Resolution of the COBE Earth Sensor Anomaly

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ABSTRACT

Since its launch on November 18, 1989, the Earth sensors on the Cosmic Background Explorer (COBE) have shown much greater noise than expected. The problem was traced to an error in Earth horizon acquisition-of-signal (AOS) times. Due to this error, the AOS timing correction was ignored, causing Earth sensor split-to-index (SI) angles to be incorrectly time-tagged to minor frame synchronization times. Resulting Earth sensor residuals, based on gyro-propagated fine attitude solutions, were as large as ±0.45 deg [much greater than ±0.10 deg from scanner specifications (Reference 1).] Also, discontinuities in single-frame coarse attitude pitch and roll angles (as large as 0.80 and 0.30 deg, respectively) were noted several times during each orbit.

However, over the course of the mission, each Earth sensor was observed to independently and unexpectedly reset and then reactivate into a new configuration. Although the telemetered AOS timing corrections are still in error, a procedure has been developed to approximate and apply these corrections. This paper describes the approach, analysis, and results of approximating and applying AOS timing adjustments to correct Earth scanner data.

Furthermore, due to the continuing degradation of COBE's gyroscopes, gyro-propagated fine attitude solutions may soon become unavailable, requiring an alternative method for attitude determination. By correcting Earth scanner AOS telemetry, as described in this paper, more accurate single-frame attitude solutions are obtained. All aforementioned pitch and roll discontinuities are removed. When proper AOS corrections are applied, the standard deviation of pitch residuals between coarse attitude and gyro-propagated fine attitude solutions decrease by a factor of 3. Also, the overall standard deviation of SI residuals from fine attitude solutions decrease by a factor of 4 (meeting sensor specifications) when AOS corrections are applied.

1. INTRODUCTION

Since its launch on November 18, 1989, the Cosmic Background Explorer's (COBE's) Earth sensors have shown greater noise than expected. It was determined that the acquisition-of-signal (AOS) timing correction was in error. Since no useful information could be extracted from this telemetry, the total AOS timing correction was ignored altogether, causing the split-to-index (SI) angles to be time-tagged incorrectly.

However, over the course of the mission, each Earth scanner was observed to independently and unexpectedly reset and then reactivate into a new configuration. Although the telemetered AOS corrections are still in error, a procedure has been developed to approximate the AOS corrections by assuming certain scanner attributes. This paper describes the approach, analysis, and results of approximating and applying these AOS timing corrections.

Section 2 describes predicted Earth scanner performance. Section 3 presents observed Earth scanner performance, both before and after reconfiguration. Section 4 explains the procedure to determine the AOS timing corrections. Section 5 compares the results both from applying and from ignoring the AOS timing corrections. Section 6 lists major assumptions and possible sources of error in the procedure.

2. PREDICTED EARTH SCANNER PERFORMANCE

COBE is equipped with three independent Earth horizon scanners (manufactured by Barnes Engineering, Inc.) to provide pitch control signals to orient the spacecraft with respect to the nadir (Earth-pointing) vector.

Each scanner consists of a small infrared telescope whose 2.5-deg diameter field-of-view (FOV) rotates at 240 ± 24 rpm by means of a spinning mirror. The rotating FOV defines a scan plane whose normal is a control axis (Reference 2).

During each revolution of the scanner FOV, the detector line of sight will nominally intersect the Earth. As it does, each sensor produces five signal pulses:

1. One pulse at the space-Earth transition (referred to as the AOS);
2. Three pulses as the scanner line of sight is aligned with respect to the spacecraft +X-axis at rotation angles of -90, 0, and +90 degrees (referred to as index pulses);
3. One pulse at the Earth-space transition (referred to as the loss-of-signal (LOS)).

It is assumed that an Earth pulse occurs midway between the AOS and LOS pulses. This Earth pulse, referred to as the "split," is the projection of the nadir vector onto the scan plane. During the primary spacecraft control mode (mission mode), the index pulse produced at 0 deg is used. These pulses start and stop clock counters that give a count proportional to the SI angle that is finally telemetered (Reference 1).

Each scanner also produces the time of occurrence (referred to as the telemetered AOS timing correction) of the AOS crossing pulse with respect to the minor frame synchronization (MFS) pulse by counting the number of changes in state of the spacecraft clock. The nominal minor frame period is 0.25 sec.

In the event that the scanner FOV is not spinning at 240 rpm, it is possible for the SI data to be referenced to a previous minor frame. Each scanner, therefore, telemeters a minor frame offset (MFO) as follows:

MFO equals zero for the current minor frame, one for one minor frame previous, two for two minor frames previous, or three for three minor frames previous.

(Under nominal scanner conditions and FOV rates, the MFO should oscillate between 0 and 1.)

Due to the 0.83 rpm spin rate of the spacecraft, total AOS timing corrections (consisting of the telemetered AOS timing correction and the MFO output) must be applied to SI measurements. At polar crossings during summer solstice, the measured SI angles (under nominal conditions) will oscillate approximately between ± 36 degrees over the 72 sec spin cycle. The rate of change of the SI angle will be (36 deg) * (2π)/(72 sec) = 3.2 deg/sec. If the total AOS correction is ignored and the SI calculation corresponds to one minor frame previous (MFO 21), the error in the SI measurement will approach 3.2 deg/sec * (1) * 0.25 sec = 0.8 deg (outside of 0.1 deg from scanner specifications).

A hypothetical plot of scanner output signal versus time is illustrated in Figure 1a (shown for a scanner FOV rate less than 240 rpm). Four pieces of information are of interest: the time of the minor frame synchronization pulse, the time of AOS crossing pulse, the time of the SI calculation from the scanner electronics, and time of the serial input/output (I/O) request for Earth scanner data. (The amount of time between the LOS crossing pulse and the SI calculation time is assumed to be small and is neglected in this analysis.) These four pieces are labeled in Figure 1a as M, A, C, and R, respectively.

An explanation of Figure 1a follows:

1. At COBE's altitude of 900 km, the full angular width of the Earth is approximately 120 deg. Thus, the time between the AOS and LOS pulses should be approximately 1/3 of a scanner FOV period, or (0.25 sec)*(1/3) = 0.0833 sec (assuming a near-nominal FOV rate).
2. The nominal transmission bit rate of 4.096 kbps requires the time between MFS pulses to be 0.25 sec.
3. The serial I/O request for Earth scanner telemetry occurs approximately midway between MFS pulses.
4. In this example, the scanner FOV rate is 216 rpm.

Figure 1b depicts the corresponding AOS and MFO output for this example.

In order for the MFO to equal 0, the AOS pulse and the updated SI angle must occur *between* the MFS pulse and its respective serial I/O request time (e.g., minor frames 1 and 2 in Figure 1a).

If the scanner FOV is spinning slower than 240 rpm, the serial I/O request time for Earth scanner telemetry will be out of phase with the SI calculation time. The request time will eventually occur before the new SI angle is calculated. When this happens, the SI angle and AOS timing correction of the previous minor frame should be telemetered and the MFO set equal to 1 (e.g., minor frame 3 in Figure 1b).

Earth scanner data corresponding to one minor frame previous will continue to be telemetered until the AOS and SI calculation times occur within the current MFS and data request times, at which time, the MFO returns to 0 (e.g., minor frame 11 in Figure 1b).

Assuming the scanner FOV rate remains relatively constant and less than 240 rpm, this output will repeat itself with a period proportional to the scanner rate. It can be shown that the scanner FOV rate can be approximated by the following equation:

$$\Omega_{FOV} = [240 - (60/T)], \qquad (1)$$

where Ω_{FOV} is the scanner FOV rate in rpm and
T is the number of seconds between successive 0-to-1 MFO transitions.

