

THE RESPONSE OF THE SEASAT AND MAGSAT
INFRARED HORIZON SCANNERS TO COLD CLOUDS

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ABSTRACT

Cold clouds over the Earth are shown to be the principal cause of pitch and roll measurement noise in flight data from the infrared horizon scanners onboard Seasat and Magsat. This paper discusses the observed effects of clouds on the fixed threshold horizon detection logic of the Magsat scanner and on the variable threshold detection logic of the Seasat scanner. National Oceanic and Atmospheric Administration (NOAA) Earth photographs marked with the scanner ground trace clearly confirm the relationship between measurement errors and Earth clouds. A one-to-one correspondence can be seen between excursions in the pitch and roll data and cloud crossings. The characteristics of the cloud-induced "noise" are discussed, and the response of the satellite control systems to the cloud errors is described. Changes to the horizon scanner designs that would reduce the effects of clouds are noted.

INTRODUCTION

The postlaunch evaluation of data from the Seasat and Magsat infrared (IR) horizon scanners has shown that cold clouds over the Earth are the principal cause of pitch and roll measurement noise¹. This paper discusses the measurement

¹Note that cold clouds are cited here as the principal cause of noise in IR scanner attitude data; this does not necessarily mean that they are the principal source of error in the attitudes.

errors that are caused by clouds. An understanding of IR scanner response to cold clouds is important for the determination of the attitude accuracy achievable using IR scanners. It is also important because control systems such as those of Seasat and Magsat use the IR scanner data as input to the control law. Most important, an accurate understanding of the scanner response to clouds can aid in the design of future scanners that will show less sensitivity to clouds.

The following sections of the paper will present a brief description of the Seasat and Magsat IR Earth sensor implementation and technology; a discussion of how cold clouds modify the Earth radiance profile in the infrared and how this affects the IR sensor Earth chord measurements; visual evidence for the cold cloud effects in the Seasat attitude data and confirmation of the coincidence of this effect in the Seasat and Magsat data with passage over clouds in the Earth IR photographs; visual evidence for cold clouds in the Magsat IR scanner data derived from comparisons with star camera attitudes; and a discussion of observations and conclusions concerning the technology of attitude sensing using IR scanners.

BACKGROUND

The Seasat IR attitude sensors were a pair of ITHACO Scanwheels¹ located on the left and right side of the spacecraft at 90 degrees to the nominal velocity vector and tilted 26 degrees below the horizontal, with 45-degree scan cones. This configuration is illustrated in Figure 1. The spacecraft flew in a nominal Earth-oriented attitude with a pitch

¹Scanwheel is a registered trademark of ITHACO, Inc.

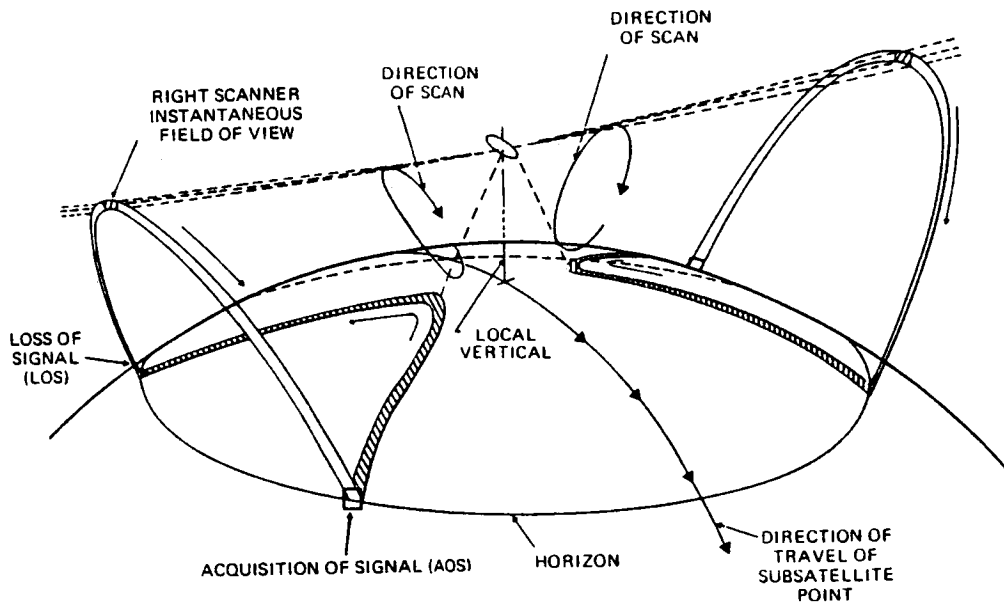


Figure 1. Seasat IR Scanner Configuration

rotation rate of 1 revolution per orbit. Although Seasat was designed to operate in a dual-IR-scanner mode, problems with Sun interference in the left scanner forced the use of a single-IR-scanner control mode. The pitch and roll¹ were derived in an onboard analog processor from the right IR scanner Earth chord measurement, according to the following equations:

$$\text{pitch} = K_p (\Omega^{\text{LOS}} - \Omega^{\text{AOS}}) \quad (1)$$

$$\text{roll} = K_r (\Omega^{\text{AOS}} + \Omega^{\text{LOS}} - \Omega_0) \quad (2)$$

¹Pitch is a right-handed rotation about negative orbit normal; roll is a right-handed rotation about the spacecraft velocity vector for a circular orbit.

where Ω^{AOS} and Ω^{LOS} are the horizon-to-spacecraft-index dihedral angles for the sky/Earth and Earth/sky portions of the scan, respectively, and Ω_0 , K_p , and K_r are constants based on the nominal Earth chord and the partials of pitch and roll with respect to Ω^{AOS} and Ω^{LOS} . The Earth horizon was detected using a normalized threshold method as illustrated in Figure 2. The horizon threshold was automatically adjusted to be 40 percent of the average of the Earth pulse amplitude between 5 and 11 scan degrees from the acquisition of signal (AOS) and loss of signal (LOS) horizons.

The Magsat Earth sensor was an ITHACO Scanwheel dual-flake IR sensor located 90 degrees to the nominal velocity vector in the horizontal plane on the left side of the spacecraft, with a 45-degree scan cone. The Earth horizon was sensed using a fixed-threshold locator logic, and the pitch and roll for Magsat were determined onboard. The ground processing

