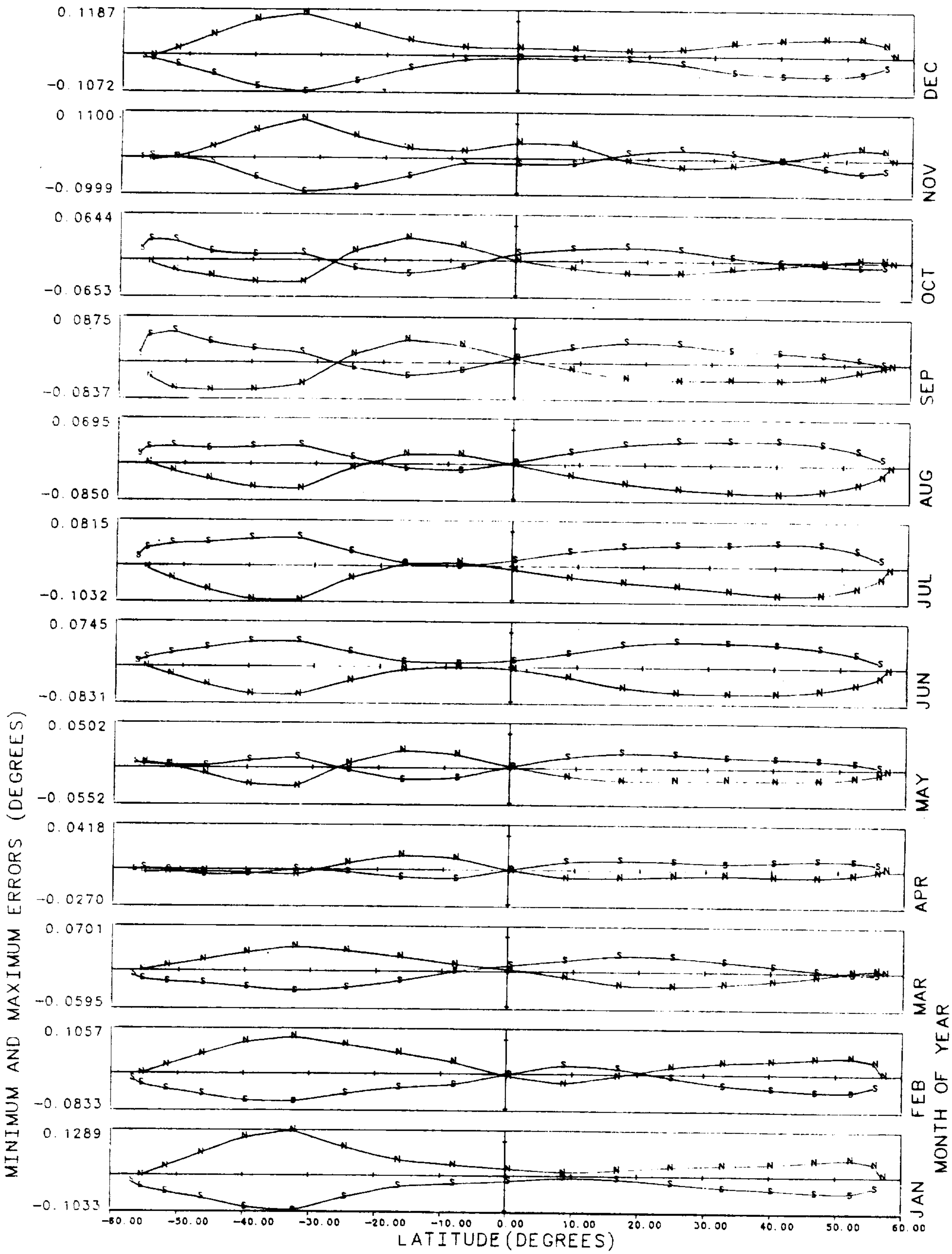

Figure 5a. Pitch Errors Versus Latitude and Month (Original Model)

