

The NOAA -14 September 28, 2006(DOY271) Tumble Anomaly

Milton C. Phenneger
ASRC Aerospace Corporation
6303 Ivy Lane, Suite 800
Greenbelt, MD 20770
310-837-5417

Milt.Phenneger@asrc aerospace.com

Jonathan Woodward ARSC Aerospace Corporation
Jonthan.Woodward@noaa.gov 301-817-4019
Ross Cox ASRC Aerospace Corporation
Ross.Cox@noaa.gov 301-817-4017
Carl Gliniak Honeywell Space Technology
Inc.
Carl.Gliniak@noaa.gov 301-817-4207

Abstract—This paper describes a NOAA-14 spacecraft loss of control event and the lessons learned from it. The lessons learned are in two categories; Contingency recovery operations and on-orbit propulsion system isolation methods. The work is motivated in recognition of the effort of the NOAA off-line engineering support team and their NOAA civil servant mission leads and operations support staff

1. INTRODUCTION

This paper explains an anomalous occurrence aboard the NOAA 14 spacecraft and the activities and analyses that were employed in the investigation. It will provide a high level description of the time line and root cause of the anomaly, a more detailed data review of key features of the event, and show how the analysis revealed the root cause. The lessons learned are then elaborated in the conclusion.

The intent is to communicate this experience and lessons learned that are pertinent to the improvement of mission planning and support.

2. Event Timeline and Root Cause Overview

On Thursday September 28th 2006 (DOY271), 20:30:50 UTC at the AOS of the Fairbanks CDA (FCDA) ground station NOAA -14 was discovered to be in a tumble. During the prior contact, at 13:51:40 UTC with the Wallops CDA (WCDA) ground station was in a completely nominal status. Subsequent analysis of playback data determined that the spacecraft had been spinning uncontrolled and out of Earth lock since 14:47 UTC. Status of all subsystems was assessed, yet recovery was not attempted during the initial Fairbanks pass, and the next scheduled contact from Wallops CDA was for 01:28:20 UTC on DOY 272. Due to concerns for

the health and safety of the spacecraft while in this state, emergency passes were subsequently scheduled for 22:24 UTC (one orbit later than the FCDA discovery pass) and at 00:04 UTC (two orbits later). By 01:00 UTC on DOY 272, the spacecraft was returned to nominal attitude with no apparent damage to the bus or payloads. This state was achieved 8 hours after the initial loss of control and 5 hours after its discovery. A detailed description of the timeline of events is presented in Table 1.

The cause of the tumble was not immediately understood from the indicators available in real time telemetry and event logs. However, by the following Monday (DOY 275), with the advantage of playback telemetry and experience with a similar type of event on NOAA-17 (Ref. 1) , it was determined to be a sudden release of propellant through the 100lbf hydrazine Rocket Engine Assembly (REA) #2. The evidence for this conclusion was a simultaneous step increase of $\sim 7^\circ\text{C}$ in the propellant line inlet and loop temperatures for thruster 2, coupled with the rapid 140 degree reverse motion of the solar array.. The prop line and loop temperature sensors are located at the entrance to the thruster valve and ~ 7 inches upstream respectively on the $\sim 3/8''\text{O.D.}$, $0.028''$ wall tubing (Ref. 2). The data also indicate a hydrazine leak which lasted ~ 45 seconds and affected the whole REA propellant manifold¹. This fact is substantiated by thermistor data indicating similar leak thrusts occurred at all 4 REA thrusters over the next 10 hours. Specifically, there were positive steps the inlet and loop thermistor temperatures at the times of Sunrise between 14:47 UTC and at the last step increase in the REA 3 thermistors at 23:56 UTC.

A representation of the NOAA-14 spacecraft is presented in Figure 1 annotated to show the REA thruster locations and to reveal their plume directions relative to the solar array.

¹ The authors thank Richard Caverly (NASA POES Program Propulsion Subsystems Engineer) for the constructive discussion and debate that led the analysis that revealed these correlations.