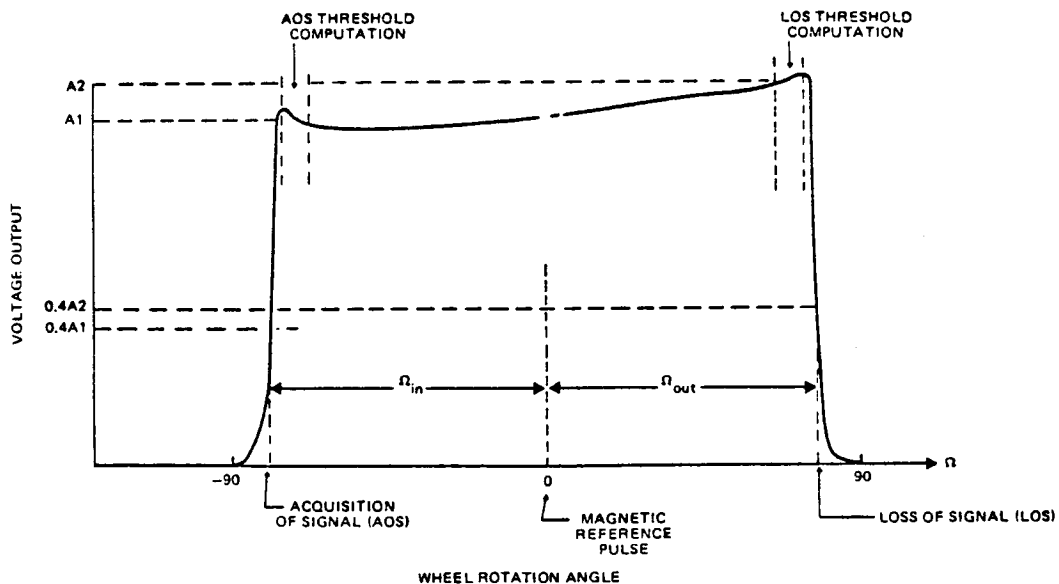


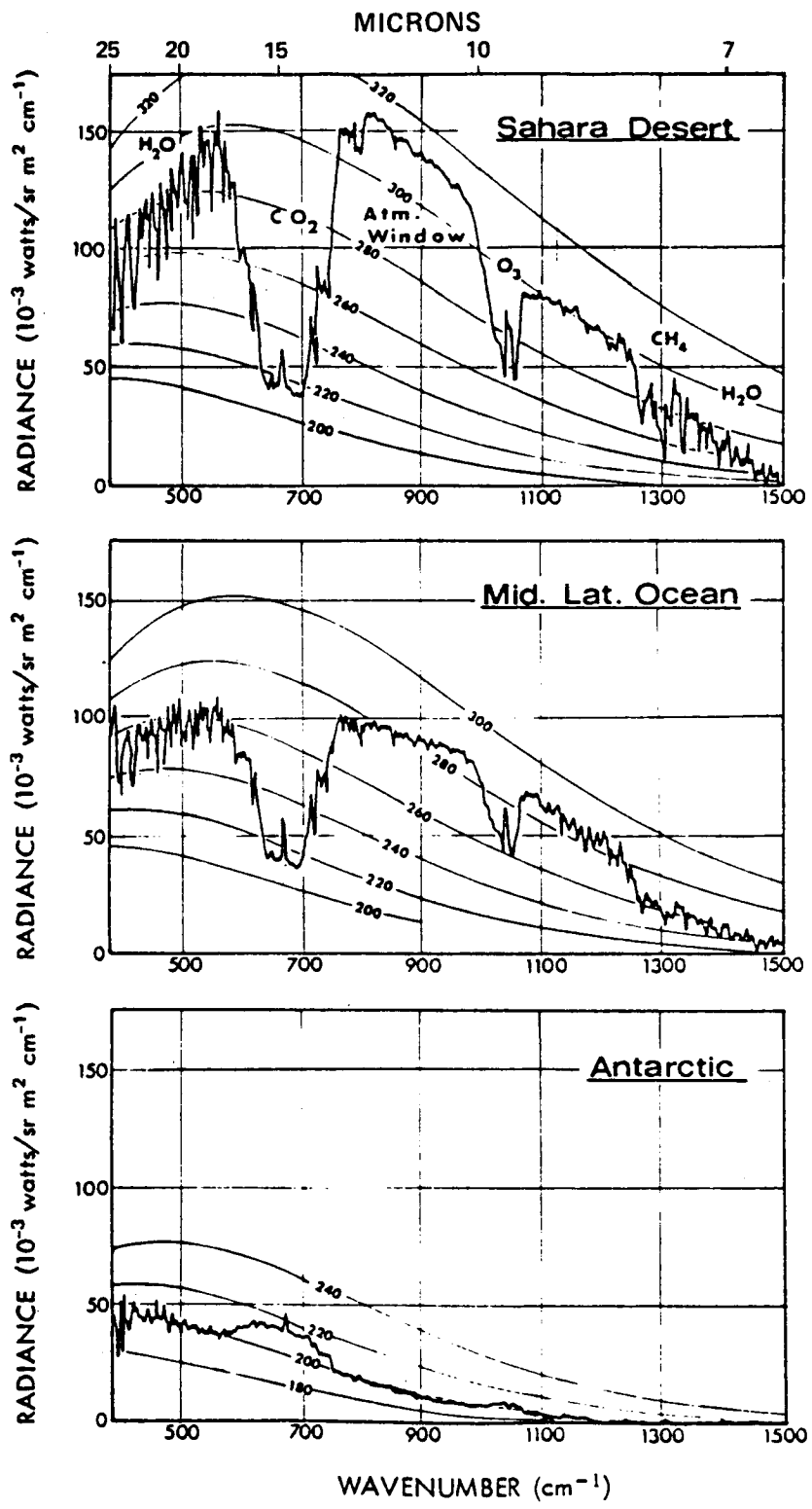
Figure 2. Seasat Horizon Locator Logic Applied to the Output from the Bolometer Signal Processing Electronics

software for both Seasat and Magsat refined the pitch and roll measurements to account for Earth oblateness, spacecraft altitude variations, and seasonal systematic Earth radiance variation effects.

EARTH RADIANCE VARIATION EFFECTS

The IR scanners operate in the 15-micron carbon dioxide (CO_2) absorption band to avoid large weather-dependent changes that occur in the Earth radiation above and below this wavelength. Figure 3 illustrates the spectrum of infrared radiation for a nadir view of the Earth for different geographical locations on April 10, 1970. It can be seen that the intensity in a narrow region centered on 15 microns ($660 \text{ centimeters}^{-1}$) shows less dependence on the surface that is viewed.

The effect of clouds on the infrared Earth radiation spectrum was simulated by Keithly and Uplinger at Lockheed Missiles & Space Company (LMSC) (Reference 1). Results from their work are illustrated in Figure 4 for a nadir viewing angle at the Equator. The simulation was accomplished by computing the Earth infrared radiation spectrum using a standard atmosphere model and integrating the emitted and absorbed radiation from different starting altitudes to the top of the atmosphere to simulate total absorption of the IR Earth radiation by low, medium, and high cold clouds. An estimate of the effect of the clouds on the Earth radiation signal at the nadir viewing angle for the Seasat and Magsat IR sensors can be made by comparing the IR sensor frequency response functions illustrated in Figure 5 with the radiation spectra for different cloud heights in Figure 4. Integrating these cold cloud radiation spectra through the Seasat IR scanner bandpass showed that high cold clouds can lower the Earth pulse in the threshold computation regions of the scan



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Thermal emission spectra (obtained from Nimbus 4 IRIS experiment during orbit 29, 10 April 1970) compared to curves of constant brightness temperatures (K).

Figure 3. Earth's Outgoing IR Radiation for Various Nadir Views

Figure 4. Radiance Variation in the Presence of Clouds of Various Altitudes According to LMSC

