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ANALYSIS OF THE TDRS MULTIPLE ACCESS SYSTEM FOR POSSIBLE USE AS AN ATTITUDE CONTROL SYSTEM SENSOR

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Summary

A member of the constellation of TDR satellites (TDRS) has experienced a failure of its prime earth sensor. Failure of the remaining earth sensor could result in the inability of the satellite to control its attitude and provide user services. Loss of the satellite would be a serious event. The multiple access (MA) antenna array on the TDRS has been proposed for use as a backup sensor for the attitude control system. This paper describes our analysis of the performance of the MA array as an interferometer used for accurate attitude determination.

A least squares fit of a plane to the MA phase information appears to represent the TDRS body roll and pitch within about 0.1°. This is sufficient for SGL pointing and MA and SSA user services. Analytic improvements that include ionospheric correction may yield sufficient accuracy for KSA user services.

Spacecraft Configuration

The Tracking Data and Relay Satellite (TDRS) is three axis stabilized and in geostationary orbit. The roll axis (X) points in the direction of orbital velocity, the pitch axis (Y) is perpendicular to the orbital plane with its sense in the south direction, and the yaw axis (Z) is toward earth nadir. Each TDRS contains two earth sensors (infrared sensors) and coarse and fine sun sensors (solar cells). When the satellite is in normal operation the earth sensor in use (the second one is a backup) is scanned across the earth at a rate of 4 Hz along a line that is 5° above the equator. The earth disk as seen by the TDRS is ± 8.6°. The length of the scan line is an indication of roll and the position of the scan line relative to scan center is an indication of pitch. The earth sensor resolution is 0.01° and knowledge of the spacecraft roll and pitch attitude is maintained to 0.08°. Mechanically the roll and pitch attitude is controlled by changing the speed of two momentum wheels whose axes are in the YZ plane and whose net vector is in the negative Y direction.

Yaw attitude is maintained separately via the course and fine sun sensors and thrusters and is not considered in the paper.

For normal operations the space-ground-link (SGL) antenna must be pointed at the White Sands Ground Terminal (WSGT). Its antenna beamwidth is ± 0.375°. The MA forward beamwidth is ± 3° and the MA return is ± 1.5°; thus, if the TDRS body can be maintained for SGL pointing, MA services can also be provided. The S-band Single Access (SSA) antenna beamwidth is ± 0.76° and the K-band Single Access (KSA) beamwidth is ± 0.12°. In order to provide KSA services the TDRS body must be maintained to, or at least known to, ± 0.08°. If accurate roll and pitch attitude were not maintained, the TDRS would not be able to function.

In the mid 1970's the ATS-6 spacecraft was used to experiment with the concept of using antenna element phases for attitude control. Using the interferometer concept, the phase between two elements was measured onboard the spacecraft and sent to the ground via telemetry. Comparison of actual attitude, also sent in the telemetry, lead to the conclusion that RF phase differences received in separate antenna elements could be used for attitude control. Previous authors have proposed using the TDRS MA antenna system for attitude control (Reference 1). This is, however, much more complicated than the system used in the ATS-6 experiment.

The TDRS MA system is composed of 30 separate antenna elements with separate amplifiers, separate IF frequencies, and

30 separate SGL carrier frequencies. The 30 separately received signals are sent to the ground at 7.5 MHz increments over a 225 MHz band at Ku-band. On the ground the 30 different SGL carrier frequencies are converted to a common IF frequency (160 MHz at the WSGT and 29.75 MHz at the Second TDRS Ground Terminal (STGT)) so that they can be phase shifted and combined into a single signal for receiving a user spacecraft's data. For normal MA communications these phases are combined on the ground after several up and down conversions using several different local oscillators (LOs) both in the spacecraft and in the ground equipment. Even with all of the LOs referenced to the ground station common time and frequency standard (CTFS), it is not uncommon for phases to drift tens of degrees over a several hour period. An MA calibration emitter is placed at a known position on the earth (at the WSGT and the STGT) so that the system can be recalibrated (every 18 minutes for WSGT). For the MA communications service where the signals are phase shifted and summed, a 40° phase error for example, in half (15) of the elements would cause only a 0.5 dB degradation, which would not result in a serious service impact. On the other hand, a 40° phase error will cause a 0.4° error in attitude determination, which is unacceptable. The fact that the MA system works for communication services does not imply that it will be good enough for attitude control.