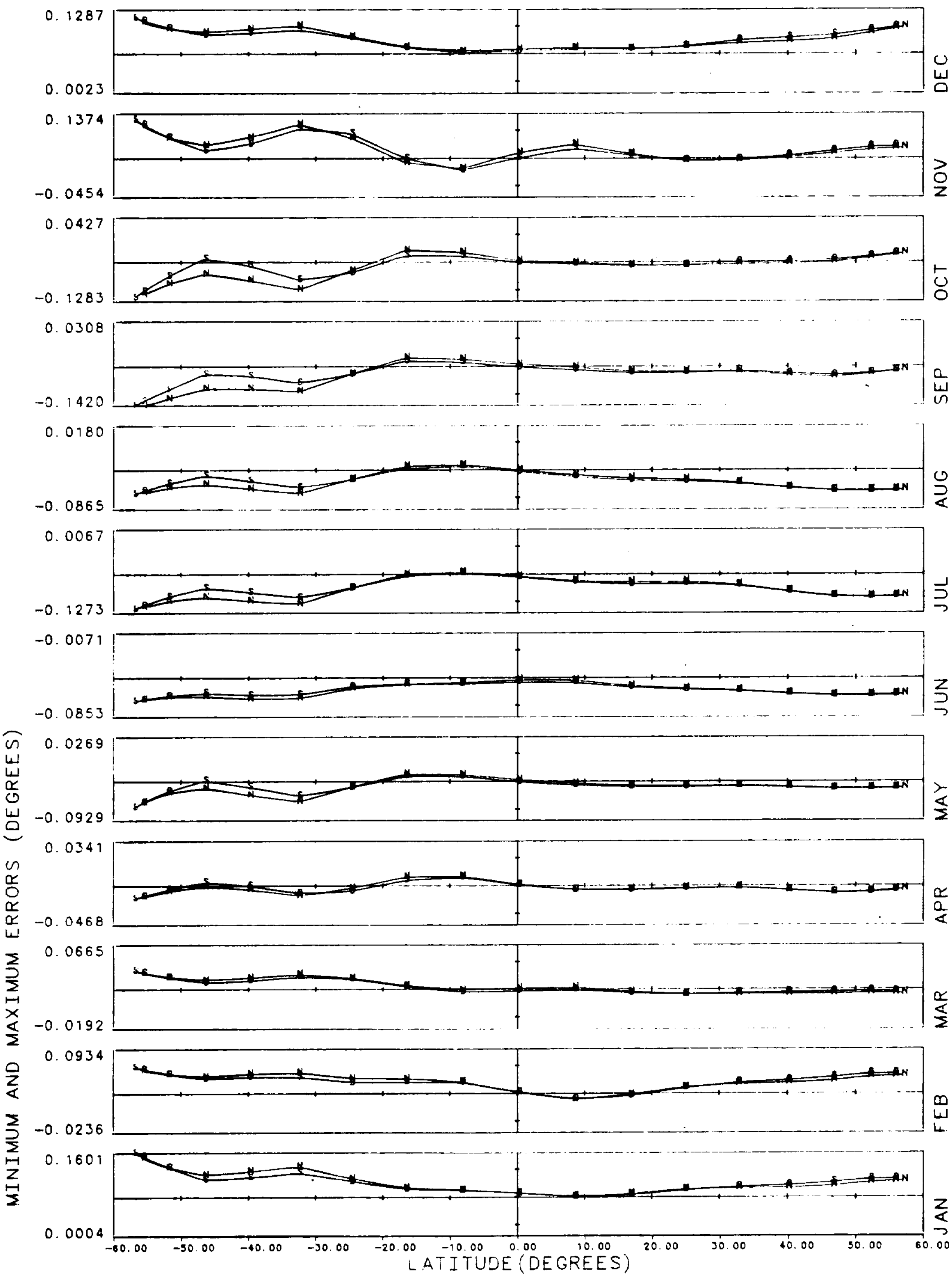

Figure 5b. Roll Errors Versus Latitude and Month (Original Model)