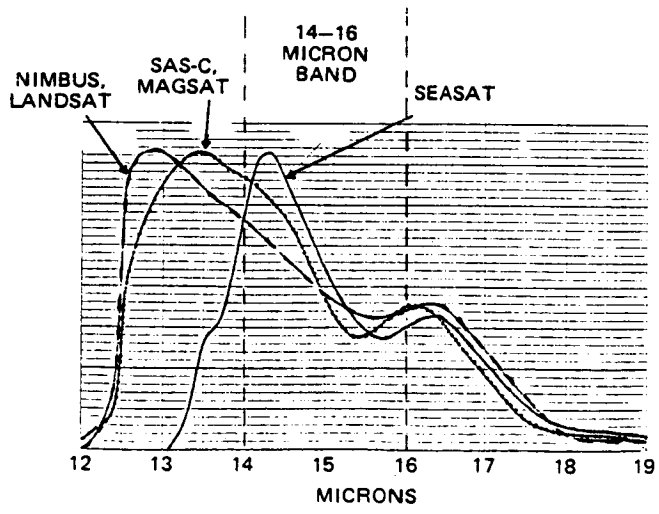
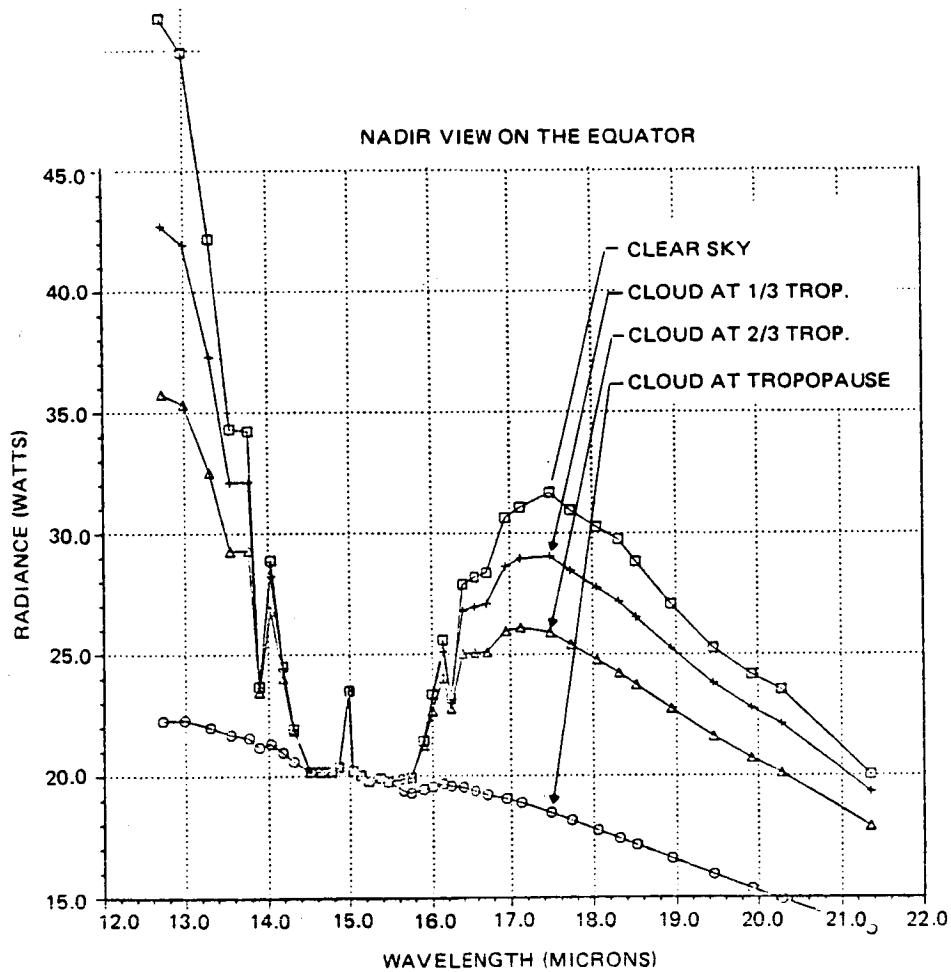


Figure 5. Spectral Response Functions of Several Spacecraft Horizon Scanners

by 30 percent (References 2 and 3). The effect of this is to lower the threshold voltage and increase the Earth chord at the AOS or LOS portion of the scan. The effect of this on the roll and pitch for Seasat, computed in Equations (1) and (2), is to increase the roll for clouds at both AOS and LOS horizons and to decrease the pitch at AOS and increase the pitch at LOS. The timing of cold-cloud-induced errors between AOS traversal and LOS traversal for the Seasat orbit is approximately 5 minutes. As the spacecraft moves along the orbit, the roll signal should show two positive pulses separated by 5 minutes, coincident with a negative and then a positive pulse in pitch, respectively. A schematic illustration of error signals from the Seasat IR sensors resulting from clouds of various sizes and locations is illustrated in Figure 6.

Seasat's Response to Clouds. Flight data from Seasat showed many striking examples of the isolated cold cloud signature. One example is shown in Figure 7, where a simultaneous negative excursion in pitch and a positive excursion in roll are followed 5 minutes later by simultaneous positive excursions in pitch and roll.

The Seasat pitch and roll values plotted in Figure 7 and the following figures were computed in the onboard analog processor and telemetered to the ground. The definitive pitch and roll, which were computed on the ground, used the data and added corrections for the effects of biases, Earth oblateness, satellite altitude variations, and seasonal systematic horizon radiance variations. These corrections are not required for the demonstration of the cold cloud effects. The observability of clouds in these data is dependent on the fact that the control system responds slowly to the pitch and roll error signals. The Seasat control system was designed to hold the spacecraft at zero pitch,

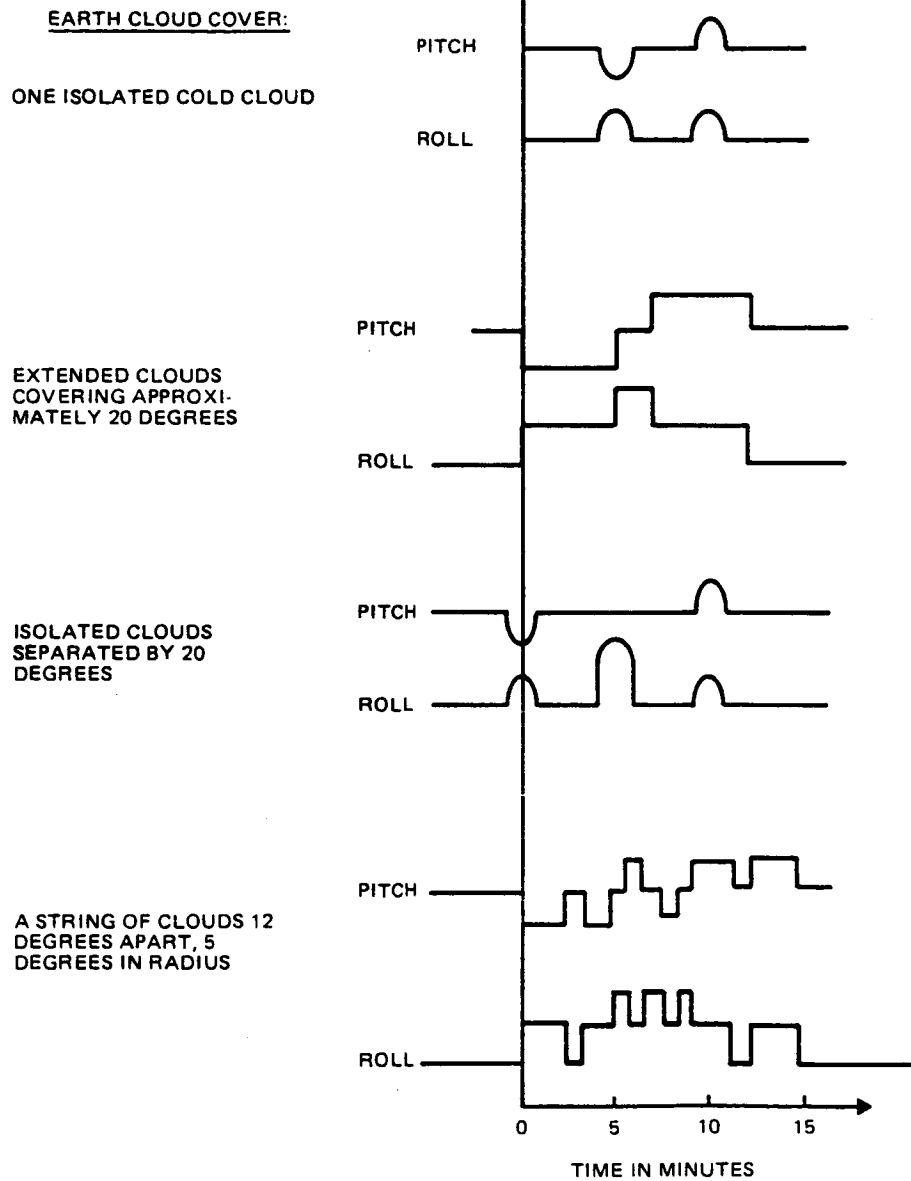


Figure 6. Schematic Illustration of Pitch and Roll Telemetry Patterns Generated by Four Specific Cloud Distributions on the Earth Surface