Attitude Control Modes

The usual attitude control modes for a standard TDRS after insertion in a geosynchronous orbit are: (1) Earth Mode, (2) Normal Mode, and (3) Sun Mode (Reference 2). The normal sequence for a TDRS after separation from the inertial upper stage is for the satellite to transition from earth mode to the normal mode. User services are provided when the satellite is in the normal mode. Upsets and stationkeeping can cause the satellite to transition from normal mode to earth mode and from earth mode to sun mode. Detailed descriptions of the modes are presented below:

Normal Mode

During normal mode operation the pitch and roll attitude is determined by one of the earth sensors. Yaw attitude is determined by ground software; there is no onboard yaw control. Yaw attitude is constrained (not controlled) by the combination of angular momentum and yaw momentum drive interactions.

Usual operation of a TDRS is in the normal mode, in which the attitude control system is coupled directly to the earth sensors. Attitude is controlled by the reaction wheels which periodically require thruster firing for unloading when the momentum becomes excessive. Even though the earth sensor is scanning the earth at a 4 Hz rate, the attitude control system requires earth roll and pitch updates at one per second and averages every two updates.

Sun Mode

Sun mode operation has pitch and yaw attitudes determined by the coarse sun sensor. Rates for all axes are determined by three of the four gyros which are turned off due to lifetime constraints when in normal mode. With the solar arrays positioned at 90° or 270°, the plus or minus X-axis is pointed at the sun. The reaction control wheels (momentum wheels) are allowed to run down, and a roll rate of 0.12°/sec to 0.25°/sec is imposed around the X-axis to provide an earth sensor sweep search mode to locate the earth. Position and rates are controlled by the reaction control system (thrusters). This mode is used for safe storage and in preparation for recovery from loss of Earth reference.

Typical transition from the sun mode to the earth mode occurs at about 6:00 a.m. or p.m. (local spacecraft time). When the earth sensor detects the earth, ground commands stop the roll rotation about the X-axis, and attitude control is established to keep the body of the spacecraft such that the earth nadir is normal to the MA array on the satellite. The earth sensor continually monitors the earth, provides roll and pitch information in the S-band telemetry for attitude control.

Earth Mode

In earth mode the pitch and roll attitude errors are determined by the earth sensor; yaw attitude is normally determined either by one or more gyros or by the fine sun sensor. Control is maintained by the reaction control system (thrusters). During earth mode the solar array drives can be ground commanded into the "clock" mode to track the sun as the body of the spacecraft rotates once per day about the - Y-axis to keep pointing at the earth's nadir.

Transition to normal mode operation is established by ground commands which spin up two reaction wheels and cycle the normal mode processing registers (Reference 2).

Normal and MA Mode Attitude Control

The normal attitude control mode is referred to as a short loop because all signals are processed onboard the TDRS. Earth sensor data, wheel speeds, and other sensor data are also reported to the ground in the telemetry. With inoperative earth sensors a new mode must be created that will use the MA phase information that is sent to the ground as part of a normal MA service. A fixed ground S-band, PN spread signal source at the MA frequency is required for the phase measurements. The MA calibration emitter is the signal of choice. The advantage of using the calibration emitter rather than a separate dedicated source is that the corrections generated by the MA system for its internal calibration provide the information needed to calculate TDRS body attitude changes from nominal. The 30 phases from each of the antenna elements can be processed into roll and pitch angles in well under one second. Based on the MA phase determined roll and pitch, momentum wheel bias commands will be sent to the spacecraft via the normal S-band command link. Propagation time from TDRS to earth and back to the TDRS is about 0.25 seconds. Since the RF speed of light propagation time plus the ground calculation time is on the order of magnitude of the current onboard ACS function (1 sec), we do not expect this new long loop control mode, which we will call "MA Mode", to severely impact operations.

Several factors degrade the accuracy of the MA mode compared to normal (earth sensor) mode. The ground received MA phase shifts are due to several factors:

1. change in attitude of the TDRS relative to the earth
2. change in range from the (calibration) signal source
3. thermal drift in components
4. propagation changes in the ionosphere
5. instability of phase locked oscillators

If item 1 was the only cause of phase shifts, accuracy would be superb. Item 2 affects the analysis but not the accuracy. It should be noted that the operational MA system assumes the spacecraft body is nadir pointed when it calculates the calibration phases. If the body is off-pointed, the calibration will allow the MA to continue to work, but the SGL signal will degrade.