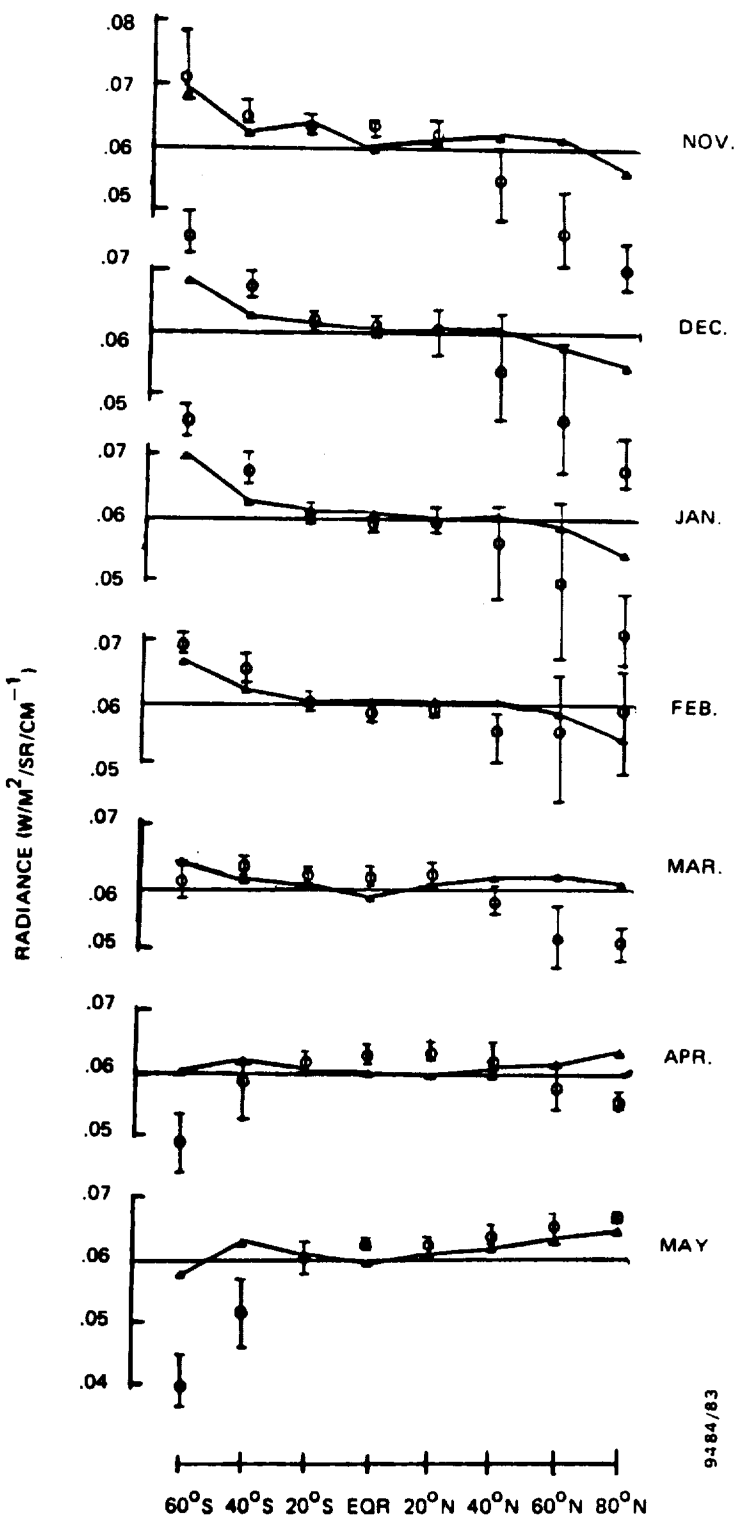

Figure 6. CO_2N Radiance Intensities at a 0-Kilometer Tangent Height Observed by LIMS (O) and Predicted by the HRDB (▲) (Bars Indicate Maximum and Minimum LIMS Values)

