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SCATHA
Mission Termination Report

154751

N93-24725

p. 17

1 August 1991

Prepared for the Consolidated Space Test Center / VOF
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1. ABSTRACT

The SCATHA (Spacecraft Charging at High Altitudes) satellite was operated from the Consolidated Space Test Center in Sunnyvale, California from February 1979 to May 1991. It was a spin stabilized vehicle in a highly eccentric orbit that collected data on spacecraft charging. The purpose of such data gathering was to predict and/or model the effects of the Earth's magnetic field on synchronous and near synchronous satellites.

During the majority of its lifetime, attitude precession maneuvers were done every 10-15 days to maintain solar panel orientation. Maneuver planning was difficult due to the structural characteristics of SCATHA. It is cylindrically shaped and has seven booms ranging in length from 2 to 50 meters. These precession maneuvers induced predictable nutation that damped out after a few days. Eventually fuel began running low due to these frequent maneuvers. Experiments that had required the spin axis be in the orbit plane had already been turned off or had collected all their data. To increase the vehicle lifetime, the spin axis was moved to ecliptic normal. While this stopped the need for frequent attitude maneuvering (only two per year required now), this movement of the spin axis caused nutation that would not damp out for the remainder of the mission.

This phase of the mission, with the ecliptic normal orientation, lasted for approximately three years. Although nutation never damped, data gathering was uninterrupted. In late 1990, when SCATHA's transmitter became seriously degraded, the Air Force decided to turn SCATHA off. This would only be done after the satellite was made "safe". The most difficult part of making the vehicle safe was quickly purging the fuel. Several plans were considered. The selected plan was to perform a series of 20 degree attitude precession maneuvers (3 days apart to allow for the worst nutation to damp) until the fuel was depleted. Although this sounded simple, the actual execution proved difficult. This was due to a nearly complete lack of available telemetry data, large undamped motion of the long booms, inadequacies in attitude determination software, and an error in the fuel level calculation software.

This paper discusses the various proposed termination plans and execution of the selected one. Attitude determination methodologies, nutation from maneuvers, and effects of the flexible booms on the termination mission are presented and analyzed from a satellite analyst point of view.

2. BACKGROUND

2.1 Mission and Orbit

The SCATHA mission was to investigate the cause or causes of numerous spacecraft anomalies due to spacecraft charging phenomena which plagued high altitude, near synchronous vehicles throughout the 1960's and 70's. On January 30, 1979, a McDonnell Douglas Delta rocket launched SCATHA into a 176 by 43,278 km transfer orbit. On February 2 it was injected into a 27,578 by 43,288 km, 7.9 degree inclination final orbit. For most of the mission, the spin stabilized satellite was operated at near 1 rpm.

SCATHA was managed and funded by the United States Air Force (USAF) Space Test Program (STP). It was one element of a cooperative NASA/USAF program to investigate various aspects of the electrical charging and discharging of geosynchronous spacecraft surfaces. Mission operations were under the administration of the U.S. Air Force office "Vehicle Operations - Complex F" (VOF). As one of several VO offices within the Consolidated Space Test Center (CSTC), VOF has historically been responsible for research and development programs. Mission planning and real-time operations were performed by the Lockheed Technical Operations Company (LTOC) Mission Control Team (MCT). Together the two organizations functioned as a mission control complex referred to as Test Support Complex-1 (TSC-1).

2.2 Vehicle Description

The primary systems relevant to fuel depletion and maneuver activity are the vehicle structure and attitude control systems.

Structure. The SCATHA vehicle has a cylindrical body with diameter and height of approximately 1 3/4 meters that supports all the subsystems and the experiments. In the on-orbit configuration it has experiments located on five extended booms (ref figure 2-1). In addition there are two 50 meter booms which comprise NASA's Electric Field Detector 100 meter antenna.

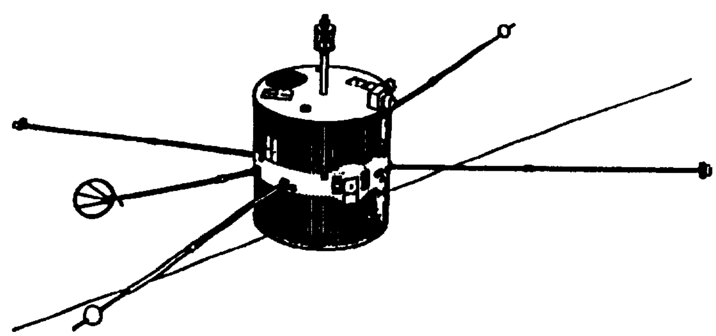

Figure 2-1. SCATHA On-orbit Configuration

Attitude Control and Determination Subsystem (AC&D). The AC&D subsystem provides attitude sensing and thrust impulse for control of the spin rate, spin axis attitude, and orbital velocity adjustments. All attitude control commands are executed in real-time. There are no provisions for on-board storage of time-tagged commands.

The AC&D system, in conjunction with ground based mission unique software, provides for attitude determination using data from two groups of space vehicle (SV) attitude sensor units. The first group consists of four digital sun sensors. Each DSAS (Digital Sun Aspect Sensor) measures the angle between the sun vector and the vehicle spin axis once per revolution. The second group of sensors consists of two Steerable Horizon Crossing Indicators (SHCIs). These detect a thermal discontinuity as the line of sight crosses the earth horizon. The line-of-sight of each unit is adjustable and capable of expanding its field-of-view (FOV) to

4π steradians. The sensor output gives the instantaneous line of sight position and horizon crossing times. Figure 2-2 shows the sun and horizon sensor configuration.

