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The 2006 NOAA-14 Tumble Anomaly

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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

Nomenclature

I_{yy}	=	Moment of inertia along the y/principal axis
lbf	=	Pound force
AOS	=	Acquisition Of Signal
CDAS	=	Command and Data Acquisition Station
CMD	=	Command
CP	=	Command Procedure
CPU	=	Central Processing Unit
DFS	=	Digital Filter Software
DOY	=	Day Of Year
FCDAS	=	Fairbanks Command and Data Acquisition Station
FSW	=	Flight SoftWare
GSFC	=	Goddard Space Flight Center
GYE	=	Gyroless Yaw Estimator
IMU	=	Inertial Measurement Unit
MOI	=	Moment Of Inertia
NOAA	=	National Oceanic and Atmospheric Administration
NSOF	=	NOAA Satellite Operations Facility
RWA	=	Reaction Wheel Assembly
SAD	=	Solar Array Drive
STD	=	Stored
TIP	=	TIROS Information Processor
TIROS	=	Television InfraRed Observation Satellite

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YGC = Yaw Gyro Compass
WCDAS = Wallops Command and Data Acquisition Station

I. 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.

II. Event Timeline and Root Cause Overview

On Thursday September 28th 2006 (DOY271), 20:30:50 UTC at the AOS of the Fairbanks CDAS (FCDAS) ground station NOAA-14 was discovered to be in a tumble. During the prior contact, at 13:51:40 UTC with the Wallops CDAS (WCDAS) ground station, it 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 CDAS 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 FCDAS 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 100 lbf hydrazine Rocket Engine Assembly (REA) #2. The evidence for this conclusion was a simultaneous step increase of ~ 7° 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 ~ 3/8" .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 manifold. 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 in 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.

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 Back Up	Hardware response to power system operations
20:42:00	AOS #1(Fairbanks) – Anomaly Detected – STD CMD Table Load Attempted	Discovery Contact at Fairbanks CDAS CMD Load unsuccessful

UTC	Activity Description	Additional Comment
	– STD CMD Table Stopped	
22:24:00 22:28:36 22:28:50 22:28:50 22:29:57	AOS #2(Fairbanks) CP START=GASON – CMD FTHRE – CMD FATUE CP START =THRUSMON	Called up Emergency Contact Enable N_2 Thrusters Enable Auto Thruster Unloading Enable thruster count telemetry (not normally enabled)
00:04:00 00:07:00	AOS #3 (DOY 272 Fairbanks) CMD ETCUP	Called up Emergency Contact 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 over-temperature test failure	Software response to overheating battery.
03:08:00 03:14:44 03:16:11 03:17:25 03:20:58 03:21:41	AOS#5(Wallops) CMD RGMOD 0002-RGMOD=Passive CP Start=MACROMON CP START=SRHLCATA CMD FATUI CMD FTHRI	 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.) Due to high yaw error, GYE attitude state entered Turn SARR(search and rescue receiver) on for power balance Inhibit Auto Thruster Unloading Inhibit All N_2 Thrusters
05:01:00 05:04:15 05:05:15 05:06:05 05:06:57 05:12:06	AOS#6(Wallops) CMD SFGC CMD CFGC CMD SFGC CP START=DMPF16KC CMD TIPMCORB	Memory Dump, attempt forced Yaw Gyrocompass mode Set Forced YGC(attempted) Clear Forced YGC Flag (successful) Set Forced YGC (attempted) Dump First Half of CPU Memory Command TIP back to Orbit Mode
06:40:00	AOS#7(Wallops) CP START=DMPL16KC CMD TIPMCORB	Memory Dump Dump 2nd half of CPU Memory Command TIP back to Orbit Mode