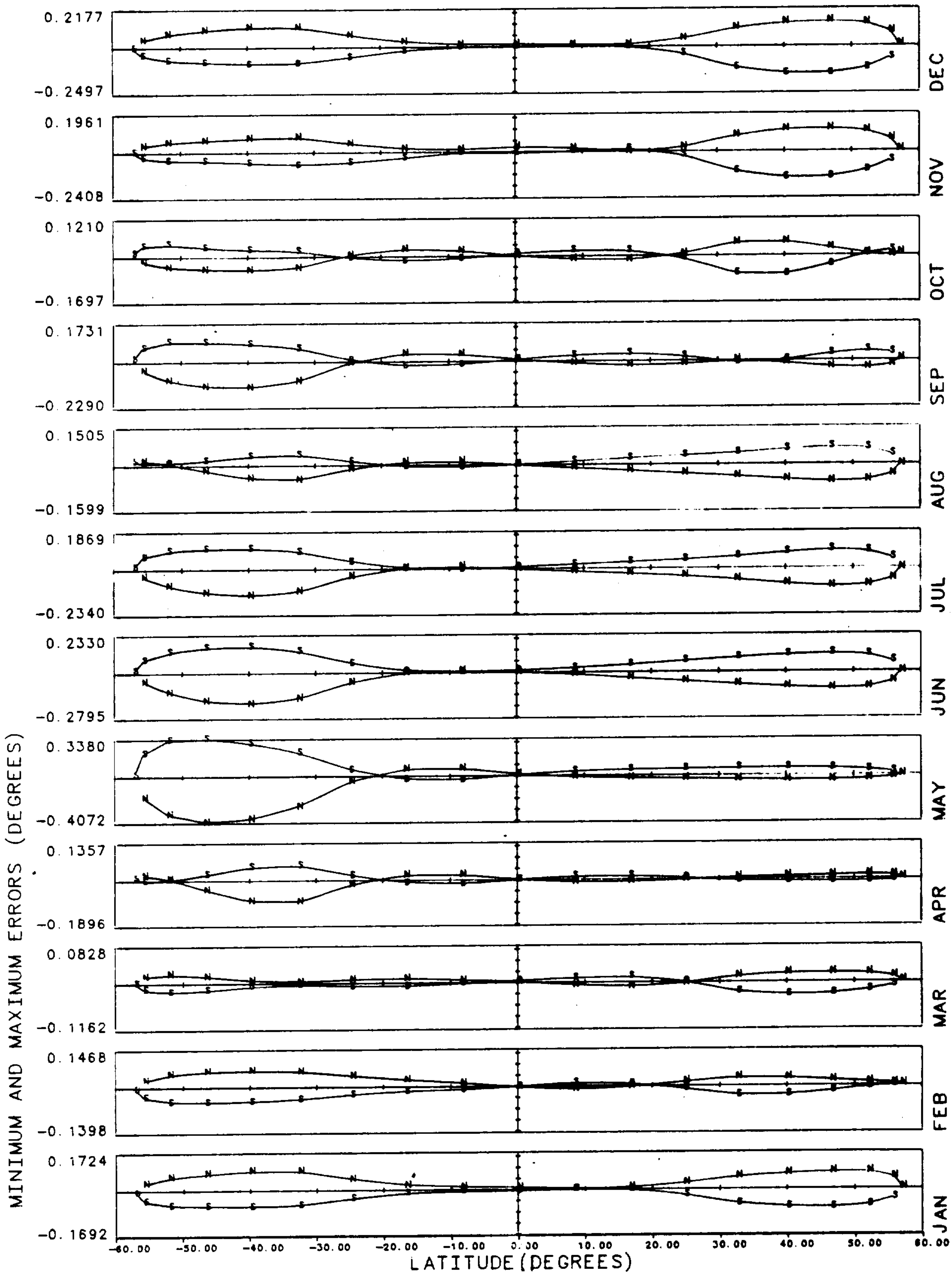

Figure 7a. Pitch Errors Versus Latitude and Month (LIMS Modified Model)