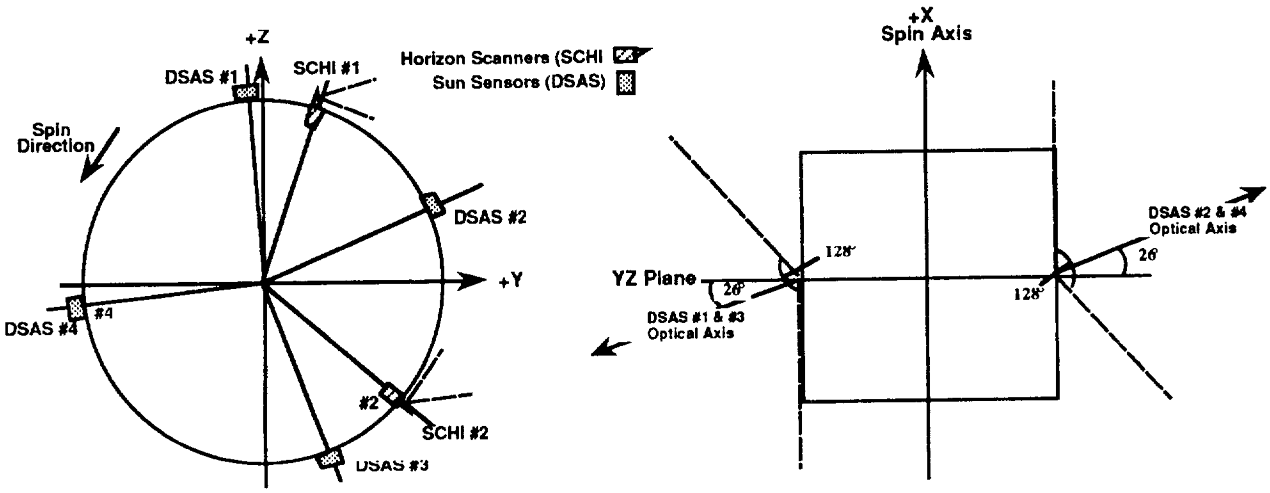

Figure 2-2. Sun and Earth Horizon Sensor Configurations

Two nutation dampers are installed to provide damping of residual nutation. The hollow rings are filled with Dow Corning dimethyl silicone fluid. They are mounted 180 degrees apart with the ring planes parallel to the vehicle spin axis and perpendicular to the axis of maximum transient moment of inertia when all experiments are fully deployed. The damping time constant for the 1.0 ± 0.1 rpm spin rate (all booms deployed) is 8 hours over the operating range.

2.3 Spacecraft Attitude Determination Methods

The DSAS and SHCI telemetered values are used together in determining the SV attitude by the ground based mission unique software. The software takes in the telemetry from the DSAS and SHCIs and combines it with calculated vehicle and solar ephemerides to obtain three derived measurement angles: Sun-vehicle-earth angle (SVE), Earth aspect angle (EA - from SHCI data), and solar aspect angle (SA - from DSAS data). The SVE angle is defined as the included angle between the nadir vector and the vector from the sun to the space vehicle (SV). The EA is defined as the included angle between the nadir vector and the positive spin axis. The SA is the angle between the positive spin axis and the sun vector.

Attitude determination software uses sets of these three derived angles in a least squares batch processor which provides a minimum variance estimate of the average inertial attitude state at a user-defined epoch. This state is output in the form of two angles: spin axis right ascension (SARA) and spin axis declination (SADEC). The specification for ground software attitude determination error is ± 1.4 degrees (3 sigma).

2.4 Orbit and Attitude Maneuvering System

The spacecraft is capable of performing three types of maneuvers: delta velocity, spin (up or down), and attitude precession (re-orientation of the vehicle's spin axis). During SCATHA's lifetime the vast majority of the maneuvers were attitude precession maneuvers to keep enough sun on the arrays to power the vehicle. SCATHA had two hydrazine fueled rocket engine modules, each with three .2 lb thrusters and a 5 lb thruster. Details on the ground based maneuver planning software are available in references 1 and 2.

3. MANEUVER OPERATION PHASES

The SCATHA mission can be broken into three different phases: Nominal, Re-orientation/Extended Life, and Termination.

3.1 Nominal Phase Maneuvers

For the first eight years of the mission (after the approximate 1 month orbit and spin axis initialization phase), the nominal attitude of SCATHA placed the vehicle spin axis oriented within the orbit plane. Due to power constraints, the vehicle sun angle (angle between spin axis and sun vector) had to be kept within +10 and -5 degrees of normal to the sun line. To stay within these bounds, attitude maneuvers with sizes between 10 and 15 degrees had to be performed every 10-15 days to counteract the apparent motion of the Sun due to the Earth's orbital motion throughout the year (approx 1 deg/day).

During this time (25 Feb 79 - 01 Jan 87), all maneuvers performed were attitude precession maneuvers. After this eight year nominal phase, software indicated approximately 2.68 lbs of fuel remained on board (originally there was 21.3 lbs). A summary of this phase can be found in figure 3-1.

Parameters	Nominal Phase Feb 79 - Jan 87	Re-orientation Phase Jan 87 - Jan 91	Termination Phase Jan 91 - May 91
Precession/Spin Maneuvers	233	11	48
Fuel Used (lbs)	10.82	.339	3.3953
Average Time Between Maneuvers	12.30 Days	200.3 Days	3.0 Days
Fuel Usage per Maneuver (lbs)	.046	.0375	.0707

Figure 3-1. Summary of SCATHA Precession/Spin Maneuvers

The performance of the attitude maneuver generation software during this phase was exceptional. The total angular error between the predicted spin axis and the determined spin axis was never greater than 1.0 degrees and 99 % of the time it was less than .5 degrees. Due to the effect of the motion of the long booms (caused by the maneuver) on the satellite, the MCT had to wait 3 days after each maneuver in order to gather useable telemetry for an accurate post maneuver attitude determination. Telemetered sun angle values showed that successive values differed by as much as 4 to 6 degrees per revolution. This difference, referred to (by the MCT) as "out-of-plane nutation", always damped to less than 2.0 degrees within 3-5 days. Undamped nutation was never a problem during this phase of the mission.

3.2 Extended Reorientation / Extended Life Maneuvers

In January of 1983, a study was performed by the MCT and the Aerospace Corporation to determine the projected date of hydrazine depletion and to recommend a course of action which might extend the fuel supply and therefore extend mission life. It was estimated that "blowdown pressure" (i.e. the point at which the pressure of N_2 would no longer be enough to move the hydrazine to the engines (approx 122 psia)) would be reached by August of 1988 if no change to vehicle operations were implemented. As a result of these studies and talks with the remaining experimenters, it was determined that the vehicle's fuel supply could be greatly extended if the vehicle were oriented so that its spin axis was normal to the ecliptic plane (see Figure 3-2). In this orientation there would be far fewer attitude maneuvers required to stay within 10-20 of normal to the sun line.