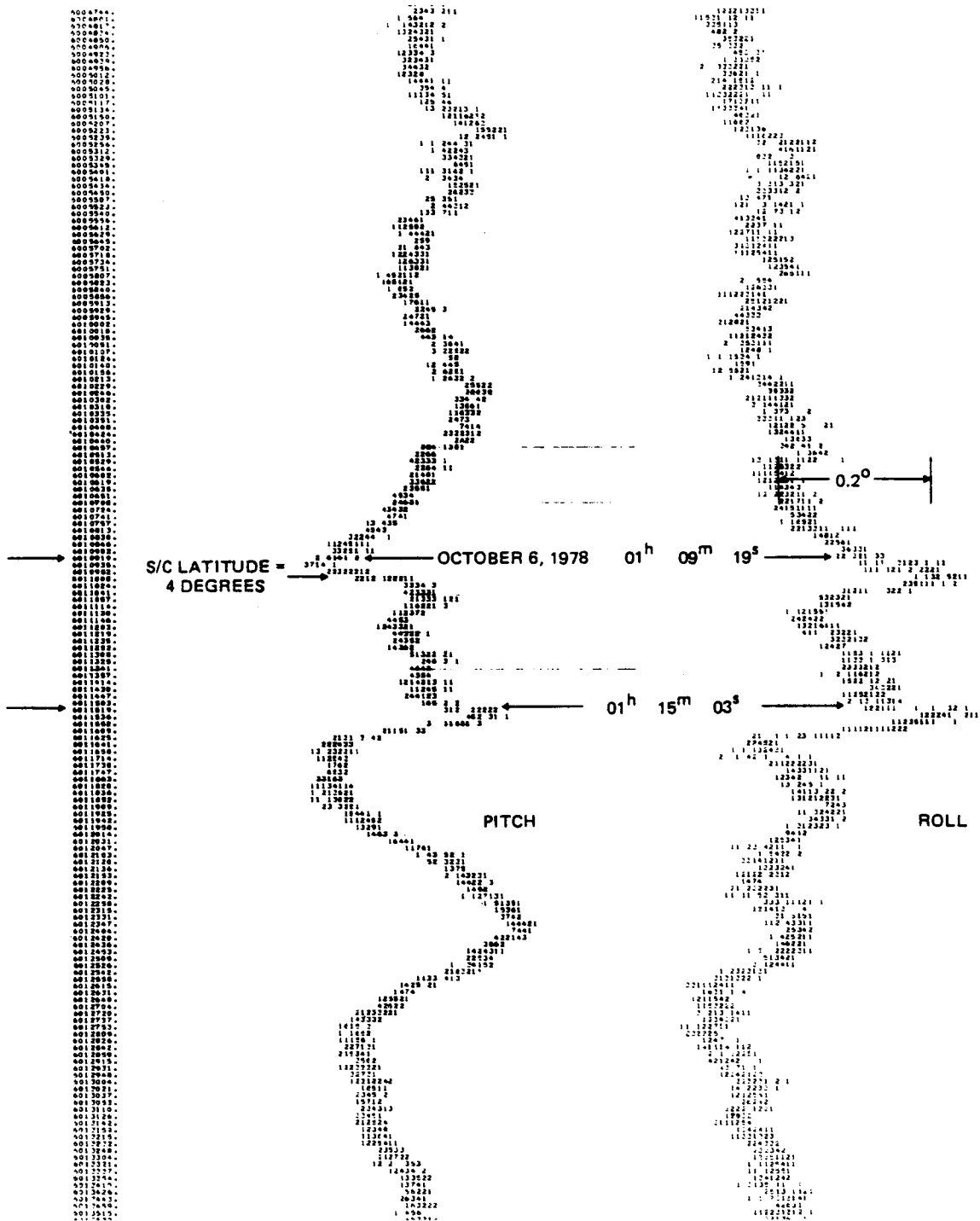


Figure 7. Seasat Fine Pitch and Roll Telemetry Data on October 6, 1978

roll, and yaw for a long time. If the spacecraft control system responded quickly to the errors from clouds, the pitch and roll voltages would be kept at zero while the spacecraft would rock back and forth in response to each cloud on the horizon. Because the roll control response is slower than the pitch response, the cloud effects are more clearly visible in the roll data.

Evidence of cold cloud signatures can be seen throughout the 12 orbits of pitch and roll data shown in Figures 8 and 9, respectively. The data was gathered from 12 consecutive orbits on October 2, 1978. Isolated clouds stand out as pairs of peaks in the roll data separated by 5 minutes. The cloud effects are harder to discern among the larger oscillations in the pitch data; nevertheless, the negative-positive signature in pitch can be picked out at the times when large clouds show their signatures in the roll data. Evidence exists in Figure 8 that the cold cloud anomalies helped induce some oscillations in the pitch.

To confirm that the cold cloud signatures in these data illustrated in Figures 8 and 9 correspond directly to features in the Earth IR image, photographs were obtained from NOAA of the Earth at the time of these data. Figure 10 shows an IR image of the Earth taken over the Pacific Ocean from the western Geosynchronous Operational Environmental Satellite (GOES) at 17:45 Greenwich mean time (GMT) on October 2, 1978. The IR scanner Earth scan is overlaid at two positions in the Seasat orbit, corresponding to 8:53 and 9:03 GMT. In each of these scans, the threshold computation regions from 5 to 11 scan degrees from the AOS and LOS horizon are marked. In Figure 11, the ground track of the middle of the threshold adjust regions is traced over four orbits, assuming a nominal attitude. The AOS threshold adjust track occurs to the west of the LOS threshold adjust