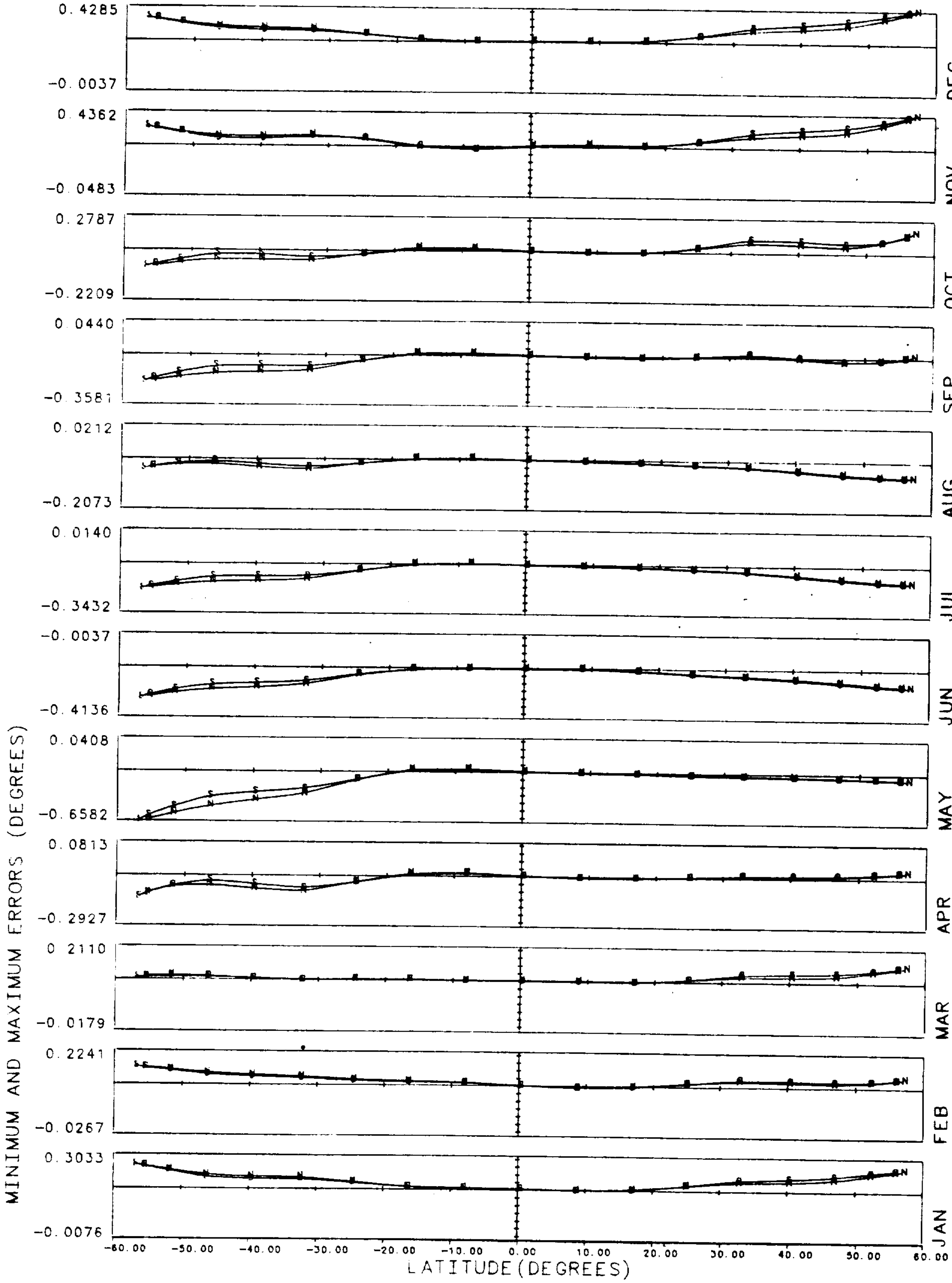

Figure 7b. Roll Errors Versus Latitude and Month (LIMS Modified Model)