Table 1. Operations Support and Command Event Timeline

| UTC | Activity Description | Additional Comment |
|----------|--|---|
| 14:47:20 | SAD Switch | Automatic FSW response due to SAD status not equal to the commanded SAD status |
| 14:47:40 | Data Bus Switched | Automatic FSW response due to SAD status not equal to the commanded SAD status |
| 15:04:35 | IMU Logic Switch | Automatic FSW response due to IMU operation and “gyro fail” status |
| 15:04:50 | DFS Overflow Count = 1 Level 9 Error Count = 1 | Overflow and Level 9 error count due to IMU operation |
| 15:05:00 | X(-Yaw) RWA off Skew(+X,+Y,-Z) RWA on | Automatic response to saturated wheels |
| 15:16:40 | CPU2 NOT OK (CPU 1 Non-Functional) | Automatic response due to IMU redundancy actions unable to remedy tumble situation |
| 15:51:08 | Mode Controller to BackUp | Hardware response to power system operations |
| 20:42:00 | AOS #1(Fairbanks) - Anomaly Detected - STD CMD Table Load Attempted - STD CMD Table Stopped | Discovery Contact at Fairbanks CDA CMD Load unsuccessful |
| 22:24:00 | AOS #2(Fairbanks) | Called up Emergency Contact |
| 22:28:36 | CP START=GASON | |
| 22:28:50 | - CMD FTHRE | Enable N ₂ Thrusters |
| 22:28:50 | - CMD FATUE | Enable Auto Thruster Unloading |
| 22:29:57 | CP START =THRUSMON | Enable thruster count telemetry (not normally enabled) |
| 00:04:00 | AOS #3 (DOY 272 Fairbanks) | Called up Emergency Contact |
| 00:07:00 | CMD ETCUP | Earth Lock Attitude not acquired yet |
| 01:28:00 | AOS#4(Wallops) Reload STD CMD Table | Scheduled Contact Yaw Gyrocompass Mode (in Acquisition phase) |
| 02:21:20 | From Playback Telemetry Battery 3 to Trickle Charge (TRC) due to overtemperature test failure | Software response to overheating battery. |
| 03:08:00 | AOS#5(Wallops) | |
| 03:14:44 | CMD RGMOD 0002-RGMOD=Passive | Reduced Gyro Control Mode (Passive Phase, ESA computes body rates but control stands by to use them if a gyro channel fails the integrity test.) |
| 03:16:11 | CP Start=MACROMON | Due to high yaw error, GYE attitude state entered |
| 03:17:25 | CP START=SRHLCATA | Turn SARR(search and rescue receiver) on for power balance |
| 03:20:58 | CMD FATUI | Inhibit Auto Thruster Unloading |
| 03:21:41 | CMD FTHRI | Inhibit All N ₂ Thrusters |
| 05:01:00 | AOS#6(Wallops) | Memory Dump, attempt forced Yaw Gyrocompass mode |
| 05:04:15 | CMD SFGC | Set Forced YGC(attempted) |
| 05:05:15 | CMD CFGC | Clear Forced YGC Flag (successful) |
| 05:06:05 | CMD SFGC | Set Forced YGC (attempted) |
| 05:06:57 | CP START=DMPF16KC | Dump First Half of CPU Memory |
| 05:12:06 | CMD TIPCORB | Command TIP back to Orbit Mode |
| 06:40:00 | AOS#7(Wallops) CP START=DMPL16KC CMD TIPCORB | Memory Dump Dump 2 nd half of CPU Memory Command TIP back to Orbit Mode |