(<u>NOTE</u>: If the telemetered AOS timing corrections decrease, the scanner FOV rate is greater than 240 rpm. In this case, Equation 1 becomes $\Omega_{FOV} = [240 + (60/T)]$.

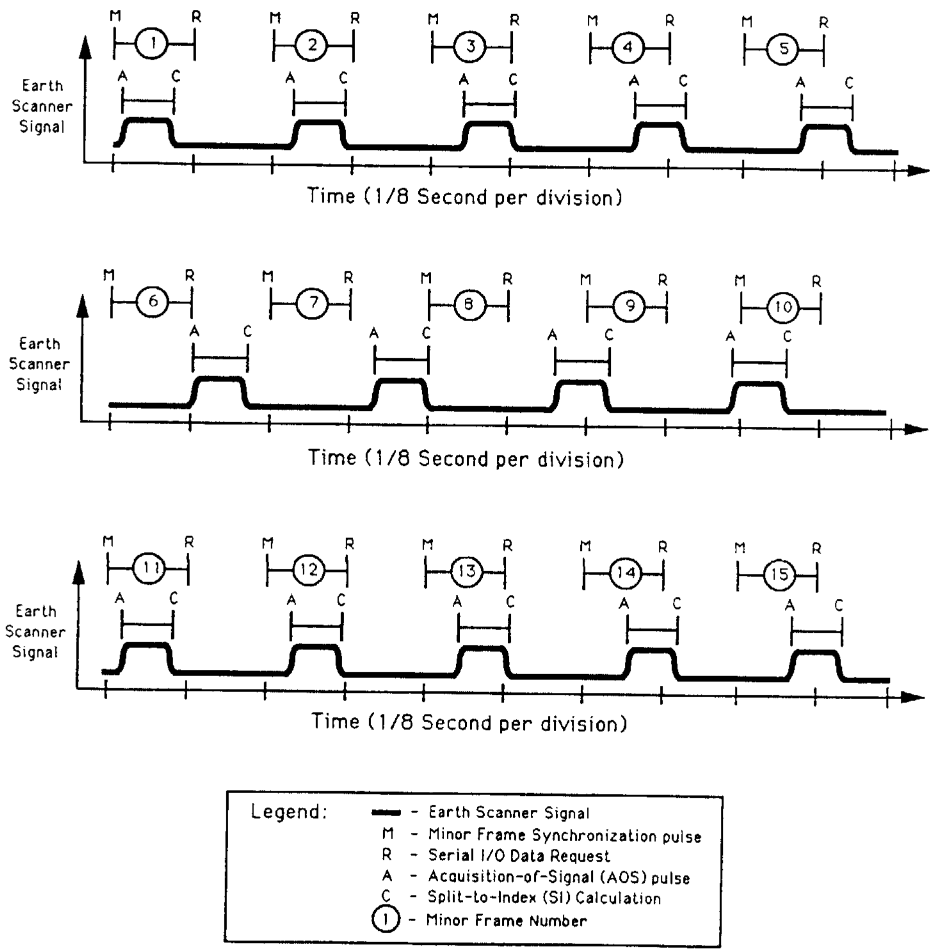


Figure 1a. Typical Phasing of Earth Scanner Output Signal for FOV Rate Less Than 240 rpm

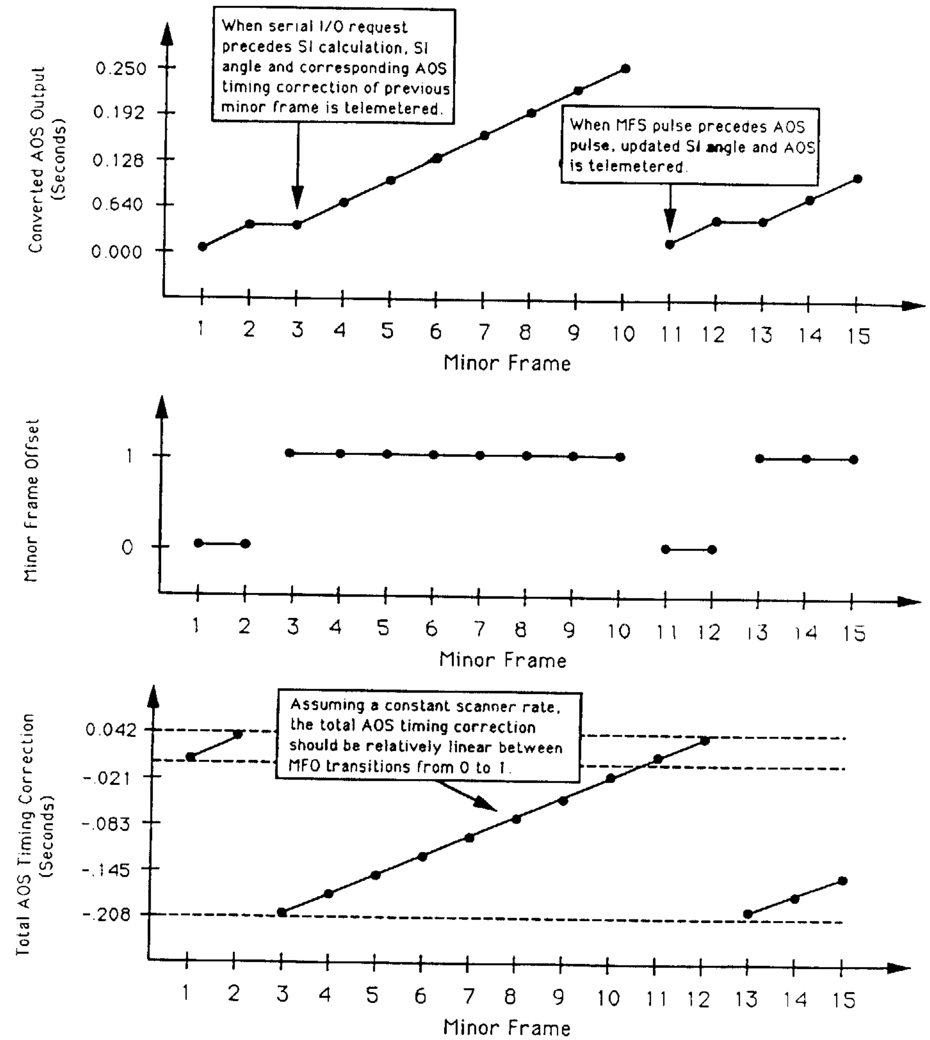


Figure 1b. Corresponding AOS and MFO Output for FOV Rate Less Than 240 rpm

Ground Processing

Once the telemetry is received, the COBE Attitude Determination System (ADS) converts the SI to angles and AOS timing corrections to seconds. The SI angle is then time-tagged to the time of the AOS pulse by the equation:

$$t_{SI} = [t_{S/C} - 64 * 8/BR] + [\delta t_{AOS} - N * (128 * 8/BR)] \quad (2)$$

where t_{SI} is the adjusted time tag of the SI angle ;

$t_{S/C}$ is the spacecraft clock time ($64 * 8$ is the bit offset of the spacecraft clock from the MFS pulse);

δt_{AOS} is the telemetered AOS timing correction (sec);

N is the MFO corresponding to the SI angle and AOS timing correction (128×8 bits = 1 minor frame); and

BR is the transmission bit rate, 4.096 kbps.