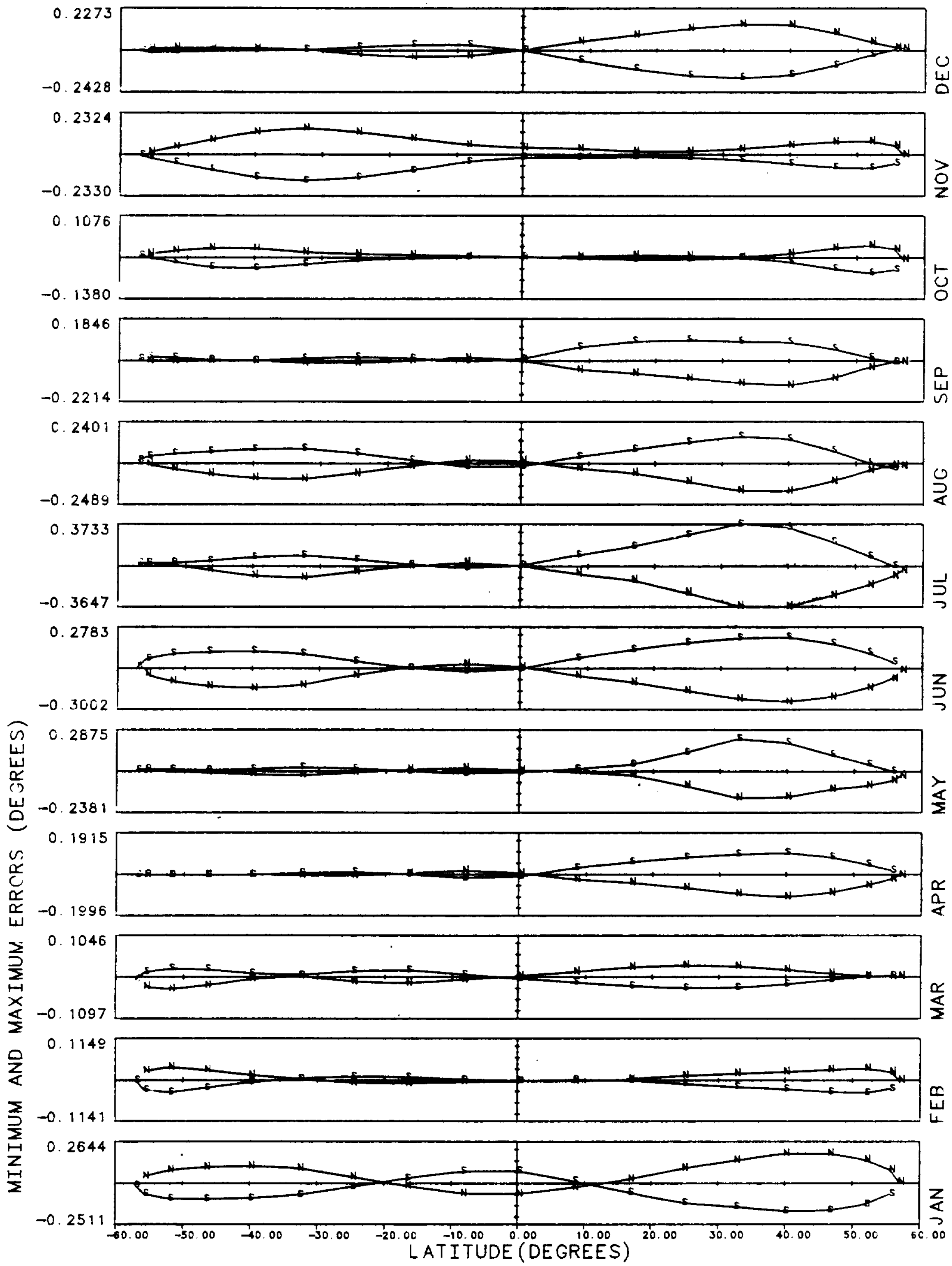

Figure 8a. Pitch Errors Versus Latitude and Month (Flight Data Modified Model)