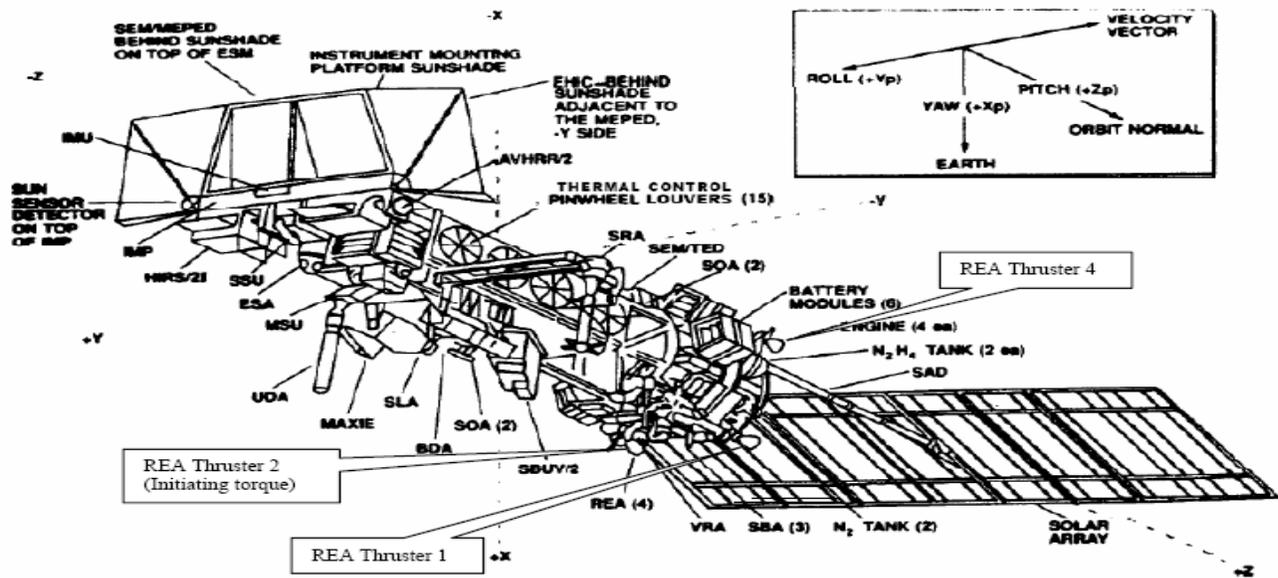


Figure 1-NOAA-14 REA Thruster Configuration and Plume Exhaust Direction

3. DATA REVIEW

Presented here are key observations from the much larger data analysis addendum to the anomaly report (ref. 3) delivered to the TIROS Operational Anomaly Report (TOAR) board at NASA/GSFC and NOAA/NSOF. The evidence that distinguishes the cause of this high impulse angular momentum event from a debris hit are the solar array reverse rotation, high body rates (beyond the limit of the capacity of one reaction wheel) and a correlation of these with the temperature steps in the 100 lbf REA thruster # 2 propellant line inlet and loop. Additional data is presented to illustrate the torque free period of the flat spin and evolution of spacecraft angular momentum in the body frame. During this time the spacecraft systems appears to be thermal and power safe.

3.1 Rates and Solar Array Data

The effect of the initial impulse on the body rates and solar array angle are illustrated in Figure 2. Notes on Figure 2 highlight the correlation between the step changes in the body rates, thruster 2 loop and inlet temperatures, and the solar array encoder angle. The data before the event is from the B and A data buses which were swapped by the On Board Computer (OBC) a few seconds after the beginning of the event. The short term evolution of the body rates is explained by the time dependent plume deflection from the windmill forced reverse motion of the solar array and its high rate return slew to the normal position and rate. The inlet and loop thermistor signals rise together, uncharacteristic of soak back heating from the

combustion chamber. The solar array encoder data shows that forced reverse motion of the array was 140 degrees in approximately 45 seconds.

3.2 The Torque Free Flat Spin Interval and De-Spin Recovery

Figure 3 shows the unfiltered body rate telemetry for 13 hours ending with the Earth capture. The y-axis (roll) rates which are saturated in this telemetry were determined to be approximately -0.9 deg/sec using the solar array current signal to determine the principal axis spin rate (I_{yy} near anti-parallel to +roll). Figure 4 shows the thermistor temperature data for all four REA thrusters for the time interval corresponding to Figure 3 revealing additional temperature step rises correlated with sunrise times. One explanation of this is that hydrazine ice from low level leaks at each of the thruster valves sublimates at sunrise causing ignition of the vapor at the catalyst. Also a detailed look at the rise times and delays between inlet and loop thermistors reveals evidence for combustion within the propellant line tubing.

From this NOAA-14 event and two earlier events on NOAA-17 (DOYs 324 and 342, 2005), it is concluded that all of the NOAA Polar spacecraft with REA thrusters, which excludes NOAA-18 and later, may experience