Next will be described the tests and analysis performed to evaluate the feasibility of creating the MA attitude control mode defined above.

Feasibility Measurement and Analysis

A series of tests conducted at WSGT and STGT have investigated the RF links required for performing attitude control with the MA system. The tests to date can be divided into three sections:

1. Forward Interference Test - Will the MA forward noise signal interfere with S-band control of a TDRS?

2. Forward Beacon Test - Can the ground station receive a forward noise signal and detect the main beam as it is swept across the station? This is required in order to transition from sun mode to earth mode, normal mode or MA mode.
3. Return Phase Test - How stable are the phases received when pointing an MA return beam at a stationary emitter?

These tests are described in more detail below.

Forward Interference Test

The MA forward system in a TDRS requires a forward drive signal for standard operation. The proposed MA ACS system acquisition mode would use the forward MA system with no input signal; thus, the forward drive signal will be noise amplified by the onboard RF equipment. The main operational concern is whether or not this noisy forward signal will couple into the S-band telemetry, tracking, and control (TT&C) receive equipment on the TDRS and interfere with operation of the satellite. During normal operations with earth sensors, the TT&C is switched to Ku-band before an MA S-band emission is activated.

The interference test showed no change in the operation of the S-band command and telemetry system as a function of the operation of MA Forward system with a noise drive signal. Our conclusion was that use of the MA forward system for acquisition would not interfere with S-band TT&C.

Forward Beacon Test

The next step was to sweep the forward noise signal across the WSGT by commanding the TDRS MA forward phase shifters. The forward signal is again a noise signal from the MA forward equipment on the satellite, since there was no link with the ground station through the K-band SGL, thus simulating the situation that would exist during an attitude reacquisition. During this test the cold sky measurement was taken as baseline for WSGT receive equipment; the MA forward beam from 12 MA elements was sequentially stepped across WSGT in East-West and North-South directions; and the received signal levels were compared to a reference signal injected into the S-band simulation receive equipment at WSGT and recorded.

Figure 1 shows the noise level when the beam was pointed directly at WSGT as well as 12° east of WSGT. When pointed 12° east, the power was less than 0.1 dB above background. Figure 2 shows the MA forward antenna pattern received at the WSGT when the noise emission was scanned along the North-South direction to simulate the spacecraft rolling prior to earth acquisition.

Return Phase Test

The Return Phase Test conducted at STGT was a first cut at determining the accuracy and resolution of the MA return system's capability of measuring the spacecraft attitude when in an MA attitude control mode. From earth sensor telemetry data we confirmed that the satellite had a stable attitude, and therefore, the phase shifts required to point the beam at the stationary user were not influenced by changes in spacecraft attitude.

The STGT Multiple Access Beamforming Equipment (MABE) can provide operators with extensive diagnostic information, in part, because of its digital design. Easy access is afforded to the computed amplitudes and phases required to calibrate the different wire lengths and component delays of the 30 signal paths from the MA antenna elements on the TDRS to the point where they are added for a user service. The 30 calibration vector phases were recorded every ten minutes over a four hour period at the common IF frequency. If there were no electronic drift factors and the spacecraft body was not rotating, the difference between any pair of calibration phases would be constant. When the TDRS body rotates the calibration phases change to compensate. We have developed an algorithm to convert the calibration phase changes into a measure of roll and pitch.

The first set of 30 phases measured at time zero was used as a reference and was subtracted from all of the following phase sets. Within each set of 30 phases at a given time, the phase of the central geometric element was subtracted from the other 29 values to compensate for TDRS longitudinal motion. We are interested in rotational motion only. The remaining phases were then converted to be between ± 180° instead of 0° to 360°. Using the wavelength of the incoming S-band signal, 0.131 m, the phases were then converted to lengths. Knowing the XY geometric position of each of the 30 MA elements on the TDRS body and using the length found from the phases as the Z value, we have 30 points in space for each data set, representing the normalized zero phase plane of the incoming RF signal. A least squares fit of a plane in three dimensional space to these points was calculated and the normal to the plane was determined. The normal or pointing vector orientation relative to the Z axis represents the body angle displacement from nadir. The pointing vector was resolved into roll and pitch angles. Figure 3 shows the variation of the roll and pitch angles over a four hour period.