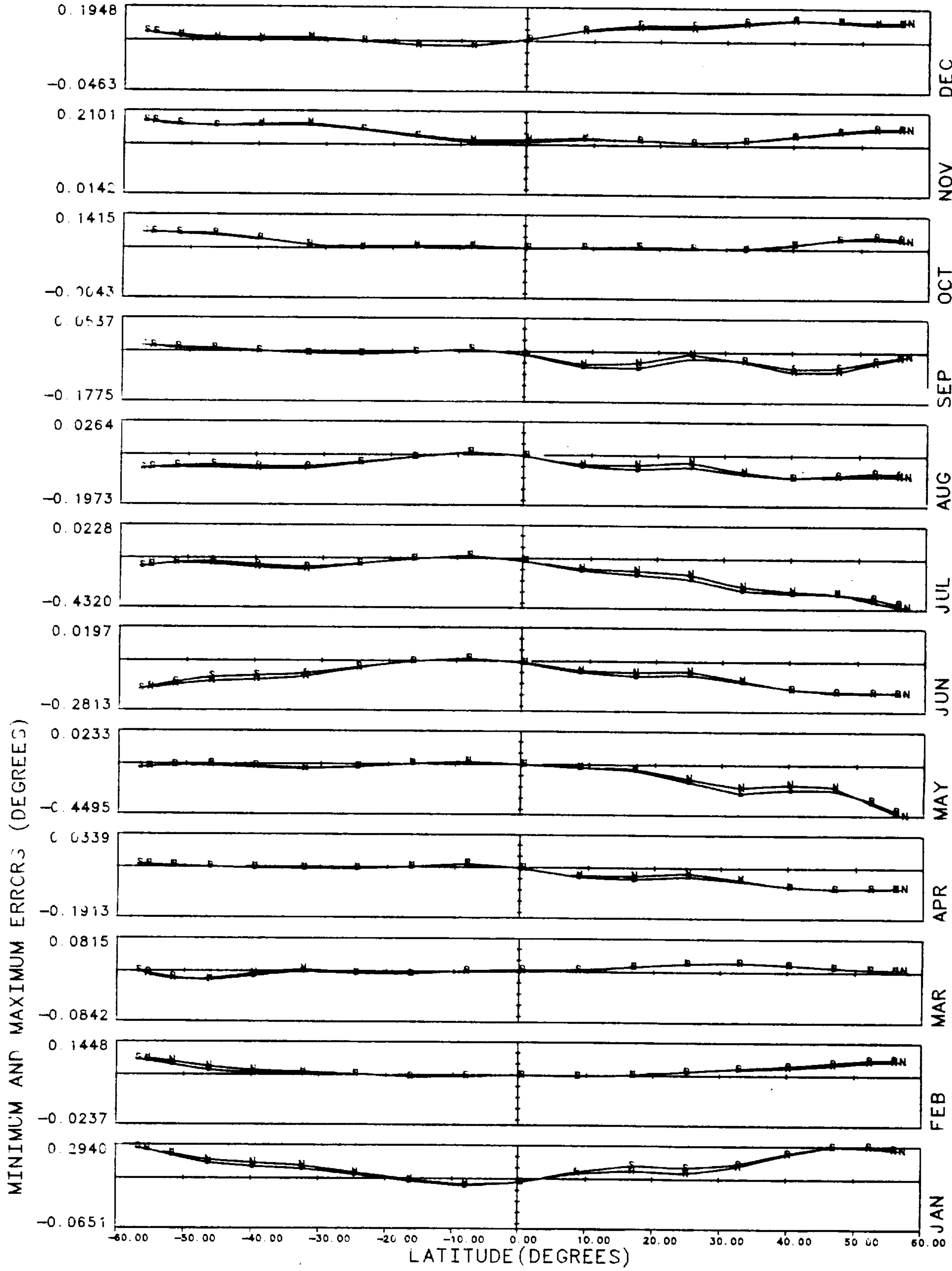

Figure 8b. Roll Errors Versus Latitude and Month
(Flight Data Modified Model)

by flattening the gradients in the high latitudes, making 40 and 80 deg radiance differences smaller in the summer and winter seasons.