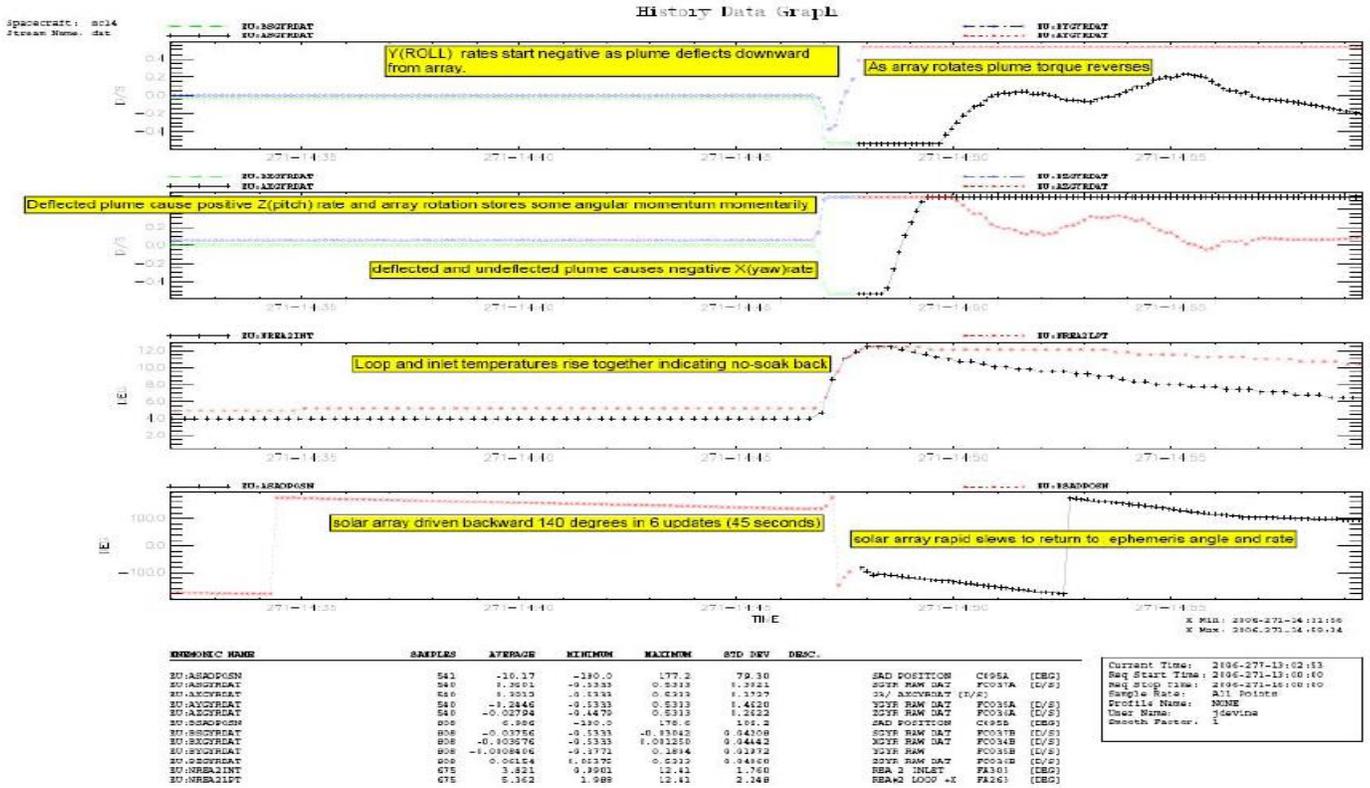


Figure 2-Unfiltered Body Rates, Line Temperatures, and Array Angles (30 Minutes)

similar events. Also, this should be considered in future development of contingency plans and propulsion system isolation and deactivation strategies on similar spacecraft.

3.3 Additional Data on Spin Dynamics and AVHRR Radiator Temperatures after Earth Acquisition.

Figure 5 shows the evolution of the angular momentum vector in the body frame. More accurately, assuming that the torque free motion occurs within 5 minutes of the initial impulse, Figure 5 illustrates the motion of the body frame around angular momentum vector which is inertially fixed in a direction close to the orbit plane and the Earth north pole. This data is derived in three steps; 1) A recovery of saturated roll rates using solar array current to determine total spin rate 2) Multiplication of this reconstructed body rate vector by the deployed MOI, from (Ref. 2 and 3) Unitization of the unit angular momentum vector and translation into body frame azimuth and elevation.

This rough attitude vector is from analysis, not documented here, which used an approximate model of Earth Sensor Assembly (ESA) quadrant cuts based upon spin rates determined from the solar array current periodicity. A stacked plot of solar array current data is show in Figure 6. Here each row of data starting at the lower left of the graph is precisely one orbit offset on

the y-axis to illustrate the similarity of each orbit and repetitive nature of the spin phase. Figure 7 shows that the history of the Advanced Very High Resolution Radiometer (AVHRR) radiator temperature throughout the event. In the figure, the long period rise and fall are correlated with spacecraft day and night, and the short noise-like saw tooth oscillations are due to the spacecraft spin as the radiator passes the Earth and/or Sun during day or night. Finally, after the de-spin at 22:30 UTC the ending geometry has the radiator aperture illuminated by direct sunlight for approximately 40 minutes.

3.4 Orbit Perturbations from Thrust

The NORAD Two Line Elements for 60 days including the event were analyzed to investigate the effects on the orbit. Figures 8 and 9 shows a discontinuity in the mean motion parameter and the corresponding impulse in the first derivative of the mean motion. From these data it was determined that the along track delta-V was +0.026 meters per second corresponding to a 0.65 Newton force applied for 45 seconds.