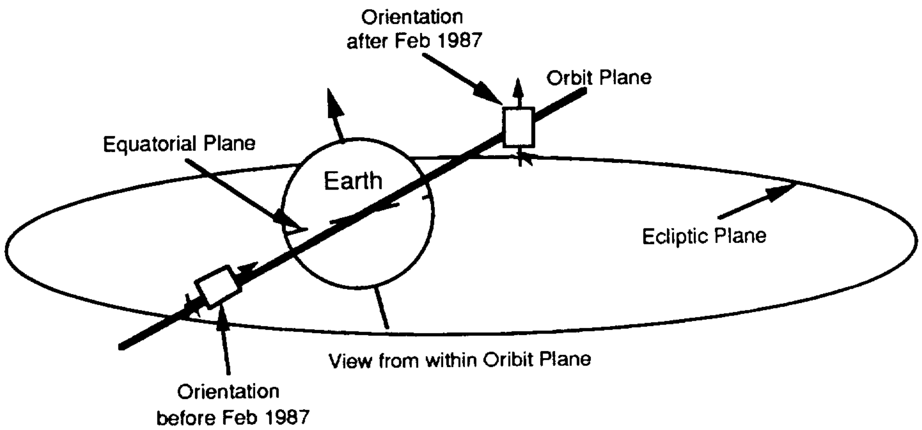

Figure 3-2. Spin Axis Orientation Relative to Orbit Plane

The requirements for a maneuver of this magnitude were extensive, especially considering the effects of such maneuvering on the long booms. It was hoped that the booms could be pulled in prior to the maneuver, thus minimizing possible damage to the booms as well as reducing the number of maneuvers. However, analysis done by the spacecraft dynamics department at Goddard Space Flight Center (GSFC) showed that dangerous resonance points would be reached at various lengths as the booms were retracted. So any plan for maneuvering would have to be performed with the booms fully deployed. After much deliberation, it was finally decided to break up the maneuver into 5 smaller maneuvers with ample time between each to allow "out of plane" nutation to damp out (nutation had to be < 6 degrees in order for the next maneuver to proceed). The attitude maneuvers were completed on 4 Feb 87, 20 days after the 1st burn. Out-of-plane nutation during these maneuvers, while higher than had been seen prior to the re-orientation maneuvers (reached 15 degrees at one point), damped out to well under the 6 degree limit within one week following the last maneuver.

Once these maneuvers were complete it was decided to do something about the vehicle's spin rate which had dropped to 0.928 RPM (very close to the lower limit for experiments). A series of small spin up maneuvers (each three days apart) was planned to raise the spin rate to its original value. After the first four maneuvers were completed, raising the spin rate to 1.021 RPM, the out of plane nutation limit of 6.0 degrees was exceeded (it was greater than 8.5 degrees). More alarming, was the spin rate variation (time from a DSAS sun cross reading to its next sun cross reading) -- it had become quite large. Measuring it in terms of an angle, called "in-plane" nutation by the MCT, it reached in excess of 14 degrees. During the following five weeks, neither the in-plane nor out-of-plane nutation consistently dropped below the 6 degree limit. Clearly, the nutation dampers, designed expressly for handling out-of-plane nutation, were unable to handle the apparent coupling of these two motions. As a result of the increased and undamped nutation, the remaining planned spin-up maneuvers were postponed indefinitely.

At the end of these maneuvers, the vehicle sun angle was 95 degrees (non-normality to sun line of 5 degrees) and the out of ecliptic plane angle was 85 degrees. This attitude, assuming no precession, should have resulted in an annual sun angle cycle of 95 to 90 to 85 to 90 to 95 degrees, etc. There was, however, a slight precession of the spin axis about the Earth's polar axis, which changed the amplitude and timing of the annual Sun cycle. As it turned out, the SARA and SADEC rates were fairly close to constant. Plots of these values were performed weekly. Figures 3-3 (a) and (b) are examples of these. First order least squares fits were performed on the data. In general the SARA drift rate was approximately -0.2 deg/day (+/- 0.02) and the SADEC drift rate was nearly 0 deg/day.

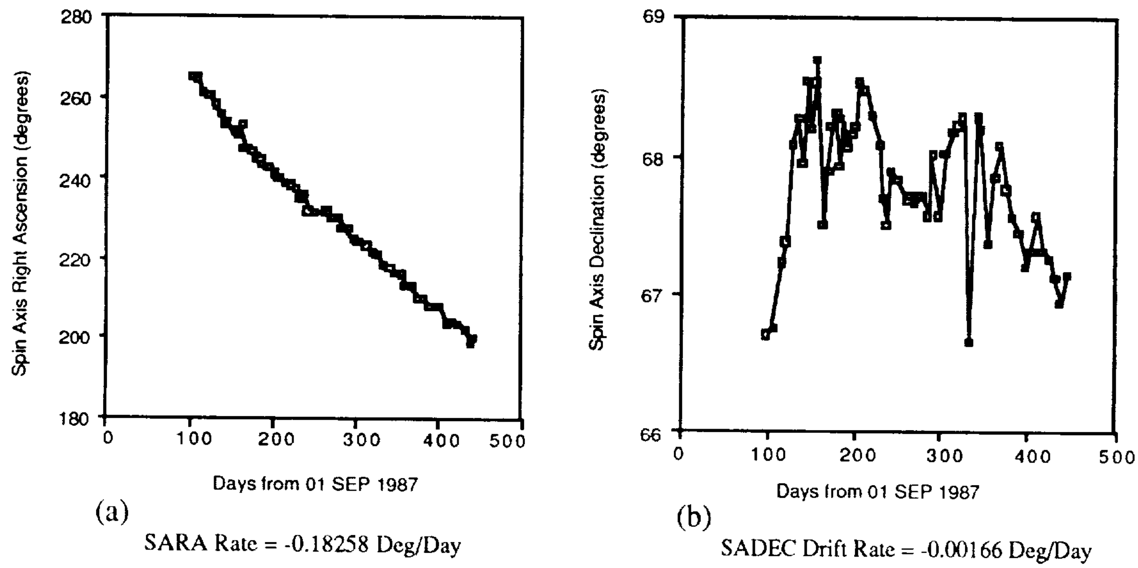

Figure 3-3. SARA and SADEC for Rate Calculation.

This motion is recognized as nearly pure precession of the spin axis about the Earth's polar axis and has a period of approximately 360/.2 = 1800 days (4.93 years). The MCT then wrote a program to predict sun angle using these rates and a Sun ephemeris generator. A resulting plot can be seen in figure 3-4 . This prediction was very accurate on the average (nutation, of course causes small deviations from the precession path). Plots of the Sun angles from actual determined attitudes were always within a degree of the predicts.