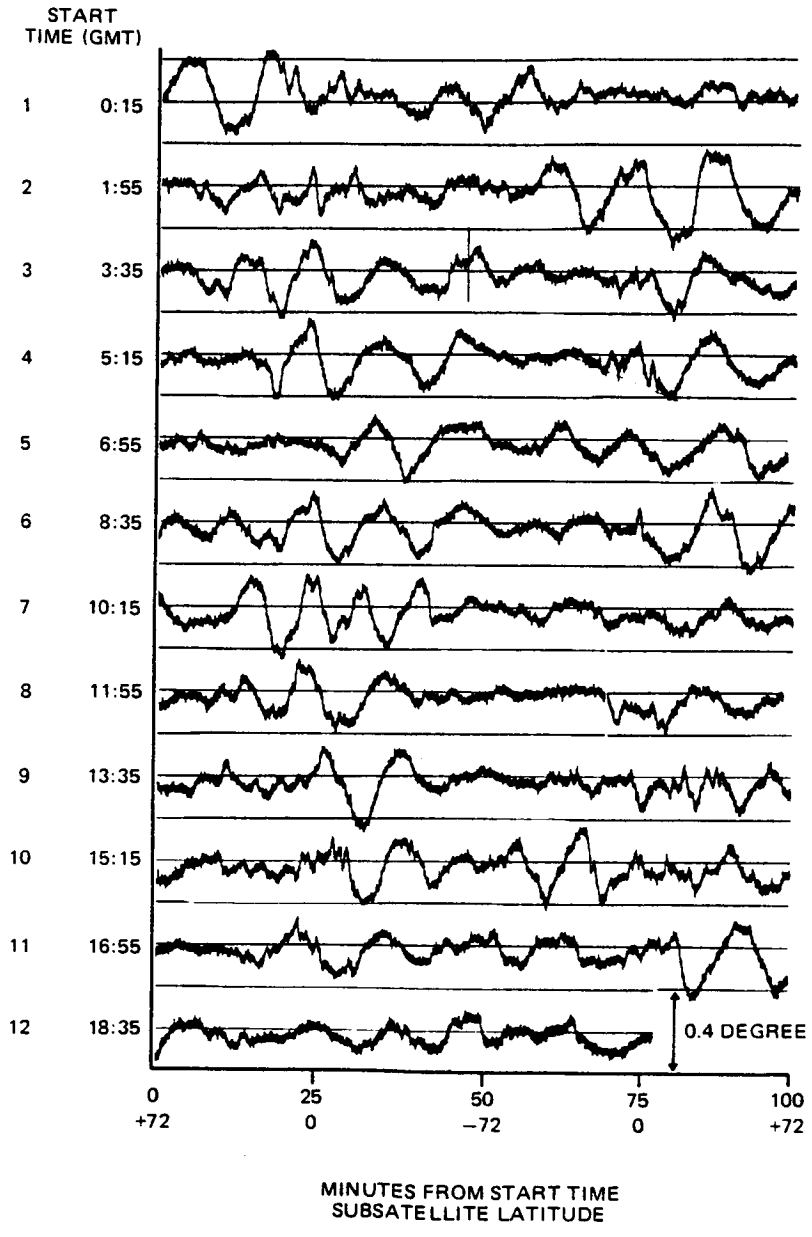


Figure 8. Seasat Pitch Telemetry for 12 Orbits on October 2, 1978

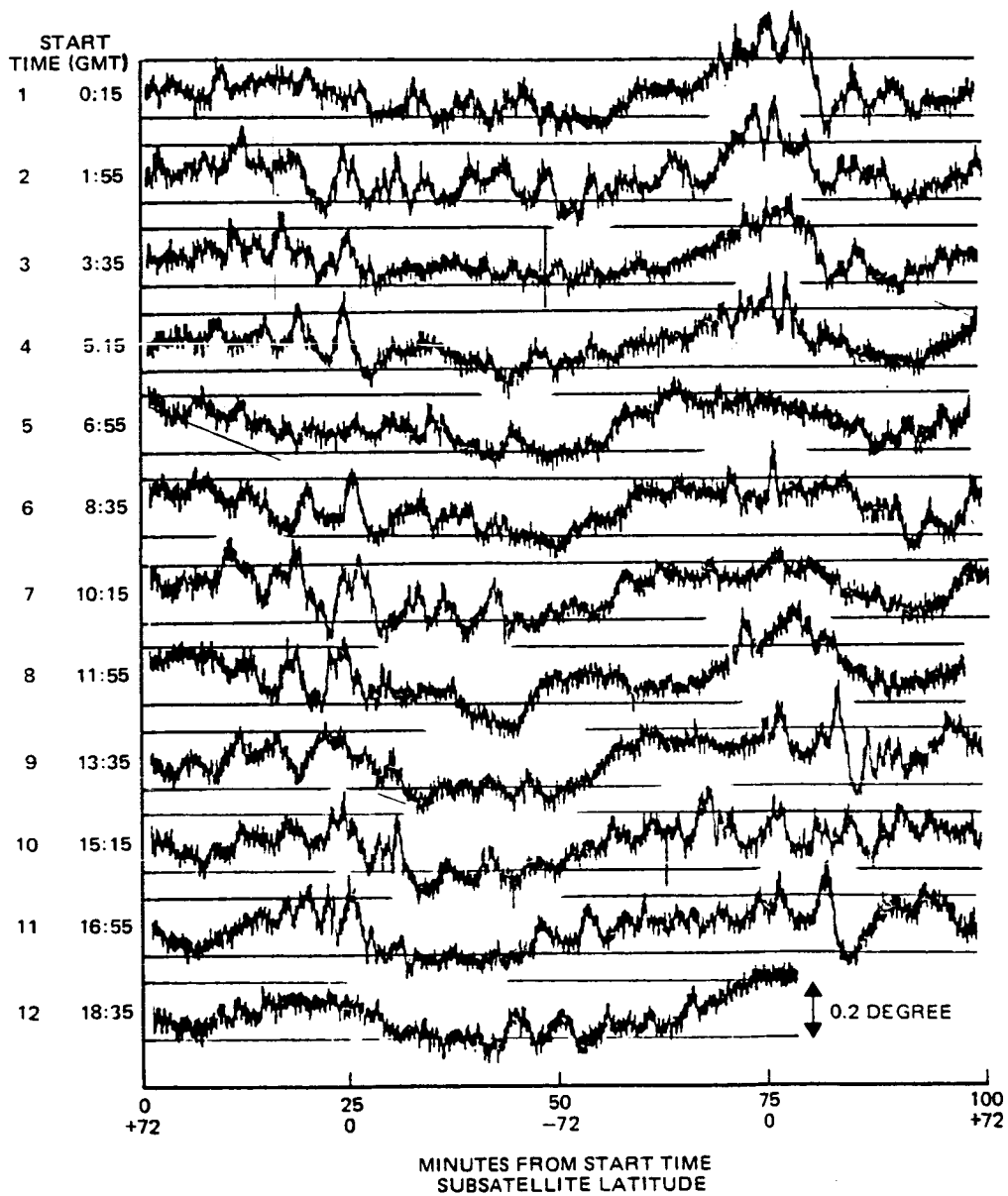


Figure 9. Seasat Roll Telemetry for 12 Orbits on October 2, 1978 Illustrating Cold Cloud Anomalies at the North and South Equator Crossings