The number in the first set of brackets is equivalent to the time of the current MFS pulse. In this report, the number in the second set is referred to as the "total AOS timing correction."

3. OBSERVED EARTH SCANNER PERFORMANCE

Before Earth Scanner Reconfigurations

Figure 2 shows MFO output and the corresponding total AOS timing corrections for Earth scanner A at the beginning of the mission. (Scanners B and C show similar output.) While scanner SI angles were correct, both the AOS timing correction and the minor frame offset telemetry were inexplicable. A characteristic 11-second rollover in the AOS timing correction (Figure 2) was observed for each scanner. This decreasing AOS correction is consistent with a FOV rate of approximately 245 rpm (greater than 240 rpm).

Given this scanner rate, the corresponding MFO should oscillate between 0 and 1 with the same 11-sec period. No such oscillation is observed. Also, at AOS rollover points, slight discontinuities in the SI angles should exist as the SI angle is updated within a given minor frame. No discontinuities in SI angles with an 11-sec period were observed.

It was therefore determined that both the AOS timing correction and minor frame offset output were incorrect. Practice became to set the total AOS timing correction to zero, thus time-tagging the SI angles to the MFS pulse (see Equation 2).

Discontinuities in SI angles were, however, observed for each scanner approximately every 5 to 10 minutes, corresponding to scanner FOV rates of approximately 239.8 to 239.9 rpm. It was postulated that total AOS timing corrections could be simulated by first locating these discontinuities in SI telemetry. Then, if various scanner attributes were assumed (see Section 2), AOS corrections could be linearly interpolated between SI discontinuities. Unfortunately, noise in SI telemetry at nodal crossings along with Sun and Moon interference made locating the SI discontinuities difficult and unreliable.

After Earth Scanner Reconfigurations

Over the course of the mission, each Earth scanner was observed to independently and unexpectedly "reset" itself. Upon its initial reactivation, each scanner would change into and remain in a new configuration. The MFO output was no longer constant at 0 but was observed to oscillate between 0 and 3 with the 11-sec AOS rollover period. The telemetered AOS timing correction, δt_{AOS}, remained unchanged in the new configuration. Figure 3 shows the new MFO output pattern and the corresponding total AOS timing correction. Even in this new configuration, the total AOS timing correction is still incorrect.

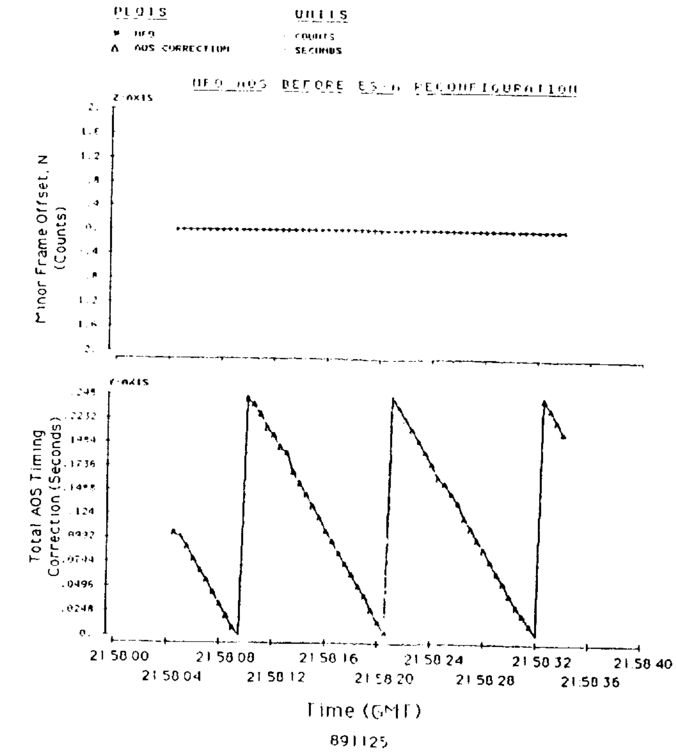


Figure 2. MFO/AOS Output Before Earth Scanner Reconfiguration (Shown for Scanner A)

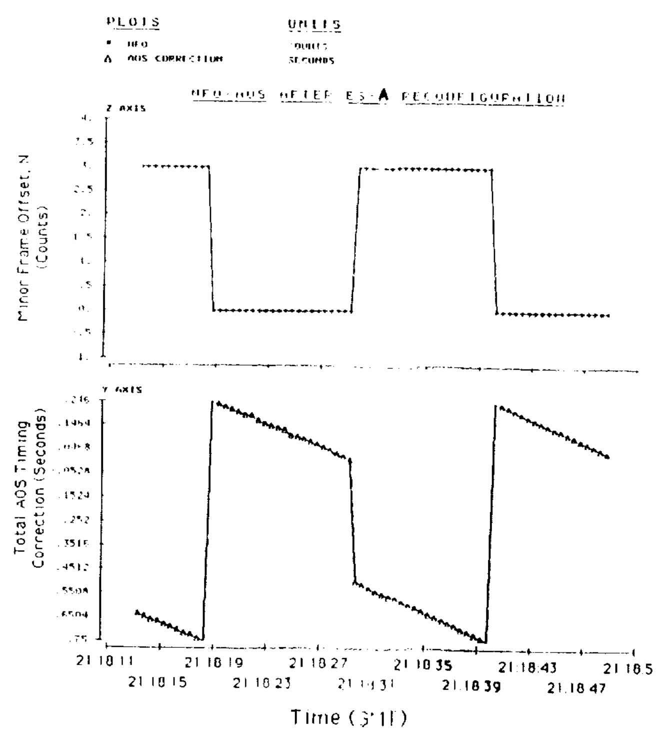


Figure 3. MFO/AOS Output After Earth Scanner Reconfiguration (Shown for Scanner A)

Fortunately, changes in this characteristic MFO output were simultaneous with discontinuities in SI angle (see Figure 4). It was therefore assumed that a "true" MFO transition occurred when the MFO pattern was broken. Since the MFO output was independent of SI noise and Sun/Moon interference, these characteristic breaks were used to reliably signal SI discontinuities due to MFO transitions. Total AOS timing corrections for each Earth scanner could then be interpolated and subsequently applied to SI angle time-tags. The reconfiguration times for each Earth scanner are recorded in Table 1.

4. PROCEDURE FOR ADJUSTING AOS TIMING CORRECTIONS

For a selected time span, minor frame offsets were compared with the AOS rollover periods for each individual Earth scanner. Each break in the MFO characteristic pattern previously described was assumed to be a "true" MFO transition from 0 to 1 or from 1 to 0.

To determine which transition had actually occurred, the number of seconds between successive "true" MFO transitions was calculated. Table 2 contains an example of MFO transition times for Earth Scanner A.

Two classifications of transitions were discovered:

1. "Type I" transitions: separated by 300 sec or more and
2. "Type II" transitions: separated by 100 sec or less.