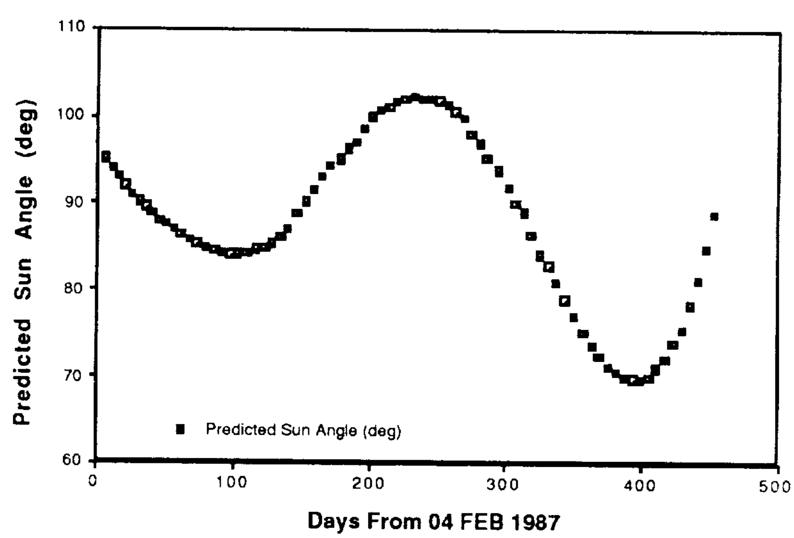

Figure 3-4. Spin Axis Sun Angle Relative to Earth-Sun Orbit Plane

During this re-orientation phase of the mission (1 Jan 87 to 1 Jan 91) only seven precession maneuvers were performed to maintain the sun angle within limits. A summary of the maneuvers in this phase can be found in Figure 3-5. At this rate of fuel consumption, the entire amount of remaining fuel would not be exhausted (ignoring blow down pressure) until the year 2025.

Initial Fuel	2.68 lbs
Final Fuel	2.34 lbs
Fuel Used by Original 5 Maneuvers	0.064 lbs
Fuel Used by 4 Spin Maneuvers	0.012 lbs
Fuel Used by 7 Normal Precession Maneuvers	0.26 lbs
Total Fuel Used	0.339 lbs
Average Time Between Maneuvers (1 Mar 87 to 1 Jan 91)	200.3 days
Average Fuel Used per Maneuver (1 Mar 87 to 1 Jan 91)	0.0375 lbs

Figure 3-5. SCATHA Re-orientation Phase Maneuver Summary

Maneuver performance for the seven normal precession maneuvers was good (see figure 3-6), although attitude determination was much more difficult during this phase due to the large amount of nutation experienced. There was more error than usual in the determined attitudes (both before and after the maneuver) as well as increased error in maneuver efficiency due to the high nutation. Still, the final attitudes were within operational accuracies (less than 1.5 deg).

Maneuver Date	Maneuver Size (Degrees)	Estimation Error (Degrees)	Max Observed In and Out of Plane Nutation(Deg) Out	In
09 Dec 87	16.20	<< 1	12.0	14.0
19 Nov 88	14.998	1.4	7.0	12.0
03 Jan 89	15.014	1.1	8.5	8.5
13 Jul 89	6.006	<< 1	4.0	5.5
08 Aug 89	6.001	1.45	5.0	6.0
17 Aug 89	4.060	< 1	4.0	6.5
09 Jul 90	12.113	No Telemetry	No Telemetry	

Figure 3-6. Maneuver Errors and Maximum Nutation for SCATHA During the Re-orientation Phase

Since the nutation did not appear to be damping, regular nutation analyses were performed. Data was collected from each contact (approximately 3 times a day) in order to calculate both in-plane and out-of-plane nutation values. Figure 3-7 shows the maximum daily calculated nutation values for a span from 1 Jan 88 to 20 May 91. Since these were derived from data collected during vehicle contacts only, the maximum values are only estimates of the true maximums during the span.

Deriving nutation maximum values using only data from contacts presented the problem of missing data (up to 19 hours of each day). The MCT explored other ways of examining the nutation data. Continuous data gathered by the vehicle tape recorders was downlinked to tracking sites and subsequently shipped to experimenters. Upon contacting some experimenters, a full week of continuous data was provided to the MCT for analysis. Figure 3-8 below shows one complete day of this data. This data was very representative of the week and shows that there is a fairly rapid short-term periodic variation in sun angle as well as a longer overriding variation. Overall, short term sun angle variations appear to occur at very regular time intervals (periods on the order of 1200 seconds) while the longer term variations are not so regular (periods of between 25000 and 30000 seconds).

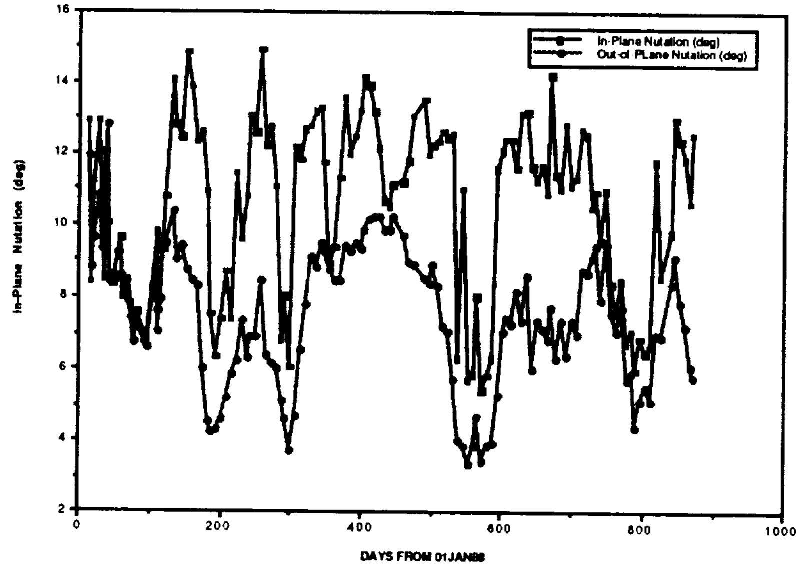

Figure 3-7. In-plane and Out-of-Plane Nutation

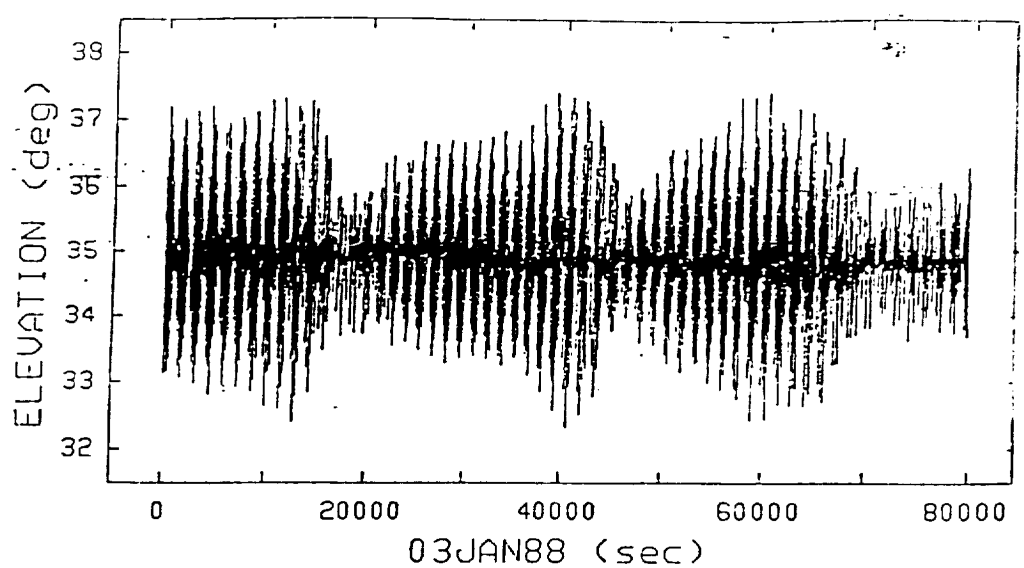

Figure 3-8. Full Day of Out-of-plane Nutation Data .