Conclusion

MA forward S-band noise emissions are detectable on the ground and can be used as a course estimate of spacecraft roll during orbital insertion or recovery from an upset.

The four hours of return data collected indicates that the phase differences of an incoming plane wave on each of the 30 MA antenna elements can be used as a sensor to accurately determine the TDRS spacecraft roll and pitch attitude.

Earth sensor readings indicated a typical body divergence less than 0.01° while the least squares fit to the MA phases indicated a divergence of about 0.12°. Thus, based on the limited data, it appears that attitude control commands should not be issued for apparent roll and pitch errors of less than 0.1° when operating in the MA mode. This would allow the SGL, MA, and SSA antennas to be pointed to well within their 3 dB beamwidth.

We are currently pursuing a more refined data analysis scheme that may yield more accurate attitude determination and we are exploring the possibility of improved results by considering the differential ionospheric phase shifts in the SGL carrier frequencies. A draft plan that outlines the further testing required for establishing an operational MA control procedure is being evaluated by NASA.

REFERENCE

1. *Ground Loop Control of Tracking and Data Relay Satellite Attitude Using RF-Interferometer Techniques*, 1992 Research and Technology Report, Goddard Space Flight Center, Paul Heffernan (Code 405), Robert Jenkens (Code 712.4), William Isley (EER), 1992.

2. *TDRS Spacecraft Systems Manual*, TM0254 Vol 1, TRW, revised Nov. 1985.