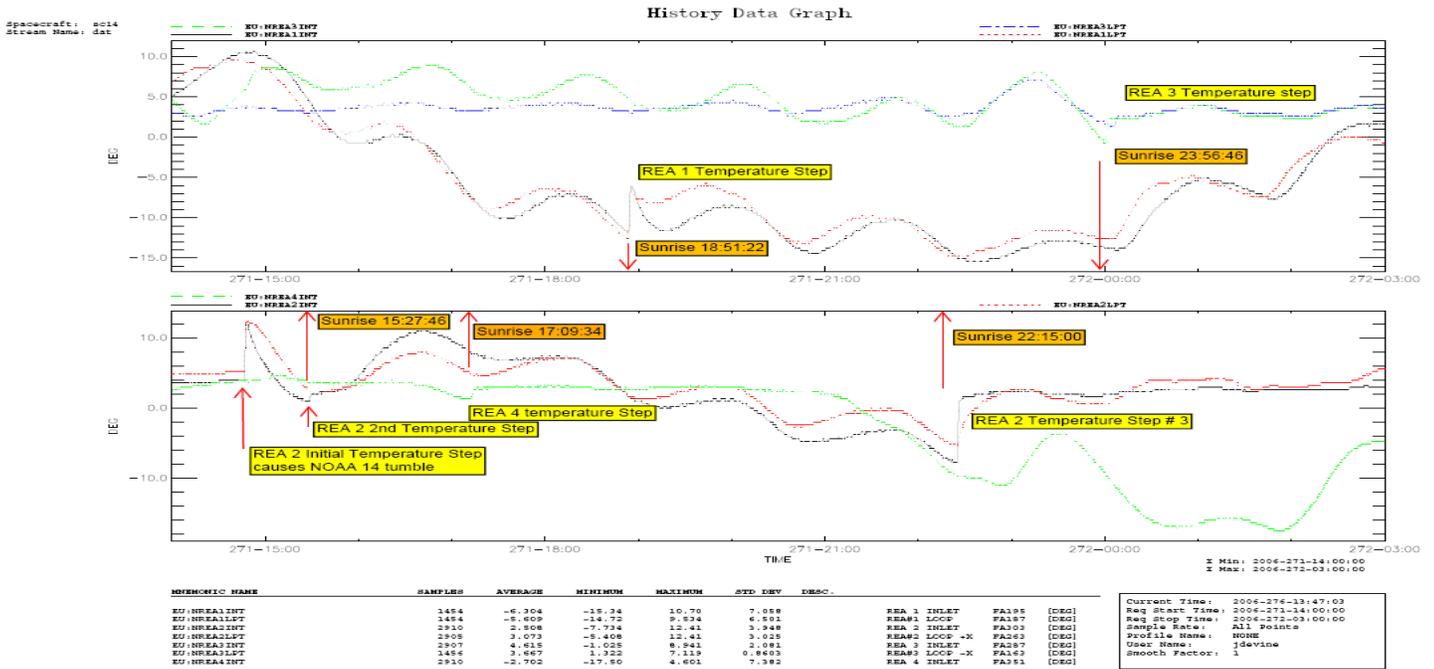


Figure 3-REA Thruster Temperatures For 13 Hours During the Event

4. Conclusions

As stated in the introduction, there are two categories of lessons learned from this anomaly, the recovery from it, and the subsequent analysis of playback data that would not have been available without a successful recovery. In the first category, the lessons is related to

early mission propulsion system venting, isolation, and mission operations propellant management. Typically, after the mission orbit is achieved, the propulsion system is isolated and vented to prevent it from interfering with mission objectives from spurious causes (inadvertent commanding, leaks, micrometeoroids, etc). The venting procedure used for the NOAA-14 spacecraft was to fire all four REA thrusters 0.5 seconds and wait 15 seconds for 10 cycles