5.0 CONCLUSIONS

The results of this analysis contribute significantly to the understanding of the effect of horizon radiance-induced errors in IR scanner systems and complement earlier work performed in the GSFC/FDD. The flight data measurements of the effect provide an important comparison to and calibration of the Earth horizon radiance model. The results also answer questions about the significance of the horizon radiance effect for attitude determination pointing control accuracy and about the chances of improving the accuracy of attitude measurements and pointing performance using horizon radiance modeling techniques. They also demonstrate an additional modeling technique using spacecraft flight data. In particular, the measurements indicate that the measured horizon radiance effect for ERBS exceeds the original HRMU-modeled value by as much as a factor of five. Measured values of 0.45 deg compare to 0.1 deg from the model of pitch errors for the midlatitudes in July. A possible source of this difference was known in 1984. It was reported then that the HRDB underestimated brightness contrast in the horizon radiance profiles for the polar latitudes in the winter and summer hemispheres. ERBS pitch and roll attitude information obtained from pure IR scanner telemetry thus requires the removal of errors as large as 0.45 deg. The accuracy of the model of these errors can be assessed from the results in three ways:

1. Applying no correction for radiance effects to the IR scanner pitch and roll limits the accuracy of the IR scanner attitude to 0.5 deg, ignoring all other errors due to biases, alignments, and electronic, optical, and mechanical noise.

2. Comparing the accuracy of pitch attitude results corrected using errors modeled from the original HRDB, there is a maximum 0.3 deg systematic error. However, applying the original horizon radiance correction model results in less error than no correction at all.

3. Comparing the results of IR pitch accuracy using the horizon radiance errors derived from a corrected IR Earth model, based on this work, to those from the uncorrected model shows that a significant component of the systematic error associated with latitude and season is eliminated. The resulting IR pitch attitude solution accuracy is then limited by the variance of the average error measured in this work and by the extremes exhibited by the longitudinal variations. The results indicate that the improved model will compensate for errors as large as 0.45 deg, with a 3σ error in the model of these values of approximately 0.3 deg.

The results of this analysis may be used for attitude determination support of ERBS in the future as a replacement for the spacecraft attitude motion model currently provided by the IRU. Additional enhancements can be made to this motion model by adding the effects of control loop magnetic torquing in response to spacecraft nutation and precession.

REFERENCES

1. NASA Technical Memorandum 86181, *Infrared Horizon Sensor Modeling for Attitude Determination and Control: Analysis and Mission Experience*, M. Phenneger, S. P. Singhal, T. H. Lee, T. Stengle, March 1985

2. Computer Sciences Corporation, CSC/SD-84/6007, *Earth Radiation Budget Satellite (ERBS) Horizon Radiance Modeling Utility (HRMU) User's Guide and System Description*, E. Burgess, June 1984

3. --, CSC/TM-83/6177, *Evaluation of the Horizon Radiance Data Base (HRDB)*, M. Phenneger, S. P. Singhal, November 1983

4. Air Force Geophysical Laboratory, Report AFGL-TR-80-0067, *Atmospheric Transmittance/Radiance: Computer Code LOWTRAN-5*, F. X. Kneizys, E. P. Shuttle, et al., February 1980

5. Computer Sciences Corporation, CSC/TM-77/6133, *A Comparison of Radiosonde Temperature and Humidity Profile Data Bases*, R. A. Nieman, August 1977

6. --, CSC/SD-83/6118, *Earth Radiation Budget Satellite (ERBS) Attitude Analysis and Support Plan*, M. Phenneger, et al., September 1983

7. --, CSC/SD-82/6013, *Earth Radiation Budget Satellite (ERBS) Attitude Ground Support System (AGSS) Functional Specifications and Requirements*, G. Nair, et al., September 1982

8. --, CSC/SD-86/6756, *Earth Radiation Budget Satellite (ERBS) Pitch and Roll Error Analysis*, J. Kronenwetter, et al., November 1986

9. Astrophysics and Space Science Library, Volume 73, *Spacecraft Attitude Determination and Control*, J. Wertz, Editor, 1978

10. Computer Sciences Corporation, CSC/SD-84/6005, *Earth Radiation Budget Satellite (ERBS) Definitive Attitude Determination System (DADS) User's Guide and System Description*, Y. Teng, July 1984

11. --, CSC/SD-84/6004UD2, *Earth Radiation Budget Satellite (ERBS) Attitude Determination System (ADS) User's Guide and System Description*, Revision 1, Update 2, R. Boyer, June 1988

12. --, CSC/SD-86/6012, *Horizon Radiance Modeling Utility Requirements and Specifications*, J. Hashmall, March 1986