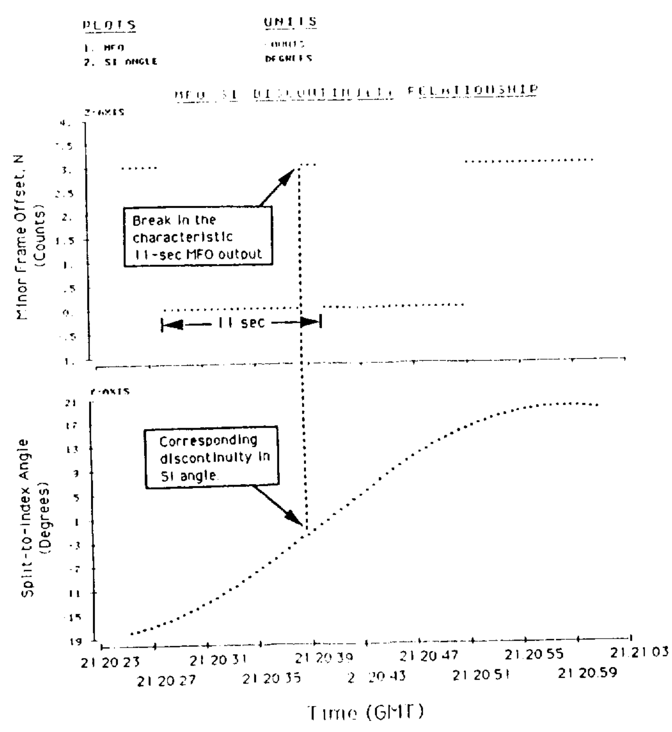


Figure 4. MFO/SI Discontinuity Relationship After Earth Scanner Reconfiguration (Shown for Scanner A)

Table 1. Reconfiguration Times of COBE Earth Scanners

Earth Scanner	Reconfiguration Time (GMT)
A	900814.130047
B	910926.173059
C	910101.181415

Table 2. MFO Transition Times for Earth Scanner A

Minor Frame Time (GMT)	Difference (sec)	Transition Type	Total AOS Correction (sec)
910504.203406267	—	—	—
910504.204050767	404.5	I	−0.208
910504.204051767	1.0	II (1)	−0.208
910504.204052267	0.5	II (2)	+0.042
910504.204055767	3.5	II (3)	−0.208
910504.204131267	35.5	II (4)	+0.042
910504.204936267	485.0	I	−0.208
910504.205007767	31.5	II (1)	−0.208
910504.205008267	0.5	II (2)	+0.042
910504.205008767	0.5	II (3)	−0.208
910504.205009267	0.5	II (4)	+0.042
910504.205010267	1.0	II (5)	−0.208
910504.205010767	0.5	II (6)	+0.042
910504.205737267	446.5	I	−0.208
910504.210458267	441.0	I	−0.208
910504.211324767	506.5	I	−0.208

The Type I transitions could be explained by the following hypothesis:

If the scanner FOV rate was slightly less than the nominal 240 rpm, then the serial I/O request would be out of phase with the SI angle calculation (see Section 2). The request time would eventually occur before the new SI angle was calculated, causing the previous minor frame SI angle to be telemetered. The "true" MFO transition would, therefore, be from 0 to 1. Furthermore, if scanner FOV rate is assumed relatively constant, this process would repeat itself periodically. Using Equation 1, for $T \geq 300$ sec, the approximate scanner FOV rates range between 239.8 and 240 rpm.

At the initial Type I MFO transition, the request time is assumed to occur just before the new SI is calculated. The AOS timing correction is then approximately equal to the time difference between the MFS pulse to data request and the AOS pulse to calculation (see Figure 5), or +0.042 sec. Since the MFO is assumed to equal 1, the total AOS timing correction, measured from the current MFS pulse (see Equation 2), is $+0.042 - (1)*0.250 = -0.208$ sec at the initial transition.

Prior to the next Type I transition, the data request time is assumed to occur just after the new SI is calculated (i.e., N equals 0 in Equation 2). The total AOS timing correction is then equal to +0.042 - (0)*0.250 = +0.042 sec. Assuming a constant scanner rate, the total AOS timing corrections for the intervening SI angles are then linearly interpolated between these two corrections according to the equation:

$$AOS_T = \{[(t_{MF} - t_1)/(t_2 - t_1)] * 0.250\} + (-0.208), \qquad (3)$$

where t_{MF} is the minor frame time; $t_1 \leq t_{MF} < t_2$;
t_1 is the time of the first Type I MFO transition;
t_2 is the time of the second Type I MFO transition; and
AOS_T is the total AOS timing correction (sec).

Type II transitions could be explained in a similar manner. The serial I/O request occurs at a fixed period of 0.250 sec. However, the period at which the SI calculation is determined is not fixed. It is dependent upon both the AOS and LOS pulses which, in turn, vary according to spacecraft attitude, orbit location, time of year, etc. It is plausible, therefore, to assume that these transitions, which are separated by less than 100 sec, result from the movement of the calculation time with respect to the serial I/O request.

When the calculation time occurs after the request time, the "true" MFO transition would be from 0 to 1 (see Figure 6), corresponding to a total AOS timing correction of

$$AOS_T = -0.208 \text{ sec}$$

When the calculation time occurs just before the request time, the MFO transition would be from 1 to 0, corresponding to a total AOS timing correction of

$$AOS_T = +0.042 \text{ sec}$$

All intervening AOS corrections are assumed constant between these Type II MFO transitions.

Assuming the scanner FOV rate is less than 240 rpm, there should always exist either zero or an even number of Type II MFO transitions between Type I transitions (see Table 2). Even though the data request and calculation times may toggle back and forth several times, the data request time eventually will remain before the calculation time. Examination of SI angle discontinuities supports both explanations of Type I and Type II MFO transitions.

In summary, the total AOS timing corrections are determined in the following manner:

1. If the SI angle occurs at or within a set of Type I MFO transitions, the total AOS timing correction is linearly interpolated according to Equation 3;

2a. If the SI angle occurs at or within an odd-numbered set of Type II MFO transitions, the total AOS timing correction is -0.208 sec;

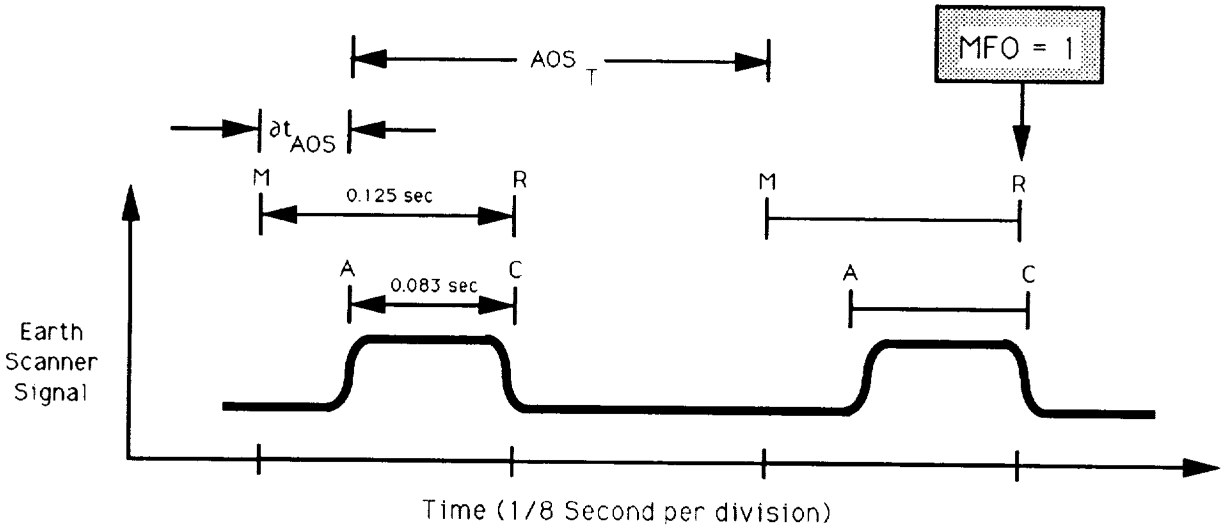
2b. If the SI angle occurs at or within an even-numbered set of Type II MFO transitions, the total AOS timing correction is +0.042 sec.