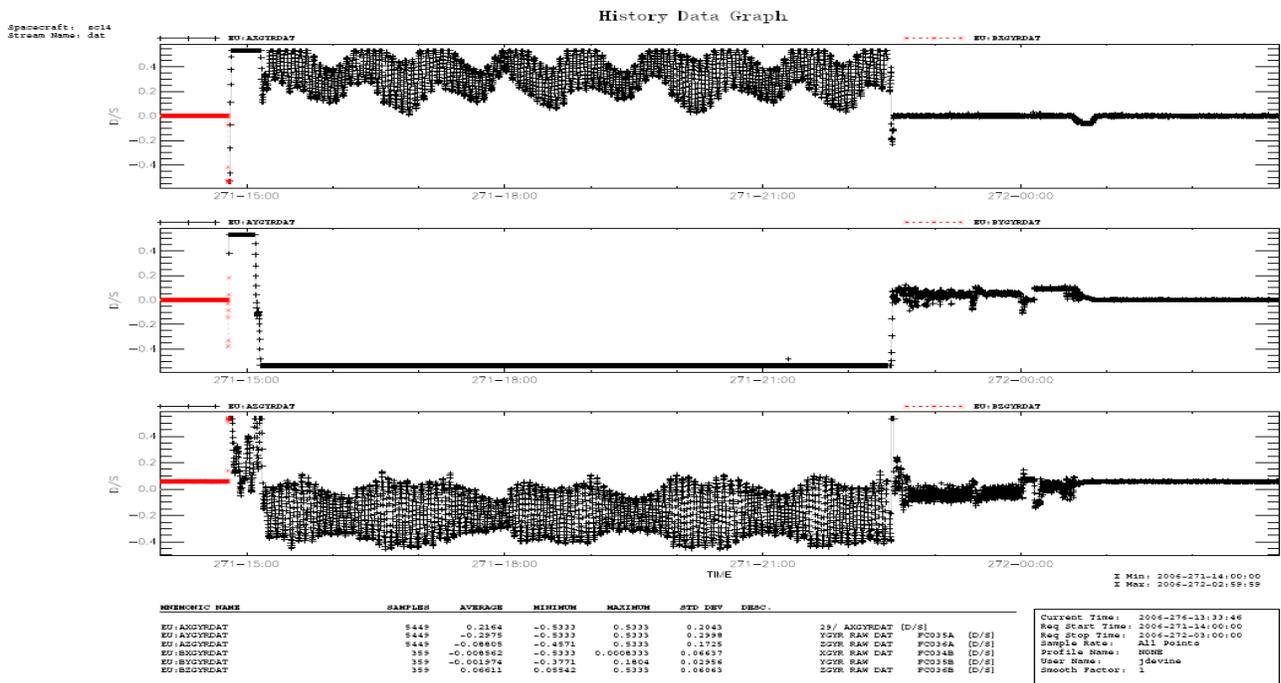


Figure 4-3 Body Rates from 14:00 UTC to 03:00 UTC (D272)

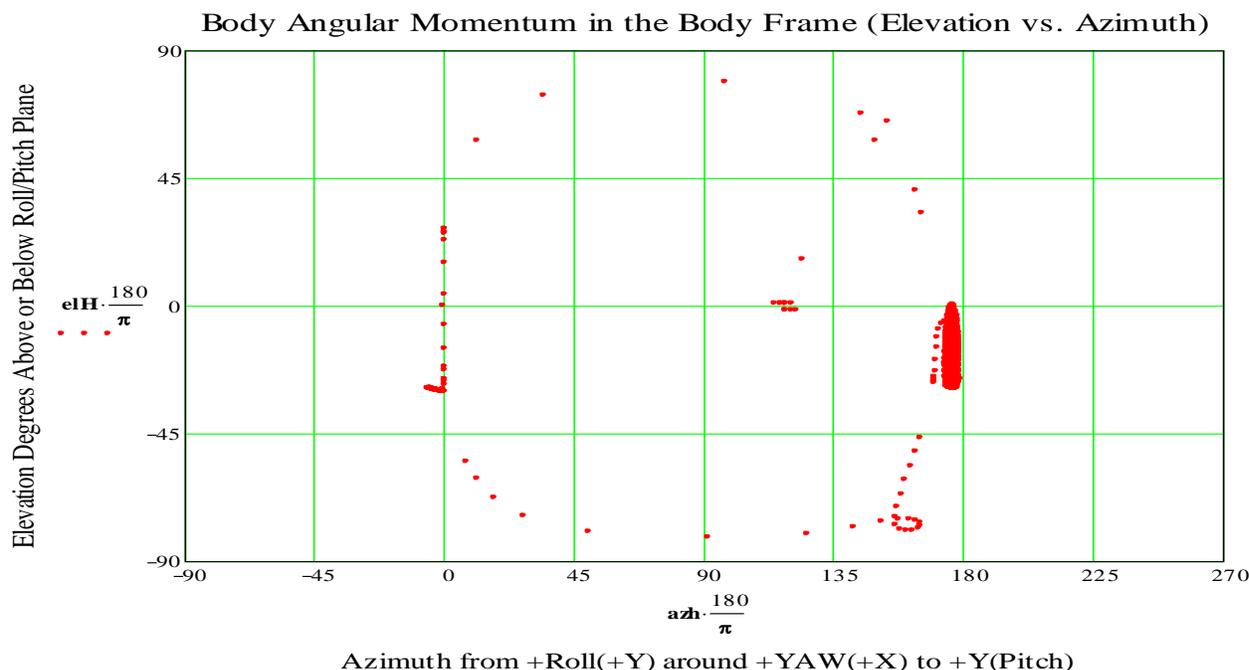


Figure 5-Total Spacecraft Angular Momentum in the Body Frame From 14:47 to 22:30 UTC

(Ref 2)., It appears from this anomaly and those on NOAA -17 that this was not sufficient to assure no risk to the mission from the fuel remnant in the tubing. Experience from the GOES I through M missions with similar isolation requirements showed that standard isolation protocols needed to be altered. It was noted during the GOES -8 mission, after orbit raising and main thruster isolation, that subsequent opening of a thruster valve to an isolated propellant and oxidizer manifold, the response is freezing of the oxidizer within the lines. For the GOES series, this was indicated by the 100 C° drop in the oxidizer line temperature in 60 seconds

Thus the procedure for the venting process was changed for GOES -8 through 13 to allow a waiting period, for line temperatures to recover and to repeat venting until the negative temperature drop ceased. This approach should be used for all similar isolation activities, if thermistors are available to sense line and valve temperatures.