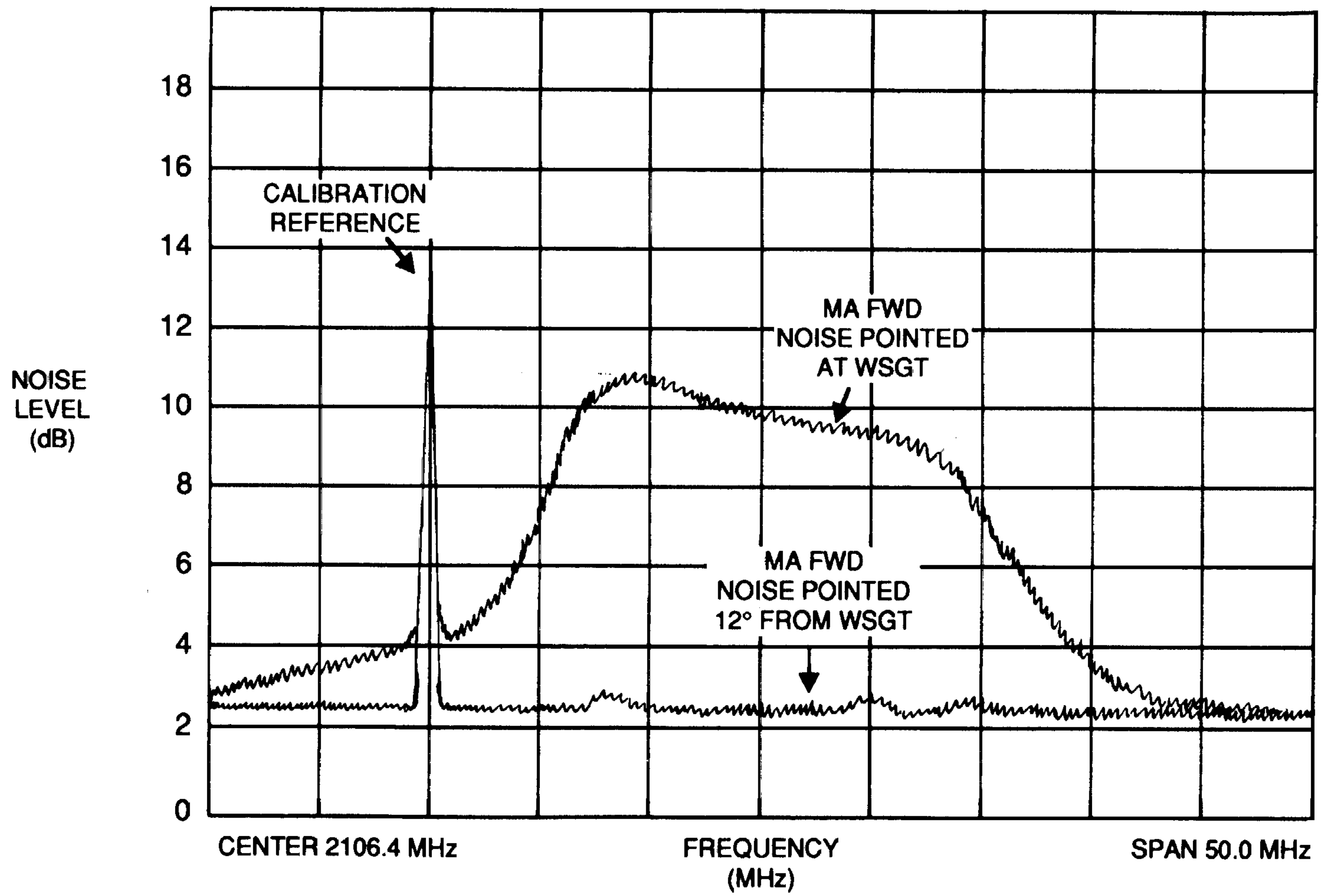

Figure 1. Forward Beacon Test

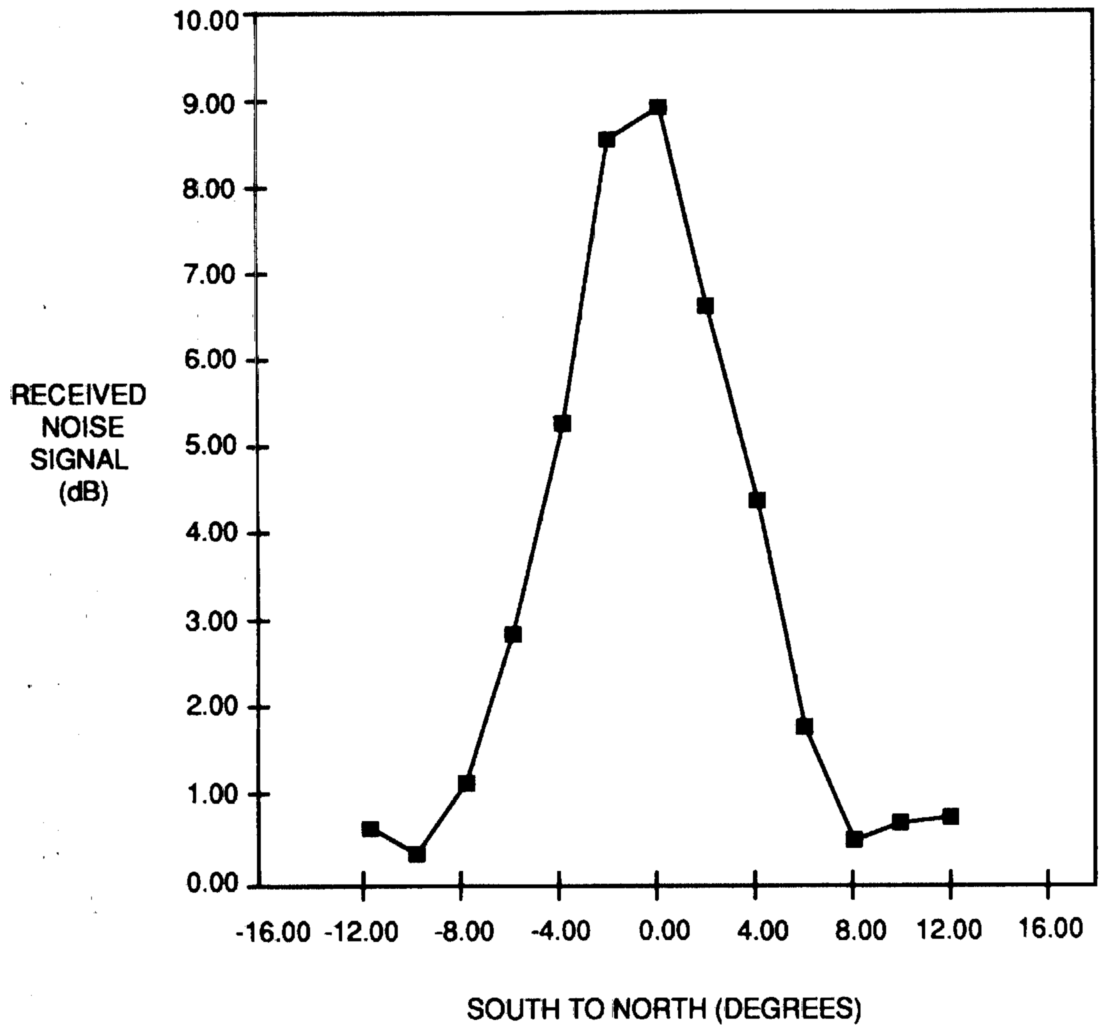

Figure 2. MA Forward Antenna Pattern