5. RESULTS

Figures 7a and 7b show coarse attitude determination subsystem (CADS) solutions over a typical 30-minute span, using the AOS timing corrections directly from telemetry. Discontinuities (as large as 2.5 deg in pitch and 1 deg in roll) are observed with an 11-sec periodicity (at all AOS rollover locations).

(<u>NOTE</u>: For all the attitude solutions contained in this report:

1. Corrections for Earth oblateness and spacecraft spin have been applied to the SI angles.
2. For the selected timespan, Earth scanner B had not yet been reactivated into the new configuration by which AOS corrections could be made. Therefore, only data from Earth scanners A and C are used.
3. In the fine attitude solutions, the X-gyro scale factor has been corrected for a known temperature dependence.)

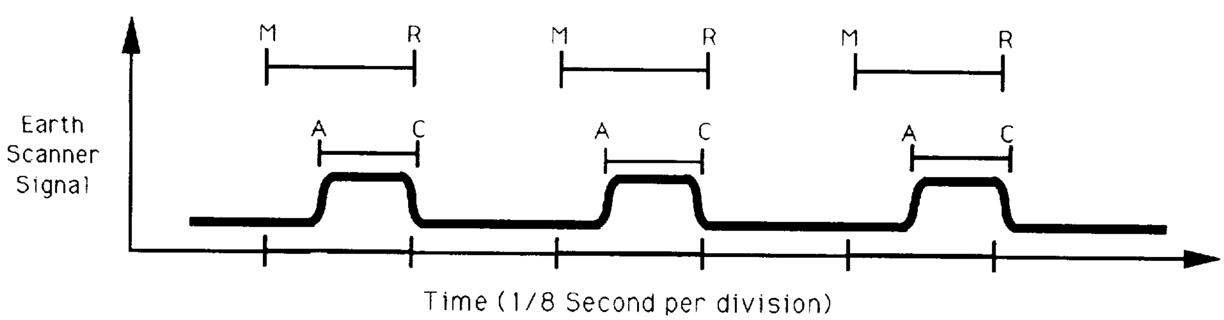


When the serial I/O data request precedes the SI calculation, the SI angle from the previous minor frame is telemetered. The corresponding total AOS timing correction, measured from the current MFS pulse, is:

$$AOS_T = \partial t_{AOS} - (1)*0.25 \text{ sec} = +0.042 \text{ sec} - 0.250 \text{ sec} = -0.208 \text{ sec}$$

Figure 5. Explanation of Type I MFO Transitions

MFO	1	0	1
∂t_{AOS}	0.042 sec	0.042 sec	0.042 sec
AOS_T	-0.208 sec	+0.042 sec	-0.208 sec



Since the AOS and LOS signals are dependent upon several factors (i.e., spacecraft attitude, orbit location, etc.), the exact SI calculation time will vary. It is possible for the calculation time to toggle before and after the serial I/O request time, causing multiple Type II MFO transitions to occur. If the scanner FOV is less than 240 rpm, there will always exist an even number of such transitions.

Figure 6. Explanation of Type II MFO Transitions

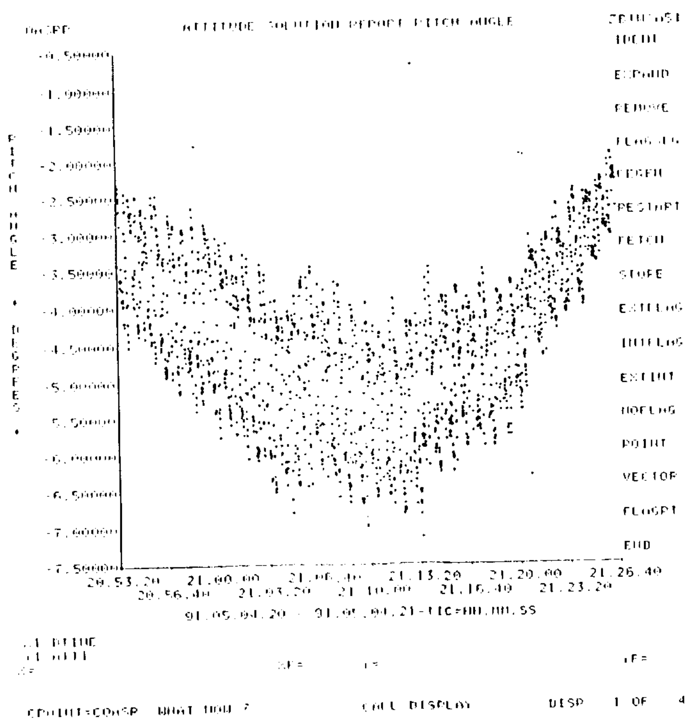


Figure 7a. Coarse Attitude Using Unadjusted AOS Timing Corrections (Pitch Angle)

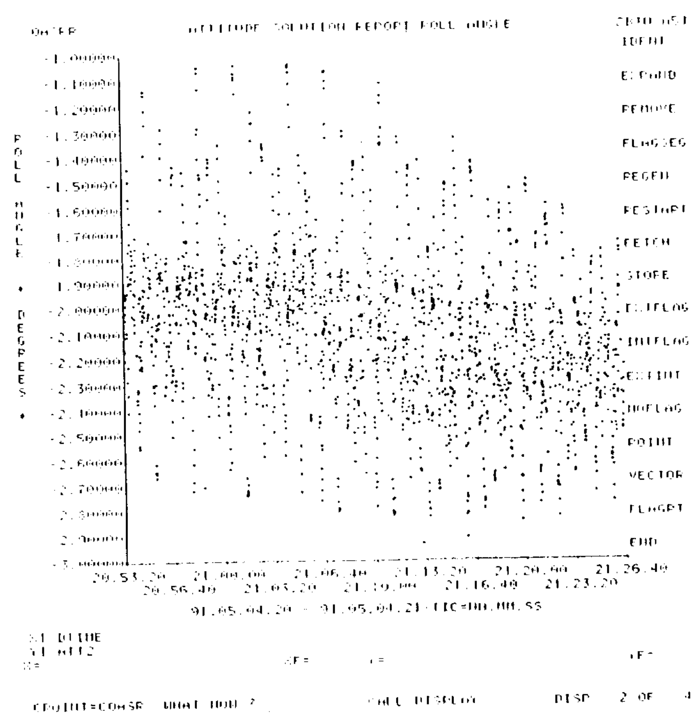


Figure 7b. Coarse Attitude Using Unadjusted AOS Timing Corrections (Roll Angle)

Figures 8a and 8b depict corresponding CADS solutions when the AOS corrections are ignored altogether (time-tagging SI angle to the MFS pulse). Discontinuities (0.80 deg in pitch, 0.30 deg in roll) are observed with a 5- to 10-minute periodicity resulting from "true" MFO transitions.

Figures 9a and 9b show CADS solutions using the AOS timing correction method presented in this paper. All attitude discontinuities are removed.

To measure the solution accuracies, two gyro-propagated fine attitude determination system (FADS) solutions were determined. One solution was computed ignoring the total AOS corrections (time-tagging SI observations to the MFS pulse), and the other applied the AOS correction procedure described above.