The configuration on NOAA-14 was subjected to modulation of thruster combustion chamber temperatures as the Sun rose and set. Also, the solar array modulates the solar input and radiative output of all 4 of the REAs. The early NOAA satellite pulse duration and time scheme was probably not sufficient to fully vent the lines. Thermal indications should always be closely watched in propulsion system isolation activities.

In the second category of lessons learned which is operational contingency planning, the lessons are as follows:

- 1) The NOAA -14 spacecraft appears to have been in a long term power and thermal safe state during the high angular momentum flat spin period following the thrust leak event. Therefore, contingency plans for this event could be adjusted to accommodate a longer period of analysis and planning of the schedule for recovery if the tumble state proves safe. The highest risk to the mission appears to have occurred at the end of the de-spin recovery shortly after Earth acquisition. Evidence for this comes from later analysis of the battery state of charge following de-spin and from the AVHRR radiator temperatures.
- 2) Three other spacecraft similar to NOAA -14, all currently in an operational at the NSOF are susceptible to this anomaly. These are NOAA -17, -16, and -15. NOAA -14 has since been deactivated. NOAA-18 and NOAA-NPRIME do not have an REA hydrazine thruster system which would require similar isolation.
- 3) Although the recovery command sequence and technique is completely designed, in the current system, a new approach to recovery from this type of contingency should be considered. That is; a) To consider a more relaxed schedule of recovery if the payload data loss can withstand it. b) To prepare command loads to take advantage of time not in view of tracking stations for despin initiation and to reserve real time commanding to mitigate the thermal power hazards should they occur after despin. c) With this

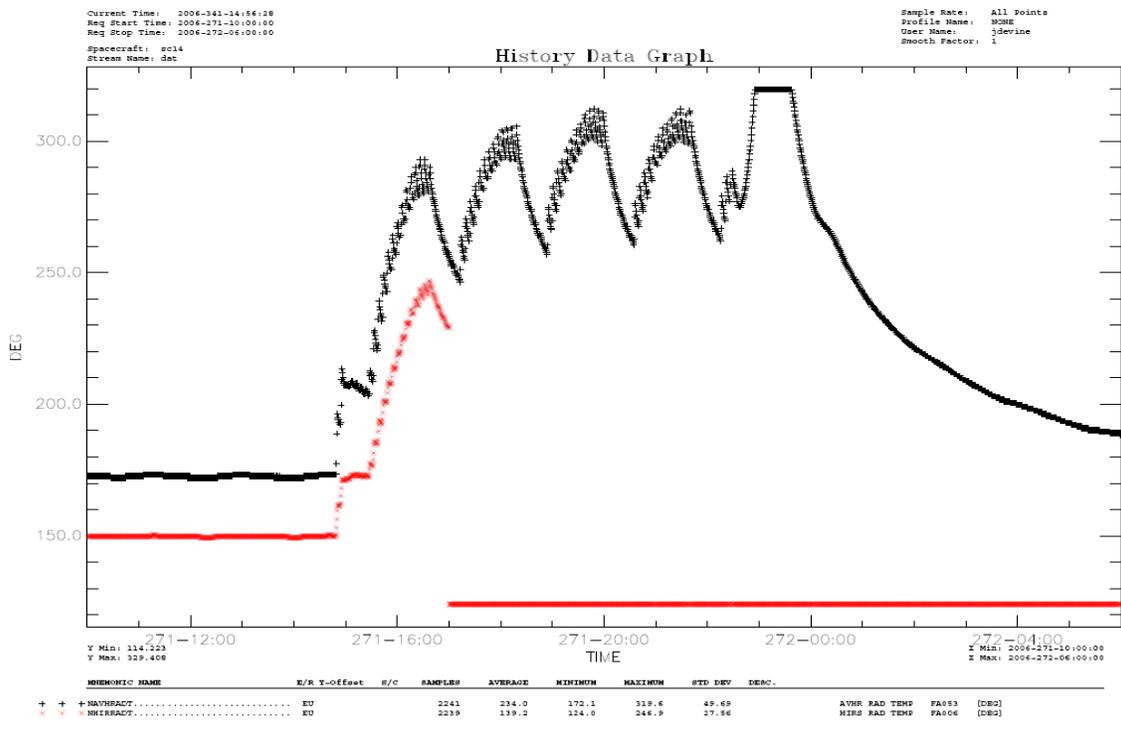


Figure 6-AVHRR Radiator Temperatures for 20 Hours Spanning the Event

new method, the schedule of pass coverage needs to be optimized to provide the longest interval of continuous coverage from multiple ground stations thus allowing real time for analysis decisions and commanding to mitigate the effects of poor power and thermal geometry which may result following de-spin and Earth acquisition.