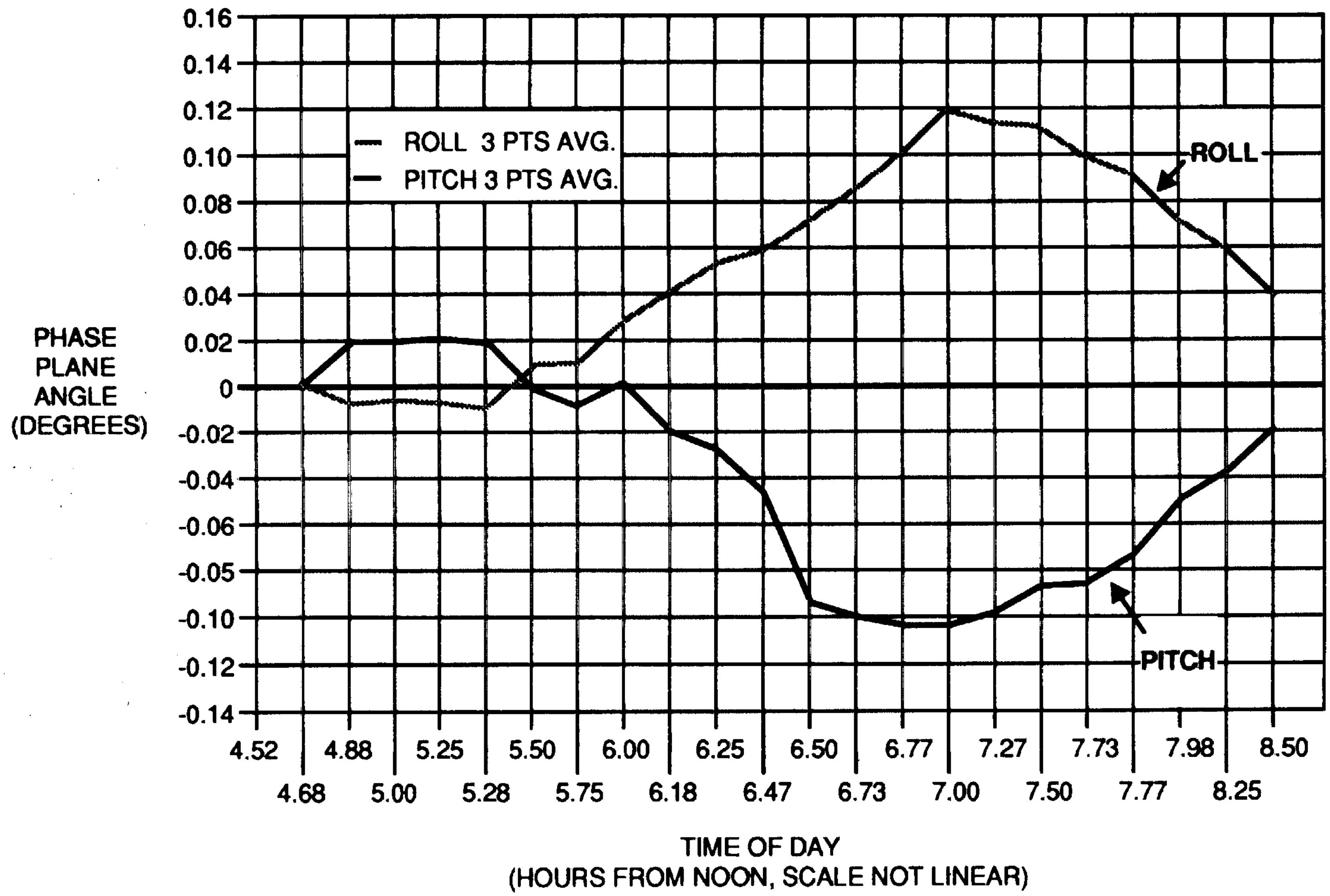

Figure 3. MA Phase Derived Attitude Stability

SESSION 4: MODELING AND SIMULATION