Graphs of SI residuals, equal to the observed SI angles minus the predicted SI angles from the gyro-propagated solution, were created for Earth scanner A without AOS corrections (Figure 10) and with AOS corrections (Figure 11). Similar results were found for Earth scanner C. By applying the corrections, the maximum SI residual was observed to decrease from ±0.45 deg to ±0.10 deg for each scanner (meeting sensor specifications). Also, the overall standard deviation of SI residuals decreased by a factor of 4, from 0.126 deg (without AOS corrections) to 0.032 deg (with AOS corrections).

The gyro-propagated fine attitude solutions were then compared with their respective coarse attitude solutions for each case. Corresponding pitch residuals (equal to the fine pitch angle minus the coarse pitch angle) are found in Figure 12 (when AOS corrections are ignored) and Figure 13 (using AOS corrections). By applying the AOS corrections, the maximum pitch residual was observed to decrease from ±0.50 deg to ±0.15 deg. Similarly, the overall standard deviation of the pitch residuals decreased by a factor of 3, from 0.159 deg (without AOS corrections) to 0.062 deg (with AOS corrections). In addition, the root mean square of the deviation angle decreased from 0.262 deg to 0.199 deg when the AOS corrections were applied.

These results indicate an increase in both fine attitude and coarse attitude accuracy when the AOS correction method is applied.

6. SOURCE OF ERRORS

The following is a list of assumptions and possible sources of error:

1. Earth scanner FOV rates are assumed to be less than 240 rpm. All examinations of SI data for each reconfigured scanner were consistent with this assumption.
2. Earth scanner FOV rates are assumed constant between both types of MFO transitions. Examination of the envelope of SI residuals using the AOS correction method (Figure 11) is not constant throughout the time span and may indicate a varying FOV rate. Application of a different interpolation method, such as a natural cubic spline, may minimize this source of error.
3. The time between AOS to LOS pulses (i.e., Earth width) is assumed constant. This measured width changes most rapidly at polar crossings, sinusoidally oscillating with spacecraft yaw angle. The width is also dependent upon the commanded spacecraft attitude and Sun declination. Unfortunately, the time span analyzed in this report is centered about the spacecraft's northern-most passage. The oscillatory behavior of the SI residuals in Figure 11 may be caused by the assumption of a constant Earth width. Further analysis is needed.
4. No correction for Earth horizon radiance is made. With the increase in accuracy of the attitude solutions, its detection and determination may now be possible.
5. A drawback to this method is its susceptibility to data dropout. If a "true" MFO transition is omitted due to data dropout, AOS timing corrections may be interpolated between improper times. It is possible, however, to predict the MFO output (using its characteristic 11-sec periodicity). By comparing the predicted and actual MFO, it can be determined if a "true" MFO transition occurred during the dropout period.

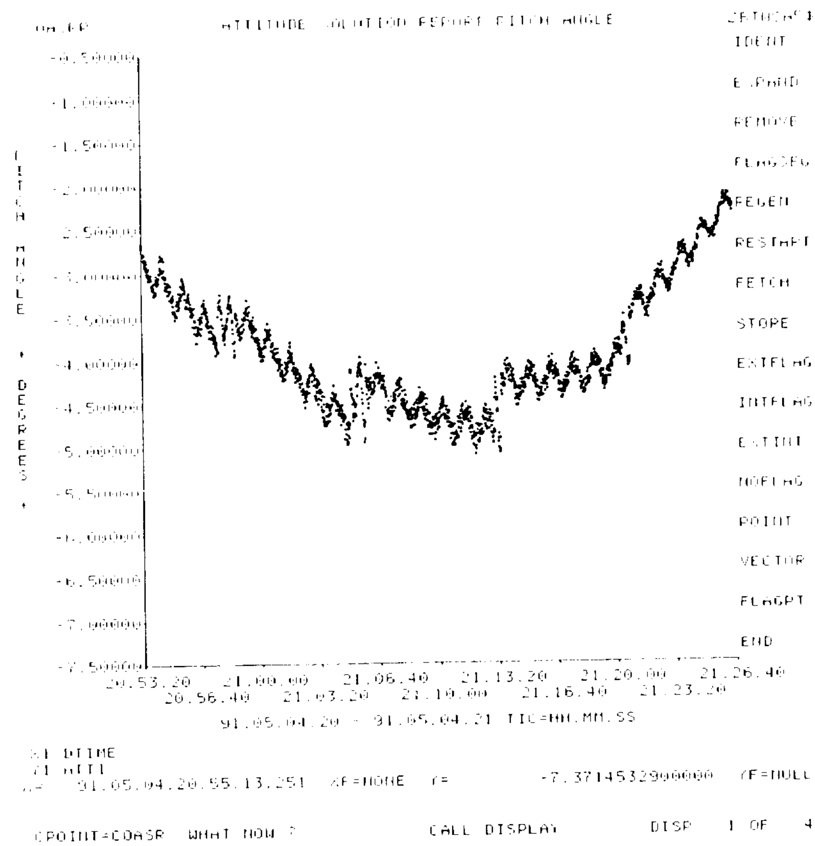


Figure 8a. Coarse Attitude Ignoring AOS Timing Corrections (Pitch Angle)

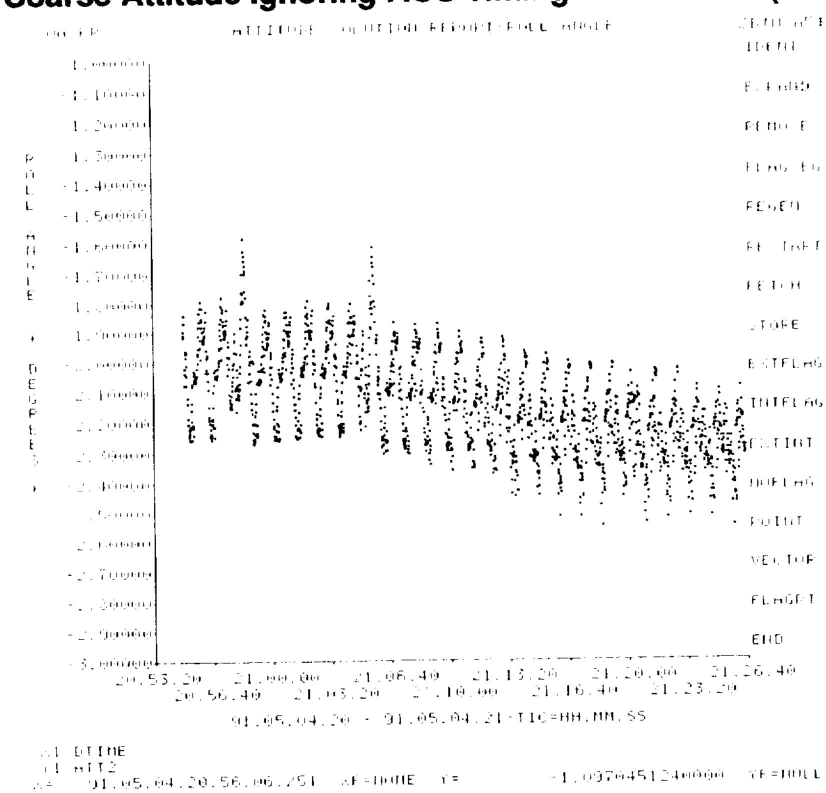


Figure 8b. Coarse Attitude Ignoring AOS Timing Corrections (Roll Angle)