↑ 09:45 020078 35A-Z 0006-1640 FULL DISC IR

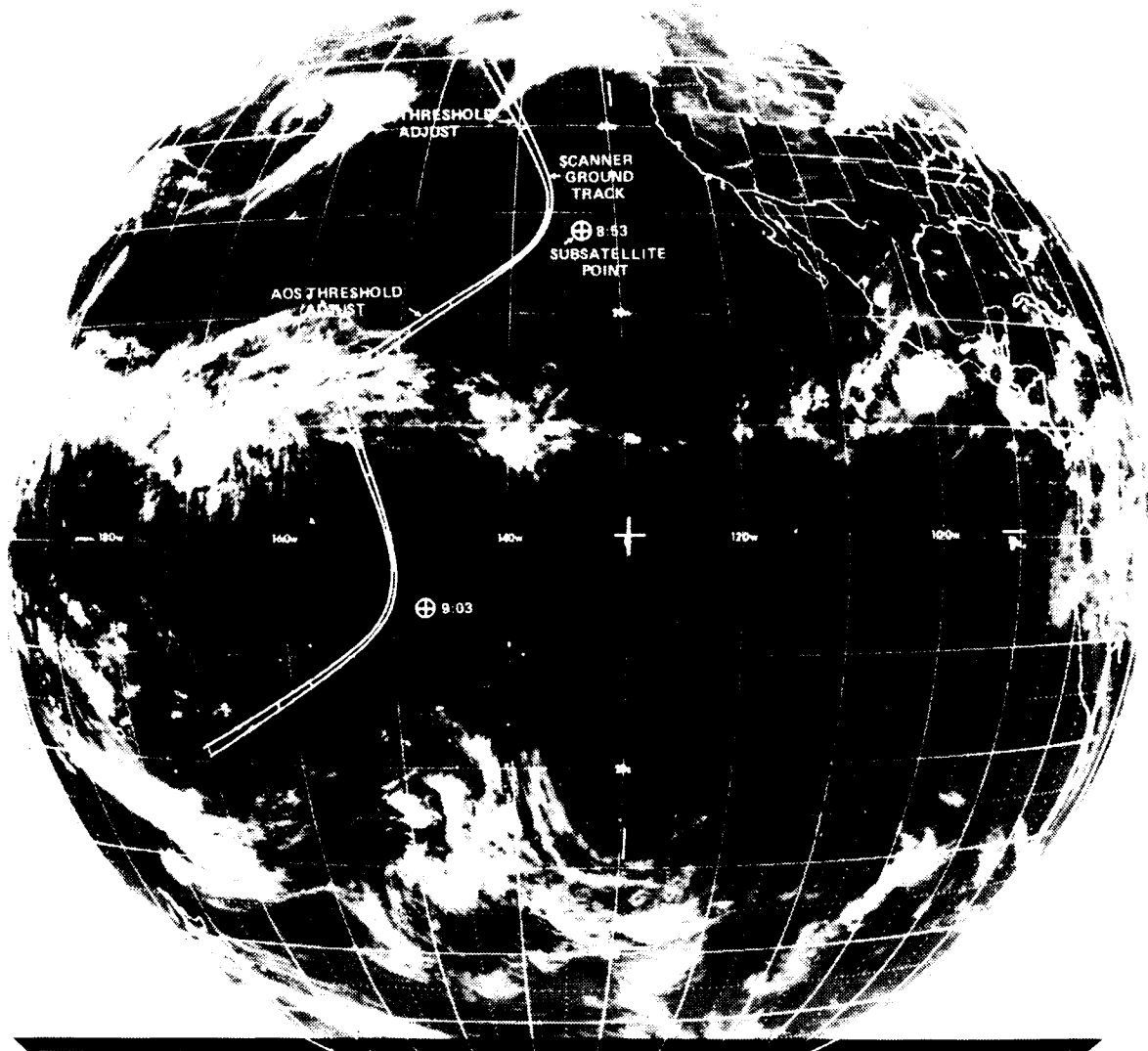


Figure 10. IR Scanner Path With Geographic Location of Horizons and Normalization Areas for a 790-kilometer Altitude (Photo from the Environmental Data Service of NOAA)

track because of the Earth rotation effects. Since cloud patterns do not change greatly during the timespan of four orbits, these ground tracks can be used to predict the cloud effects that will be seen near the descending node in orbits 4, 5, 6 and 7 for the data in Figures 8 and 9. Comparison of Figure 11 with Figures 8 and 9 confirms that excursions in the pitch and roll data result from clouds visible in the IR photograph. In orbit 4, the threshold adjust region passes an isolated tropical storm, near 5:37 GMT; in orbit 5, no cloud is passed at the Equator; and in orbit 7, several large cloud systems are encountered simultaneously in the AOS and LOS. Numerous examples in the data can be correlated with the visual information in Figure 11 with a more detailed analysis.

Magsat's Response to Clouds. The procedures developed for Seasat cloud noise identification were applied to Magsat mission data analysis. The results of the cloud error analysis for Magsat are summarized below.

The signature of an isolated cloud in the Magsat data is a positive error followed by a negative error in pitch and two positive errors in roll. It differs from the Seasat signature because of differences in the horizon locator logic and the scanner mounting positions. The time separation between the AOS and LOS encounter of a cloud is approximately 4-1/2 minutes for the Magsat orbit and scan geometry.

Two Fixed-Head Star Trackers and a high-resolution Sun sensor provided an accurate attitude reference for evaluating the Magsat IR scanner data.

Figures 12 and 13 show the differences between the pitch and roll computed from the IR scanner and the pitch and roll computed from star camera data for 14 orbits on December 28, 1979. Numerous cold cloud signatures appear in these data. Orbital frequency systematic errors are also present,

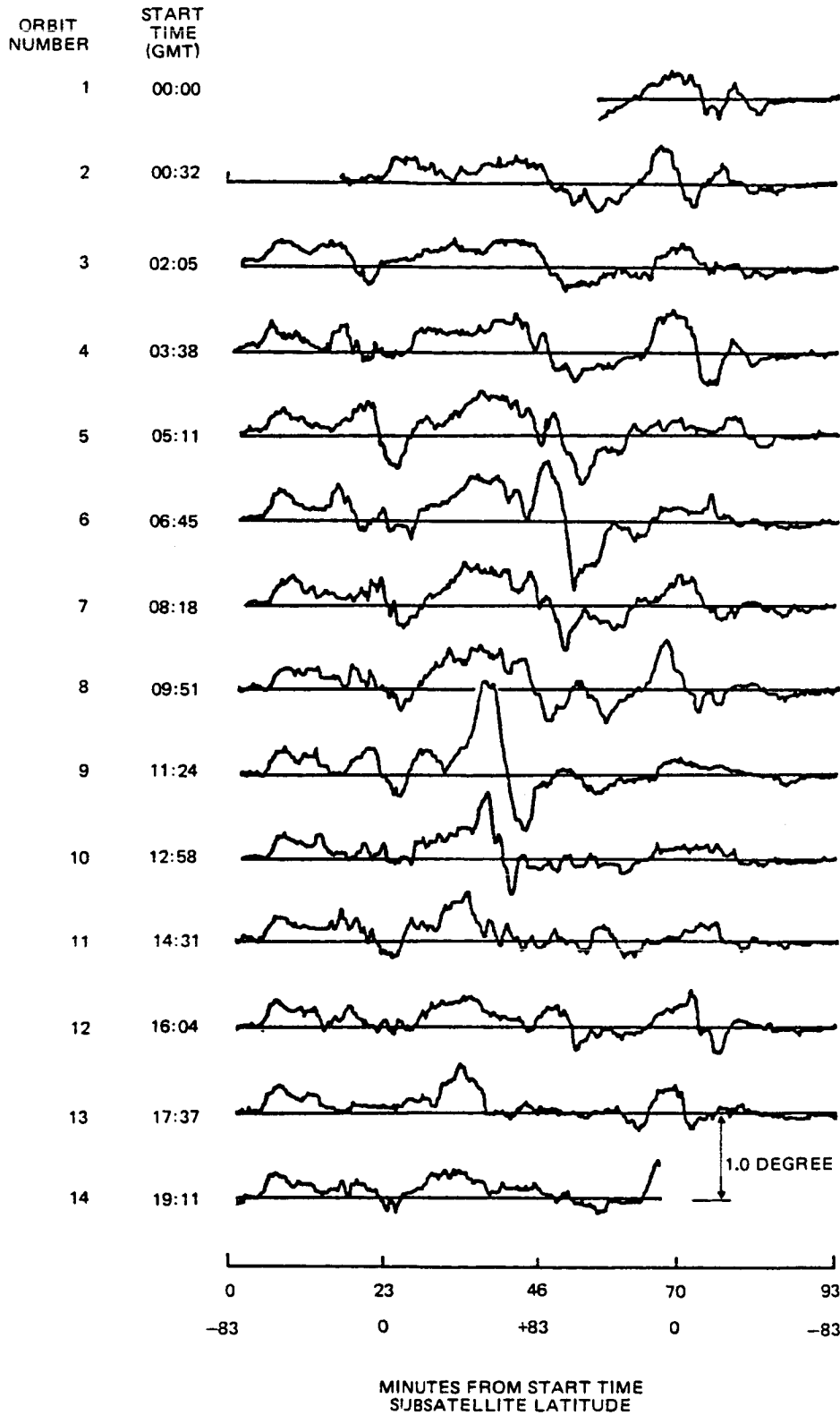


Figure 12. Difference Between Magsat IR-Scanner-Measured Pitch and Star-Camera-Measured Pitch on December 28, 1979