Although plots of data from the other three sun sensors (for the same time span) appear to be similar, much more data needs to be collected and processed to be able to determine a true pattern and to derive a method to predict nutation. With a large data base of this type of information, it was hoped to be able to at least find a pattern in the data that will suggest methods of predicting the nutation. Being able to predict "quiet" times would have helped dramatically in chosing future maneuver times. Unfortunately facilities to quickly process this data were not available at this time and now much of the experimenter data is no longer available so plans for future analysis are up in the air.

Figure 3-9 shows another way of looking at the details of out of plane nutation. This plot combines data from all four sun sensors, rather than waiting an entire spin period (about 1 minute) for a sun angle reading. This allows for a plot of sun angle every one-quarter spin period and may provide indication of any very short-term variation patterns in sun angle.

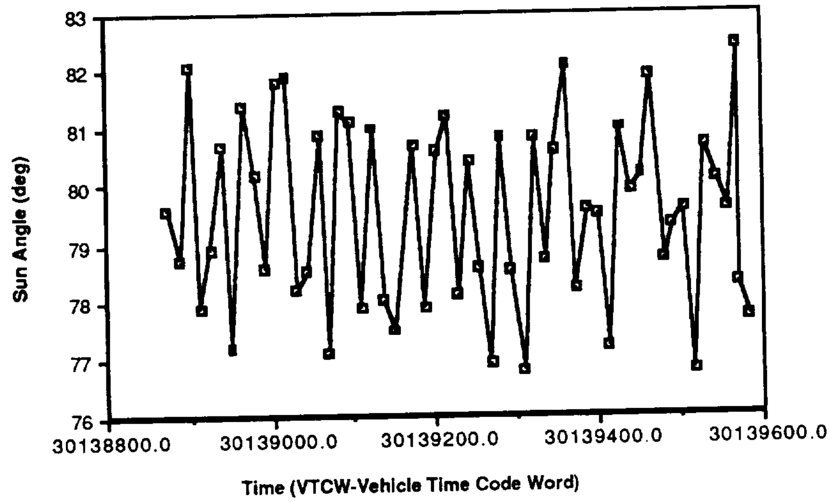

Figure 3-9. High Resolution Sun Angle Data.

4. MISSION TERMINATION

4.1 Pre-termination Activities

On May 20, 1990 SCATHA's transmitter #1, while in real-time support, displayed a sudden cut off to zero power output. All attempts to "revive" it failed. The only possible alternative was to go to transmitter #2 (the backup). Unfortunately, three years earlier, transmitter #2 had exhibited a similar drop in power, although only from the nominal 14.8 watts to 8.5 watts.

Real-time data retrieval became minimal and distorted. Playback data was all but impossible to retrieve. The ability of the MCT to collect attitude data was almost completely gone. Signal strength was very low, causing frequent loss of sync and data dropouts. These dropouts were especially detrimental to the collection of earth chords, one of the two types of attitude data. In order to get a valid earth chord angle, both a leading and trailing edge for that passage must be collected. Unfortunately, the dropouts were so common that valid earth chord data was extremely rare. The ground based software was completely unable to cope with such poor earth chord data. Many attempts were made to process the data but all failed. Attitude determination with sun sensor data only was tried but it gave unreliable results since data was too sparse. The last valid attitude determination by the original ground based software was done on May 19, 1990. For the next nine months, predictions of sun angles, earth chords, and attitudes were done using known SARA and SADEC rates and this last derived attitude.

By December, the retrieval of this low quality data became a major issue. The only useable telemetry that could be retrieved was collected during perigee supports which were available only 15 minutes a day. Even then only about 50% of the downlink data was usable. Even out-of-plane nutation calculations could rarely be done since it was so difficult to get consecutive sun crossings.

4.2 Termination Plan

The Systems Program Office (SPO) directed TSC-1 that SCATHA no longer needed to remain active after 31 Dec 1990. The MCT was directed to put SCATHA into a safe orientation and deplete all remaining fuel.

Many studies were done and options considered for using up all the remaining fuel as quickly and safely as possible. The quickest way to do this was to first retract the large booms and then perform a large velocity change maneuver (or series of maneuvers) to lower perigee as much as possible. This method had th added benefit of giving even better link margins at perigee and hence having more opportunities to gather goo data. However, this method was rejected for a number of reasons. First, in order to do an efficient burn to lower perigee, a huge precession maneuver (>50 deg) had to be done to align the spin axis with the negative velocity vector. This would use quite a bit of the remaining fuel and the subsequent delta velocity maneuver could only lower perigee by a couple hundred nautical miles. Second, and most importantly, the GSFC study (ref section 3.2, para 3) showed that bringing in the booms was extremely dangerous to vehicle stability. Of course, if the velocity change maneuver were done with the long booms out, they would bend and wrap around the vehicle if not break off entirely. Either way, the vehicle could not be considered to be in a safe configuration. So all future options would only be considered if the long booms remained fully deployed.

A second option considered was to spin the vehicle up (slowly) with hopes of placing it in a more stable configuration. However, the MCT experience with spin up maneuvers in the ecliptic normal configuration had not been very successful. The spin axis motion had not been the same since those four spin up maneuvers in February of 1987. The MCT considered the idea of bringing the spin axis back down into the orbit plane and then spinning it up, but spin maneuvers of any kind were viewed by the Air Force as too unsafe.

Finally, the decision was made to execute a series of 20 degree attitude precession maneuvers until the remaining fuel was gone. From past experience the worst (short term) out-of-plane nutation had taken three days to a week to damp out to smaller acceptable levels. As 1 January 1991 approached, there was a strong desire by the Air Force to "terminate" the satellite as soon as possible. Thus, only a 2 to 3 day separation between maneuvers was considered an acceptable risk. The Orbit Analysts in TSC-1 then performed a study to deplete the fuel in the requested manner. For purposes of study, the maneuvers were chosen so that only SADEC changed (i.e. add 20 degrees to SADEC, then subtract 20 degrees, then add, etc.). This study showed that it would take about 31 maneuvers to deplete all the remaining fuel. It was hoped that blow down pressure would be reached well before then, but the ground based software indicated that a tank pressure of 133 psia would be reached as the fuel hit 0 lbs. This was not the only odd output from the software. Maneuvers were allowed to be planned even after reaching 0 lbs of fuel remaining. The software even printed out a negative amount of fuel remaining. Although we found these things alarming (and they haunted us later on), the ultimate objective forced the MCT to continue with the plan and assume the ground software would accurately generate maneuvers with low or negative fuel indicated.