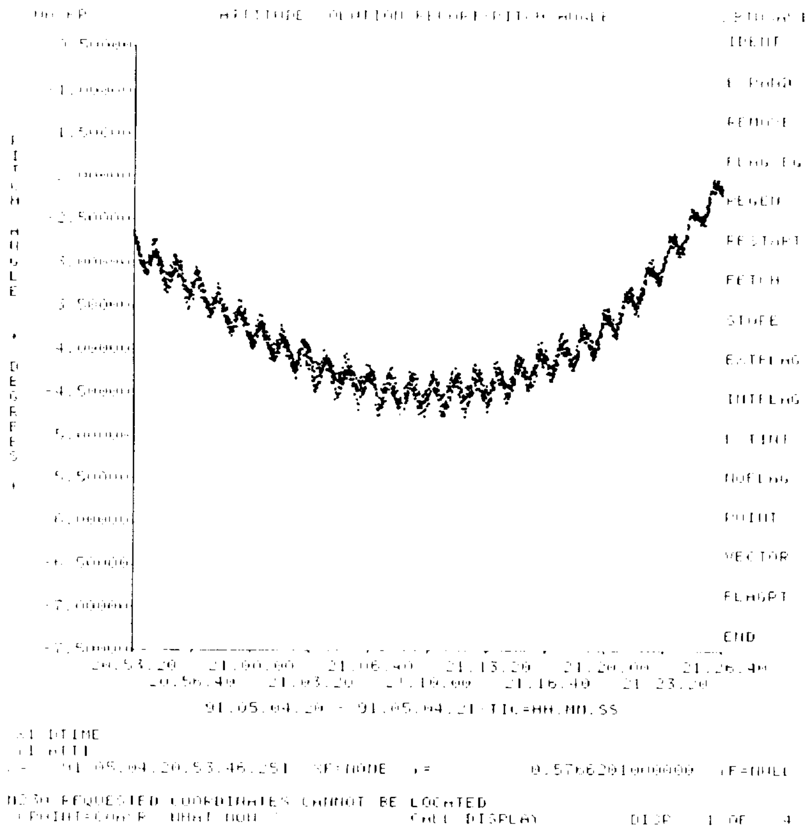


Figure 9a. Coarse Attitude Using Adjusted AOS Timing Corrections (Pitch Angle)

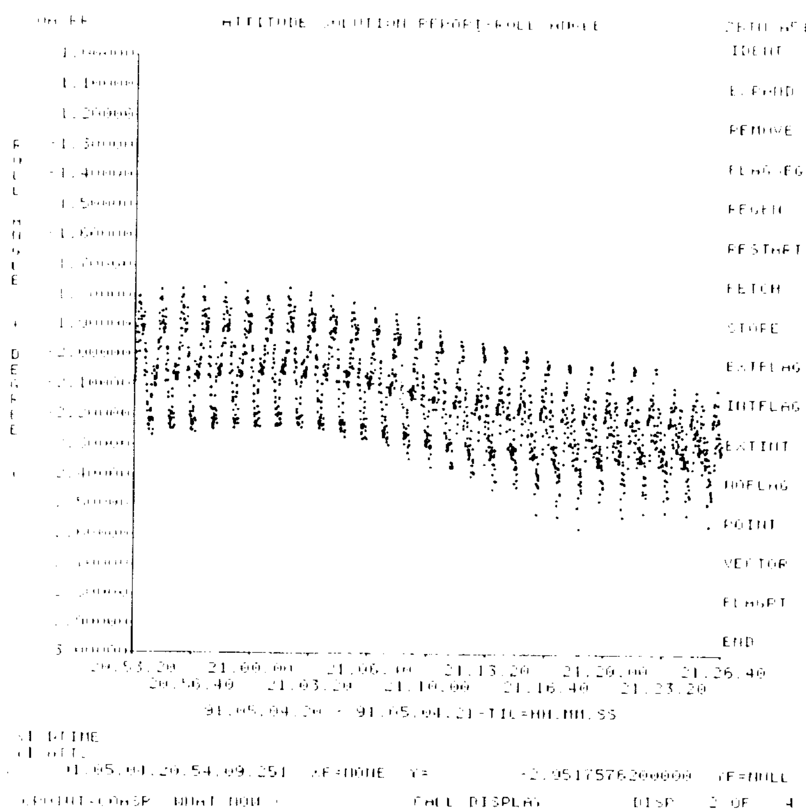


Figure 9b. Coarse Attitude Using Adjusted AOS Timing Corrections (Roll Angle)

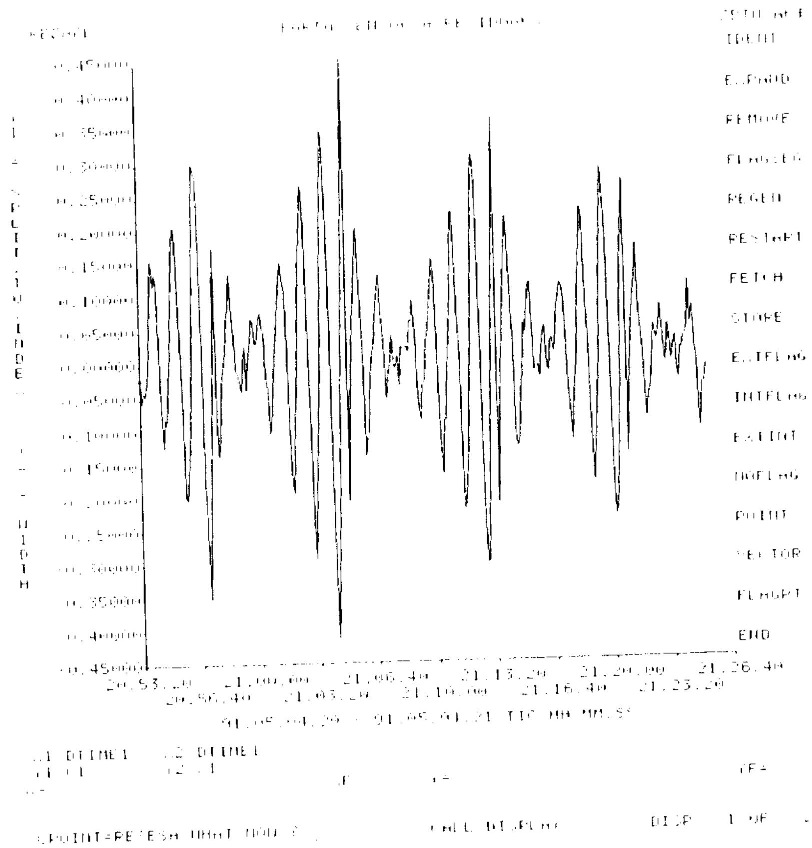


Figure 10. Earth Scanner A SI Residuals (Ignoring AOS Timing Corrections)