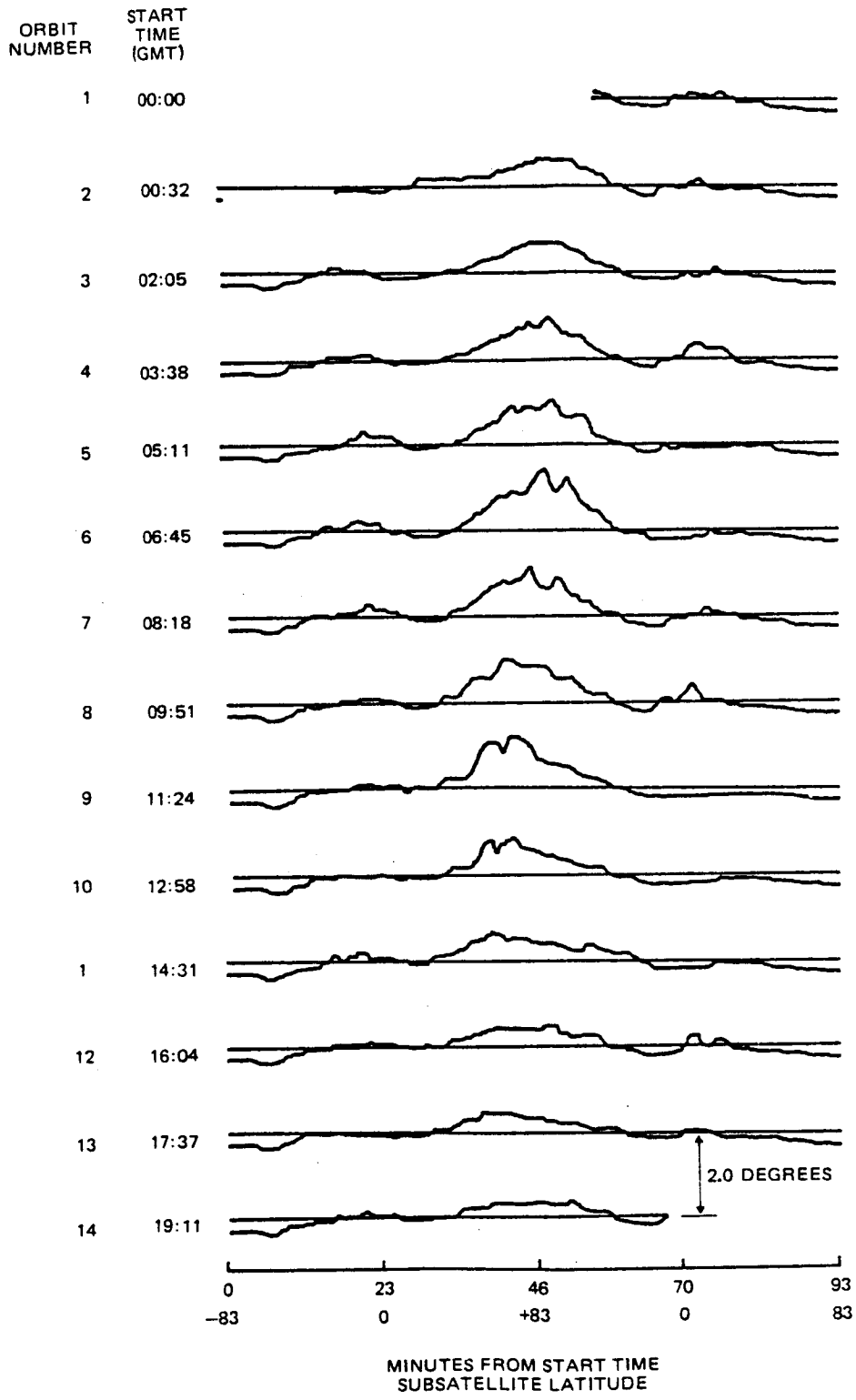
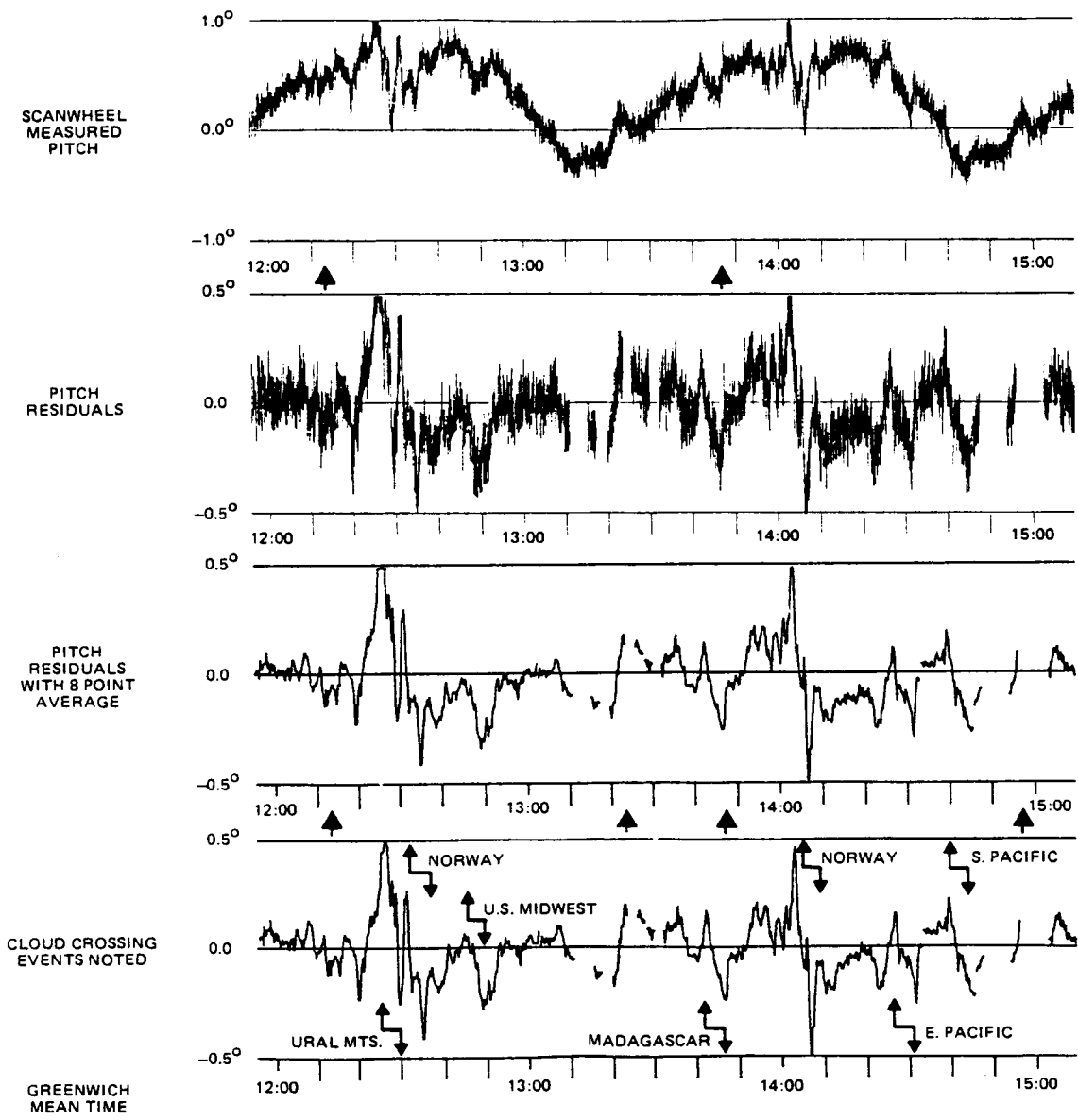


Figure 13. Difference Between Magsat IR-Scanner-Measured Roll and Star-Camera-Measured Roll on December 28, 1979

especially in the roll data. As of this writing, those systematic errors are not well understood. The large roll residuals may be due to systematic horizon radiance variations. The effects of satellite altitude variations and Earth oblateness were eliminated in the computation of IR scanner pitch and roll, but systematic horizon radiance variations were not. An anomaly in the data which regularly occurs just past the minimum subsatellite latitude crossing has been tentatively associated with the momentary shading of sunlight on the IR scanner by an aerodynamic trim boom on Magsat.