4) It may be possible to address this type of anomaly with automation in the Attitude Determination and Control System (ADACS) software. The signature of this event is saturated wheel speeds coupled with saturated gyro rates and modulating solar array power. The current design appears to interpret these signatures as failures in gyros, wheels, or processors, none of which occurred in this case.

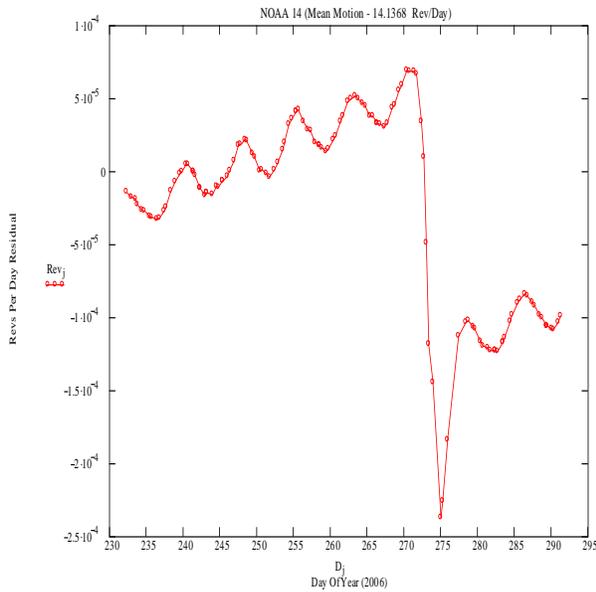


Figure 7-NORAD Two Line Elements for Mean Motion minus 14.1368 Revs per Day.

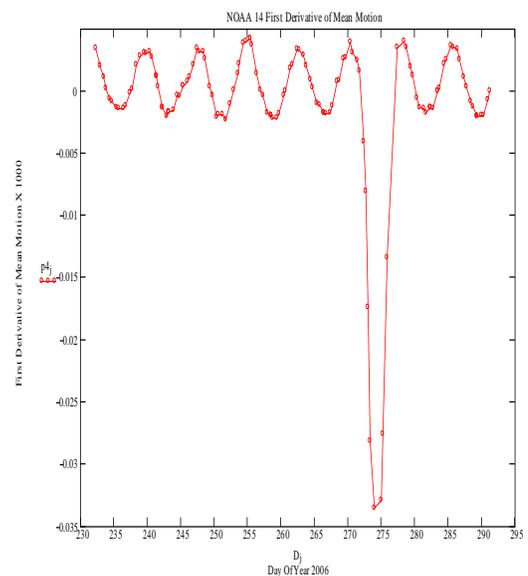


Figure 8-NORAD Two Line Elements for First Derivative of Mean Motion Showing

REFERENCES

- 1) NOAA -17 Anomaly Report for 2005, D324 and D342; S-NOAA-17-(M) -0026 (E-6561)
- 2) NOAA HIJ Design Report, (1989) Prepared by RCA Astro for NASA GSFC.
- 3) Data Analysis Addendum to the NOAA -14 anomaly report: S-NOAA-14-(j)-0030 (E-2436)

BIOGRAPHY

Milton C. Phenneger is a senior systems engineer and consultant with 33 years of experience working in satellite attitude and orbit operations and engineering analysis support at Goddard Space Flight Center. Most recently he supported NASA in preparations for GOES IM and N launch and operations at the NOAA Spacecraft Operations Facility (NSOF) GOES and POES Satellite operations. Milt has MS and PhD degrees in Nuclear Physics from The College of William and Mary and a B.S. in Physics from The Pennsylvania State University.

Jonathan Woodward is a senior subsystem engineer with 6 years of experience working in satellite Command and Control and Flight Software operations. Jonathan currently supports daily operations on the POES project at the NOAA Spacecraft Operations Facility (NSOF). Jonathan has a Bachelor of Science of Aerospace Engineering from Virginia Polytechnic and State University.

Ross M. Cox is a senior systems engineer with 22 years of spacecraft operations experience in all mission phases from mission requirements through satellite decommissioning. He is currently working at the NOAA Spacecraft Operations Facility on the GOES mission in support of the integration of the newest ground systems and also in contingency and anomaly responsiveness. Ross holds a Bachelor of Aerospace Engineering degree from the University of Maryland at College Park.

Carl Gliniak is a senior system engineer with 25 years of experience working in optical and rf systems for DOD and NASA at Amecom Division of Litton Systems, Inc, Goddard Space Flight Center, and NRL, and most recently at NOAA Spacecraft Operations Facility (NSOF) in support of daily POES Satellite operations. Carl has double MS from Northeastern University in Solid State physics and Georgia Tech in Optical Systems from the School of Electrical Engineering.