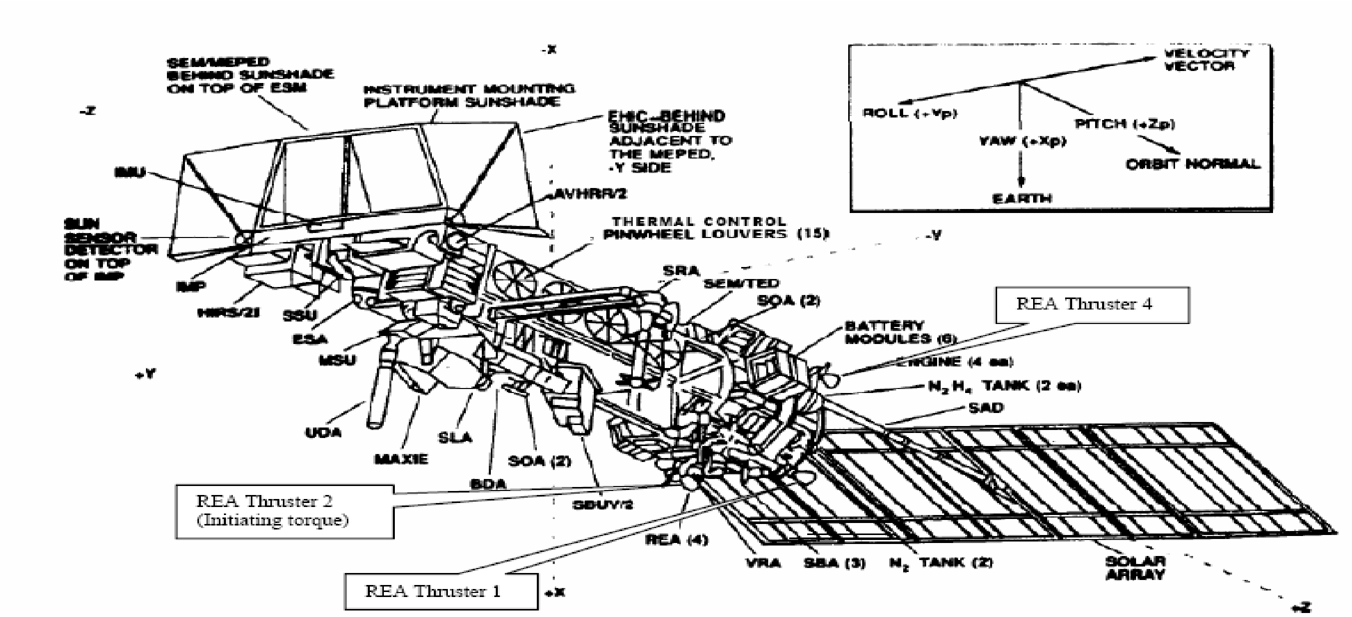

Figure 1. NOAA-14 REA Thruster Configuration and Plume Exhaust Direction

III. 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.

A. 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.

B. 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 sublimes 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