The Orbit Analysts performed one more study before taking the results to the Air Force. This study was to determine the best attitude in which to leave the satellite. From past experience, the MCT has been asked to turn off satellites with no regard to the spacecraft orientation. On a couple of occasions, vehicles were attempted to be turned on 1 to 2 years later. On all occasions it was impossible to turn on the vehicles due to their orientations. So, this time it was decided to try and leave SCATHA in an attitude that would leave it secure, but allow it to be possibly turned on in the future if needed. The attitude chosen was one that put the spin axis parallel to the Earth's polar axis. The natural precession of the satellite's spin axis about the vector parallel to the Earth's polar axis causes the sun angle to sinusoidally walk further from normality to the sun-line (ref section 3.2 and figure 3-4). With this choice of final attitude, the spin axis would not precess and the sun angle would constantly (and sinusoidally) walk between -23.5 degrees non-normality to sun line and +23.5 degrees non-normality to the sun line. These sun angles would provide SCATHA enough power to turr on in the future if needed . Fuel depletion and achievement of the final attitude for this plan would not occur until April 6th, if maneuvers were performed every three days. However, there appeared to be no viable, safe, alternative plan.

Unfortunately, the plan did have some problems. The maneuver sequence would be planned with attitudes that were propagated from the last determination in May 1990, which was when the last viable attitude data was collected. Attitude prediction accuracy studies had not been done for so long a span. However, sun angle predictions from the last good attitude and the sun angle observed were within a couple of degrees of each other. While this certainly didn't imply that the predicted attitude was within two degrees of actual attitude (since an infinite number of attitudes have the same sun angle), it was probable that the attitude estimate was useable. Further confirmation of this fact came from new prediction accuracy studies. Estimates were made by predicting old attitude states six months or more ahead (no maneuvers included) and comparing them with actual determined attitudes at that time. For nearly all of the spans covered, the error of prediction was less than 1.0 degree when predicting for 200 days. Figure 4-1 shows a representative sample of predicted and determined attitudes.

Attitude Epoch	Determined (Deg)		*Predicted (Deg)		Total Angular Error (Deg)
	SARA	SADEC	SARA	SADEC	
08 Jan 88 0000Z	257.865	68.094			
08 Jul 88 0000Z	223.775	68.173	224.635	67.794	0.4976
11 Aug 88 0000Z	216.683	68.195	218.428	67.738	0.7980

* Rates Used: SARA rate = -.18258 deg/day; SADEC rate = -.0016502 deg/day

Figure 4-1. Predicted and Determined SARA and SADEC

While these predicts worked well for times when there were no attitude maneuvers, they could not be solely relied on for times when attitude maneuvers were being performed. Each maneuver introduces a small uncertainty in the predicted attitude after the maneuver due mostly to spacecraft nutation but also to imperfect knowledge of thruster efficiencies and non-perfect attitude rates. It was readily apparent when the maneuvers started that some method of estimating the vehicle attitude would be needed.

As it turned out, the Orbit Analysts had already been working on a simpler version of generic attitude determination software. This method is based on the Earth Midscan Rotation Angle / Sun Angle method found in Wertz "Spacecraft Attitude Determination and Control". It requires only one sun sensor (DSAS) measurement and one steerable horizon crossing indicator (SHCI) leading edge-trailing edge pair collected within the same spin period. Using this data, as well as vehicle and sun position, the method produces four possible choices for the attitude (the intersection of two cones). Two of these values can be immediately eliminated since they are physically impossible. The user can then eliminate the remaining bad attitude by comparison with an apriori approximation of the true attitude. While this method is fairly easy to perform (once you've gathered all the data), it's accuracy is very much affected by variations in spin period and measured sun angle. Unfortunately, variation in spin period and out of plane nutation were common during this time and so determined attitudes even from data in the same pass were often not consistent. Sometimes averaging a few of the determined attitudes assisted in getting a better attitude state.

4.3 Summary of Termination Phase Maneuvers

The final phase of SCATHA's mission life covered the span from 01 Jan 91 through 24 May 91. During this time, 48 precession maneuvers were performed 45 of which were 20 degrees in size while the others were less. Figure 4-2 provides a summary of fuel usage for the final maneuvers. As the chart shows, things did not go as anticipated. The predicted end date of April 6th passed without depleting the fuel. The software continued to operate accurately even though it was using "negative fuel". Also, the sequence of maneuvers was disrupted at times and new requirements were given to the MCT as the maneuvers progressed. The remainder of section 4 is devoted to explaining how events differed from the original schedule along with an analysis and explanation of the gathered data.

Number of Maneuvers	48
Initial Fuel	2.3425 lbs
Final Fuel (Apparent)	-1.0523 lbs
Total Fuel Used	3.3953 lbs
Average Time Between Maneuvers	3.0 days
Average Fuel Used per Maneuver	0.0707

Figure 4-2. Summary of Termination Phase Maneuvers

4.4 Maneuver Schedule and Analysis

The first maneuver was executed as planned on 4 Jan 1991. The next maneuver was to be performed three days later, but was postponed. Due to reduced tracking supports covering only the perigee half of the orbit, the Orbit Analysts had a very difficult time determining the vehicle's orbit. Predictions with a newly determined orbit the day prior to the next maneuver were very poor so the maneuver was postponed until January 9th when the orbit was better defined. The next five maneuvers went as planned through January 21 (9th, 12th, 15th, 18th, and 21st). At that point, the lack of tracking data caused an inability to obtain lockup on the vehicle for a sizeable portion of the pass. Clearly, the lack of good tracking data and inaccuracies in maneuver modeling were making maneuver planning and operations difficult. Also, at this time, there was still no ability to determine the post maneuver attitudes. For the next two weeks the Orbit Analysts worked at determining the actual orbit based on increased tracking data. At the end of the two weeks, it was decided that the increased number of passes needed for orbit determination accuracy couldn't be justified for a vehicle that was being phased out. Vectors (2 Line Mean Element Sets) for SCATHA were sent from the NORAD (North American Air Defense Command) Space Surveillance Center on a daily basis. This solved the problem for the remainder of the mission.