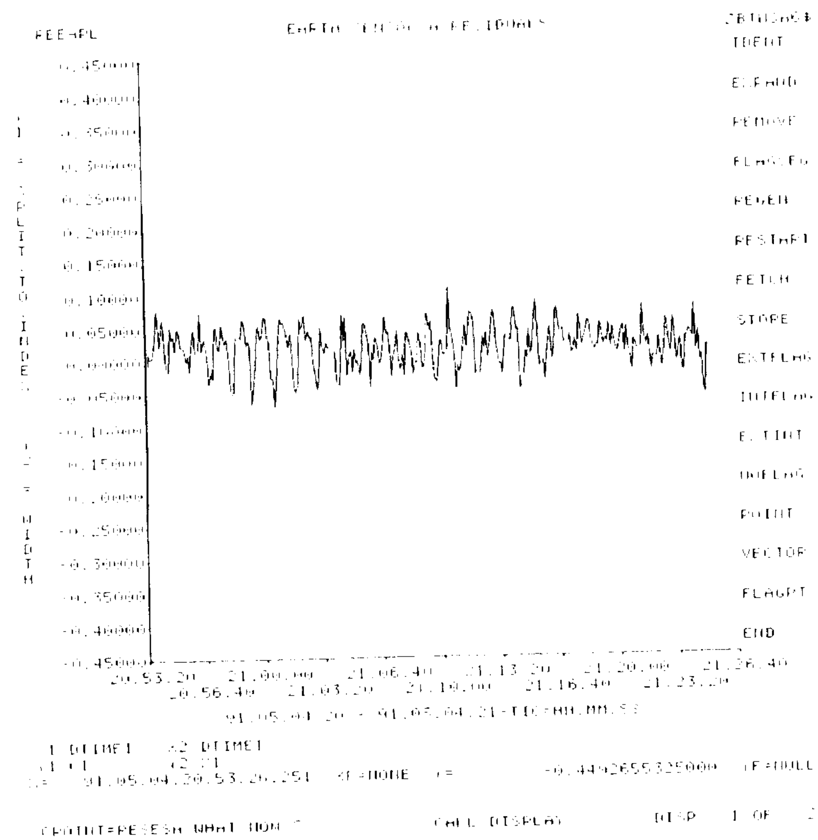


Figure 11. Earth Scanner A SI Residuals (Applying AOS Timing Corrections)

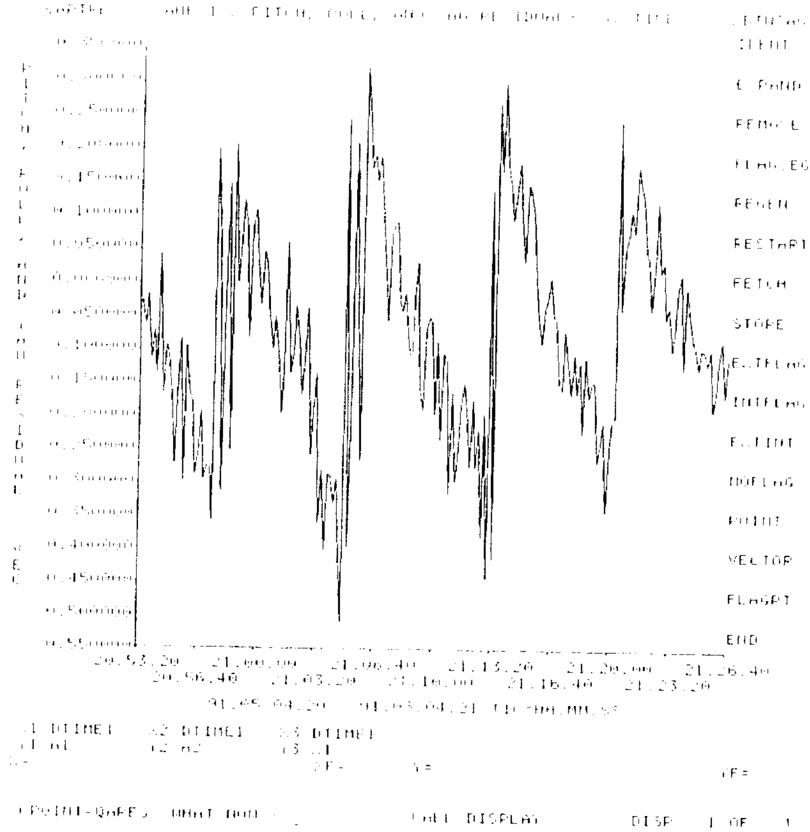


Figure 12. Gyro-Propagated Fine Pitch Angle Minus Coarse Attitude Pitch Angle (Ignoring AOS Timing Corrections)

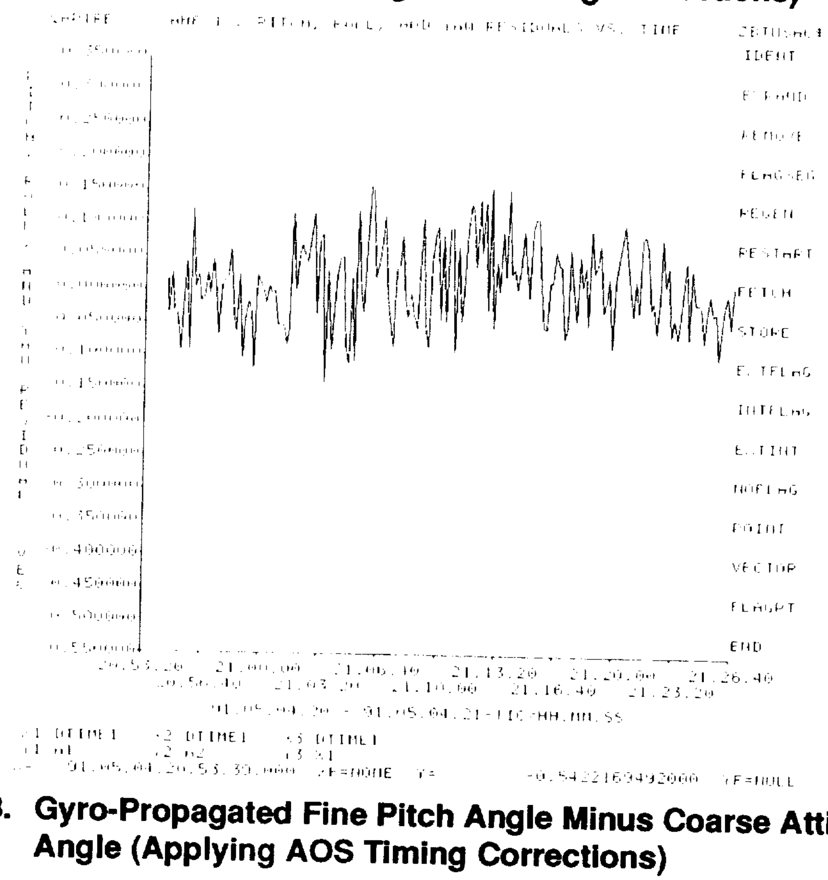


Figure 13. Gyro-Propagated Fine Pitch Angle Minus Coarse Attitude Pitch Angle (Applying AOS Timing Corrections)

7. CONCLUSION

Using the new scanner configuration, "true" MFO transitions can be located and total AOS timing corrections can be interpolated accurately and reliably. When the AOS timing corrections are applied, Earth scanner accuracy is observed to be within ± 0.10 deg (meeting sensor specifications), yielding more accurate coarse attitude and fine attitude solutions.

Furthermore, with the continued degradation of COBE's gyroscopes, gyro-propagated fine attitude solutions may soon become unavailable, requiring an alternative method for attitude determination. By correcting Earth scanner AOS telemetry, as described in this paper, more accurate single-frame attitude solutions are obtained and all pitch and roll discontinuities are removed. When proper AOS corrections are applied, the standard deviation of pitch residuals between coarse attitude and gyro-propagated fine attitude solutions decreases by a factor of 3. Also, the overall standard deviation of SI residuals from fine attitude solutions decreases by a factor of 4 (meeting sensor specifications) when AOS corrections are applied.

This method of adjusting the AOS timing correction was formulated solely from observations in telemetry and assuming scanner attributes. It is hoped that an inspection of the actual electronics diagram may assist in the development of a more sophisticated and accurate AOS adjustment procedure for each Earth scanner, especially before the scanner reconfiguration times listed in Table 1.

REFERENCES

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