Detailed comparisons of the noise in the Magsat IR scanner data with Earth IR photographs were made, as was done for Seasat. These comparisons demonstrated that nearly every short-period excursion in the IR scanner data could be associated with cold cloud features on the Earth. The exception was the feature that was associated with the trim boom shading of the Sun. Figure 14 indicates specific cloud crossing events that were identified in 3 hours of pitch data. This figure also demonstrates that the high-frequency electronics noise in the pitch is effectively reduced with a simple 8-data-point average.

The response of the Magsat control system to a cold cloud crossing can be seen in Figure 15, where star camera pitch solutions are compared to the IR scanner pitch data. The control system responds to the pitch measurement error as if it is a true error in the pitch of the spacecraft. Thus, when the pitch measurement rises positive as the AOS portion of the Earth scan views the cloud, the control system moves the true pitch in the negative direction. When the LOS portion of the Earth scan views the cloud and the pitch measurement falls negative, the control system drives the pitch back in the positive direction.



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Figure 14. Magsat Scanwheel Pitch Measurement Errors with Errors Due to Cold Clouds Noted

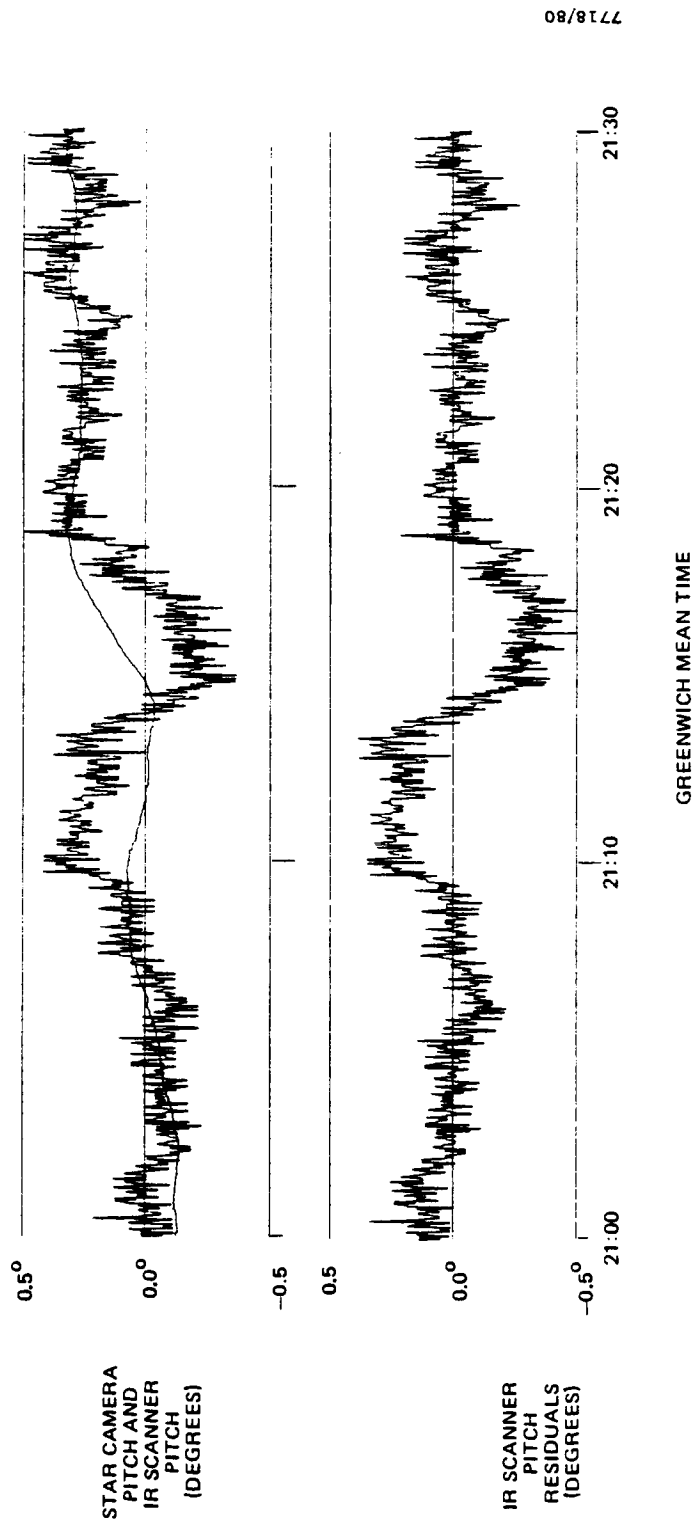


Figure 15. IR Sensor and Star Camera Pitch Data from Magsat on November 8, 1979

The clouds that show their signatures in Figures 12, 13, and 14 are much larger in the northern latitudes than in the southern latitudes. There are several possible explanations for the effect. First, the radiation from the CO₂ band is weaker in the winter hemisphere. Therefore, the radiation from outside the CO₂ band, which is influenced by clouds, may contribute a larger percentage of the total radiation incoming to the bolometer. Second, a fixed temperature difference between cloud top and ground means a greater percentage change in radiance for lower temperatures. A third explanation requires some understanding of the Magsat sensor signal processing electronics. In the electronics, the signal from the bolometer is passed through a preamplifier and a peaking amplifier, and then it is clipped at 1.2 volts, a level that is intended to correspond to a minimum Earth pulse height. If the signal level at this time is actually smaller than 1.2 volts, the response to this change in the noise filter that follows will cause the horizon detection error to be somewhat amplified. It is obvious that care should be taken to ensure that fixed-threshold horizon sensors do not trigger near the minimum Earth signal for the mission.

CONCLUSIONS AND RECOMMENDATIONS

Straightforward procedures have been developed for demonstrating that features in the IR scanner attitude data from the Seasat and Magsat missions correspond to meteorological features in the Earth's atmosphere. These procedures were made possible in part by NOAA's distribution of Earth imagery data from operational weather satellites.

From these procedures, it has been proved that cold cloud effects and other systematic Earth radiance variation effects dominate a large portion of the IR scanner attitude data for

the Seasat and Magsat missions. Proof of the origin of these noise features in the IR scanner data further justifies efforts to upgrade the IR sensor technology and the data processing software. Methods have been developed or are being developed at Computer Sciences Corporation that facilitate the study of changes in IR scanner technology in the area of spectral response function and signal processing and horizon triggering electronics. More work using the data analysis described above is needed to upgrade the ground processing software to reduce errors associated with random and systematic horizon radiance variations.

ACKNOWLEDGMENT

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