Maneuvers resumed on February 2nd. However, there was a new twist to the maneuvers. One of the experimenters requested that when doing the maneuvers, the MCT try to keep the sun angle at a 100 degrees ± 2.0 degrees. Until this point, the only restriction on maneuvers was that they be 20 degrees in size and within 15 degrees of the sun line. However, this request was met as well as all other requirements. The 20 degree maneuvers continued approximately every three days until April 16 when the software indicated that the fuel had dipped below 0.1 lbs. At this point the spin axis was very near parallel to the Earth's polar axis. Smaller maneuvers were decided to be used to deplete the remaining fuel but not stray far from the desired final attitude. After two 6 degree maneuvers on the 16th and 18th of April, it was realized that we were still 5 psia above blowdown pressure. Also, the Orbit Analyst attitude determination program was now complete, and it became apparent that the maneuvers were reaching very near the full arc length (although not necessarily to the right target).

At this point there was confirmation that the maneuver software or database definitely had a problem. However, at that time it wasn't known what was wrong. Investigations into the problem began and the twenty degree maneuvers continued again since there was clearly more fuel on-board than the ground software indicated and the Air Force was pushing to quickly turn-off the satellite.The 20 degree maneuvers continued every Tuesday, Thursday, and Saturday until the final maneuver on May 24. At this point, the maneuvers were still executing efficiently (not expected at such impossible propellant levels), but the MCT was asked to discontinue maneuvers anyway. The final maneuver was only 9.1 degrees in arc length, putting the spin axis as near as could be estimated to parallel to the Earth's polar axis.

4.5 Fuel Consumption / Depletion Analysis

It had been hoped to carefully analyze the propulsion system performance as the fuel was depleted. Careful analysis of the changing thruster efficiencies and an accurate measure of actual blowdown pressure could have been invaluable for future missions. However, at this time the CSTC was in the final stages of the process of converting from an old computer system to a new brand new one. The telemetry processing and attitude determination software for SCATHA was hosted on the old system. Also, SCATHA was one of the few programs with software on this system and its mission was considered to be finished by the Air Force. So, termination of the mission as soon as possible was a very high priority. It was assumed that there was very little fuel remaining in the tanks and so the vehicle was considered "safe" enough to turn off.

Although analysis of the propulsion system could not be performed at this time, regular monitoring of propulsion system parameters was done during the final phase. Predicted and actual telemetry values were very close. Figure 4-3 shows tank pressure for the final months before turnoff. Occasional discontinuities in calculated pressure values are due to software database updates with an actual telemetered value. The Orbit Analysts made changes at these points in order to more accurately reflect the on-board pressure and temperature. With these periodic updates, the ground based software performed accurate modeling of the actual telemetered values.

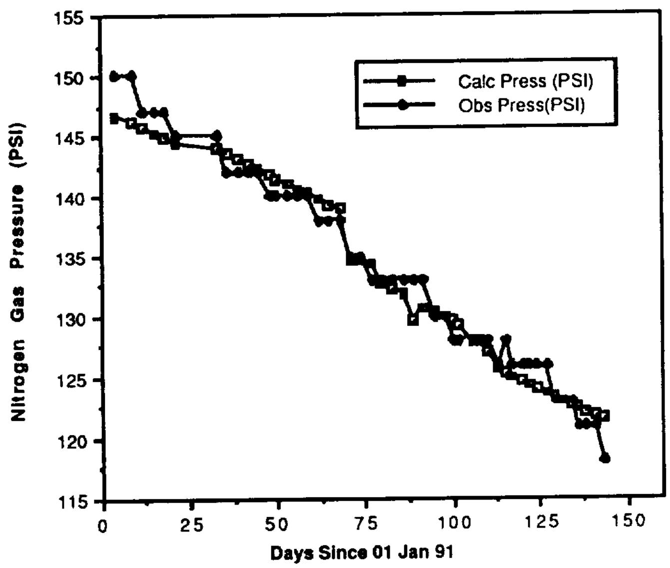

Figure 4-3. Observed and Calculated Nitrogen Tank Pressure vs Time

Unfortunately the problem of negative fuel went unsolved until after SCATHA had been terminated. As it turns out, the error lies in two places: the software and the database. The program that generated the maneuver calls a subroutine to actually calculate the maneuver and the amount of fuel necessary. The amount of fuel necessary for the maneuver was passed to the main program but the newly calculated pre-maneuver fuel mass was not. The main program then updates the latest stored value of fuel remaining by subtracting the amount of fuel needed for the maneuver. This would not be a problem unless the stored initial propellant mass was incorrect. Unfortunately, this value was incorrectly updated during the first week or so of the mission (back in 1979). The value input was approximately three lbs too low. The error was further compounded when new tank temperature and pressures from observed telemetry were manually input. While the calculated starting mass was accurate, the initial stored mass was incorrect. Since the stored initial mass is never really used for anything but display, it was never noticed as being a problem especially since all maneuvers appeared to reach the target attitude (within attitude determination accuracies). Maneuvers were done with the mass calculated from input data, not from the displayed mass.

With the error discovered, it is then appropriate to figure out how much fuel was really left in the tanks. Quick calculation shows there was nearly 2.5 lbs of fuel remaining on board SCATHA. It can be seen that thirty-three 20 degree maneuvers would have been necessary to use all the fuel remaining (blowdown pressure and thruster efficiencies permitting). If maneuvers were continued at the same rate, three times per week, the fuel would would have been depleted by August 10, 1991. This probably would be completed at least 2-3 weeks before due to blowdown pressure being reached.

4.6 Termination Phase Nutation Analysis

It was very difficult to get a true measure of the out-of-plane nutation and nearly impossible to get any measure of in-plane nutation during this phase. As mentioned in section 4.1, consistent telemetry data collection was difficult due to degraded transmitter performance. It was a tedious process to manually go through the telemetry, find consecutive sun angle readings, and calculate out-of-plane nutation. However, data was calculated for all available telemetry and the maximum values (among all four sun sensors) per pass were plotted in the graph show in figure 4-4.

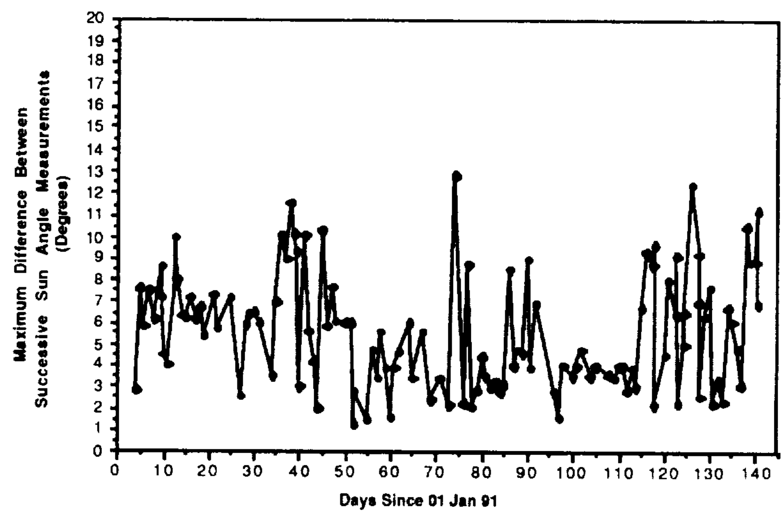

Figure 4-4. Maximum Sun Angle Difference

It is important to note that quality data was gathered for only 2 1/2 hours a day at most. Even if 2 1/2 hours of good data was gathered every day (1 hour was close to reality) for the entire termination phase (144 days), then only 10% of all possible SCATHA data was available for examination. Thus the graph in figure 4-4 shows the smallest that the maximum nutation could be during each day of the final termination phase. Clearly, there was a large amount of nutation throughout the entire phase.

In-plane nutation turned out to be extremely difficult to calculate accurately since the instantaneous spin rate was not output in telemetry and output sun crossing times were rounded to the nearest second. For this reason the in-plane nutation was not computed and plotted for this phase. At times, however, that successive spin rate calculations using successive sun crossing times (for a particular DSAS) were as much as 2 seconds off. This indicates a possible 12 degree in-plane nutation error.

4.7 Determined Attitudes and Maneuver Performance

Due to the nutation and lack of consistent telemetry information, attitude determination during this phase was difficult and at times required many attempts. The following chart (figure 4-5) gives a comparison of the determined sun angle (from the determined attitude) and the observed sun angle during the last half of the termination phase. The data in figure 4-5 does not prove that the determined attitude was actually quite close to the observed, since there are an infinite number of attitudes with the same sun angle. Still, it seems appropriate to assume that the predicted attitude is well within 5 degrees of the actual attitude, since the above data is consistently within 3 degrees at a wide variety of attitudes.

Pre-Maneuver Date (1991)	Determined Sun Angle(Deg)	Observed Sun Angle (Deg)
16 Apr	101.98	103
20 Apr	105.37	103
23 Apr	103.76	102
25 Apr	97.76	95
27 Apr	114.73	113
30 Apr	95.86	95
2 May	114.11	113
4 May	98.79	99
7 May	116.28	113
14 May	93.15	95
16 May	112.82	111
18 May	105.97	107
21 May	119.49	117
23 May	105.62	103

Figure 4-5. Determined and Observed Sun Angle

Maneuver performance is very difficult to analyze for the termination phase of the mission. From 1 Jan 91 to 16 Apr 91 there was no method of attitude determination following the maneuvers. During this time, there were three basic criteria for determining whether to continue with maneuvers:

(1) Nutation must be consistently less than 10 degrees on the pass prior to the maneuver.
(2) The Sun angle must be within 3 degrees of the predicted Sun angle.
(3) The orbit must be good enough to acquire the vehicle.

For this time span, the maneuvers had to be stopped twice. Both times were due to poor orbit predictions. The other two criteria were violated only once, the exception being the 21 degree maneuver at the end of the span. Since the Sun angle was consistently within 3 degrees of the observed through a wide variety of attitudes, it seemed very probable that the attitude was within 3-5 degrees of the actual attitude. The difference between the determined and predicted Sun angles during the termination phase are shown in figure 4-6.

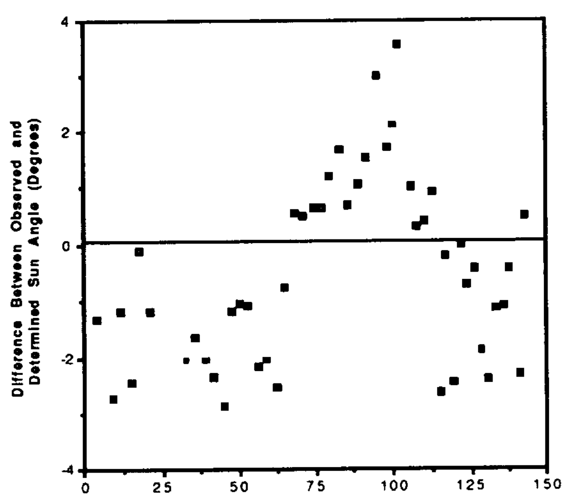

Figure 4-6. Difference Between Observed and Predicted Sun Angle

By April 20th, the in-house attitude software was completed and checked out. A rough attitude determination, using this software, was now possible before most of the remaining attitude maneuvers. For the maneuvers from April 20th to May 23rd, the difference in observed and predicted Sun angles (see figure 4-6) as well as the total angular error between attitude fits could be determined. The total angular errors are shown in Figure 4-7

Maneuver Date (1991)	Angular Error Between Predicted and Determined (Deg)
18 Apr	21.067
20 Apr	3.900
23 Apr	19.223
25 Apr	4.949
27 Apr	0.611
30 Apr	5.174
2 May	2.385
4 May	7.101
11 May	5.034
14 May	10.766
16 May	2.490
18 May	4.979
21 May	7.650

Figure 4-7. Angular Error Between Predicted and Determined Post-maneuver Attitudes

The results are mixed. While the differences between predicted and observed sun angles are consistently within 3 degrees of the actual (exception in the case of the largest maneuver), the angular error between determined (post-maneuver) and predicted attitude was quite variable. The largest errors are most likely due tc selecting the image solution rather than the correct solution. The large nutation also contributes to attitude determination error. Most of the errors can be explained this way. These solutions seemed reasonable considering there was so little consistent data and so much nutation.

5. SUMMARY

SCATHA presented the MCT with several challenges over it's 12 year life with the termination phase being the most demanding. A summary of the MCT's activity and findings follow:

1) The fuel depletion sequence was only partially successful. Most of the fuel was depleted but an estimated 2.5 lbs still remains on-board.

2) The maneuver planning and execution were severely restrained by SCATHA's flexible booms that spanned 100 meters.

3) Undamped nutation became a problem only after the spin-up maneuvers in the new ecliptic normal attitude. The undamped nutation required attitude maneuvers be spaced at least 3 days apart, dramatically hindered accurate attitude determination, and made precession maneuvers potentially very inaccurate.

4) A long standing error in the software and database was discovered. The error remained hidden du(in large part to the high degree of accuracy and efficiency of all maneuvers performed. Correction of this error provided the basis for estimating the on-board fuel left on SCATHA after mission termination.

5) Attitude determination software, created in the final days of the mission, worked well at providing a rough attitude despite the nutation.

6) The series of 48 attitude maneuvers during the termination phase appeared nominal even though telemetry was scarce and attitude determination rough.

7) The final attitude should leave SCATHA in an attitude that will provide enough power so there is a good chance of turning on the vehicle in the future.

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