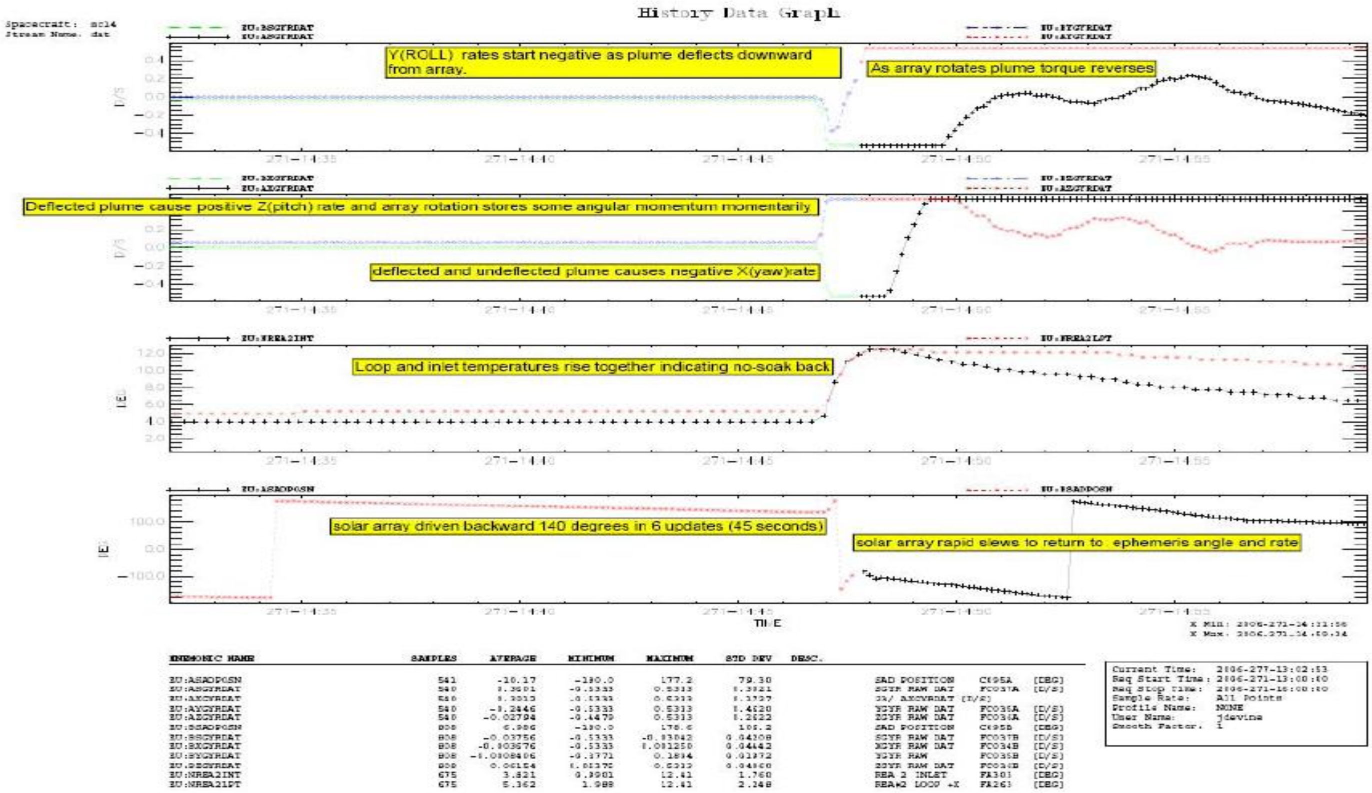

Figure 3. Unfiltered Body Rates, Line Temperatures, and Array Angles (30 Minutes)

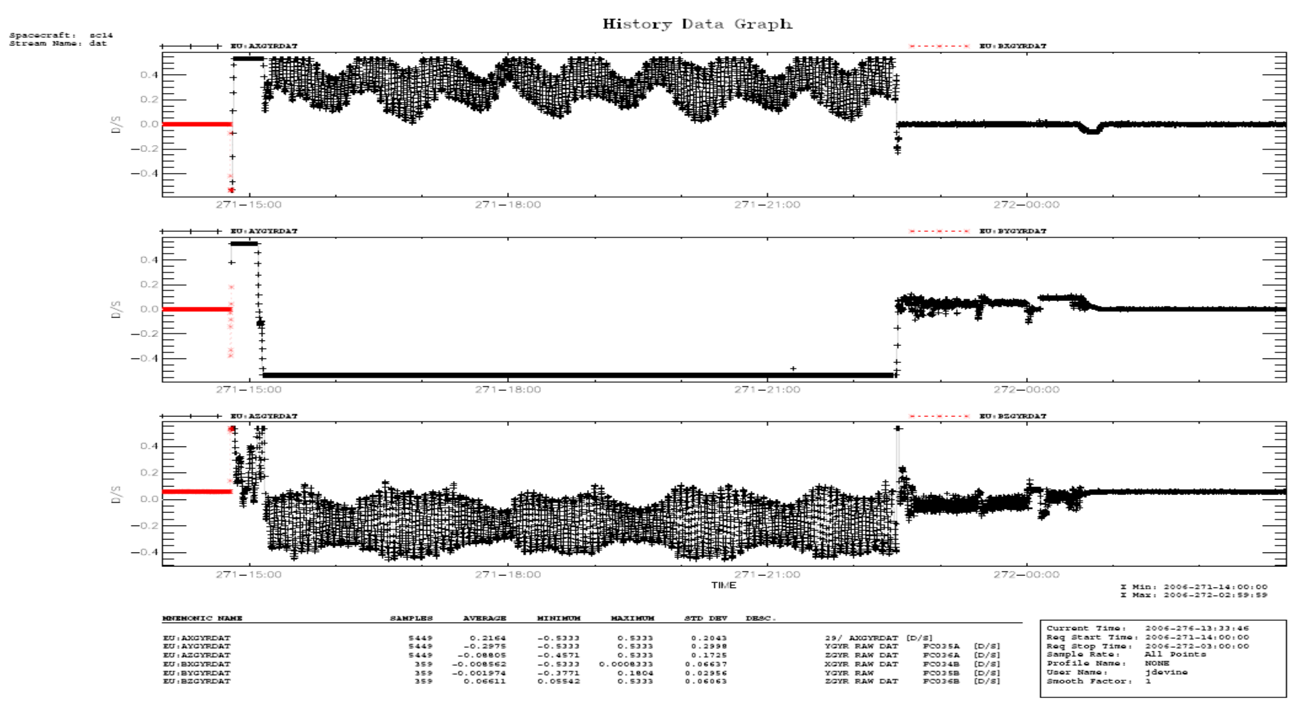

Figure 2. 3-Axis Body Rates from 14:00 UTC to 03:00 UTC (D272)

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

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

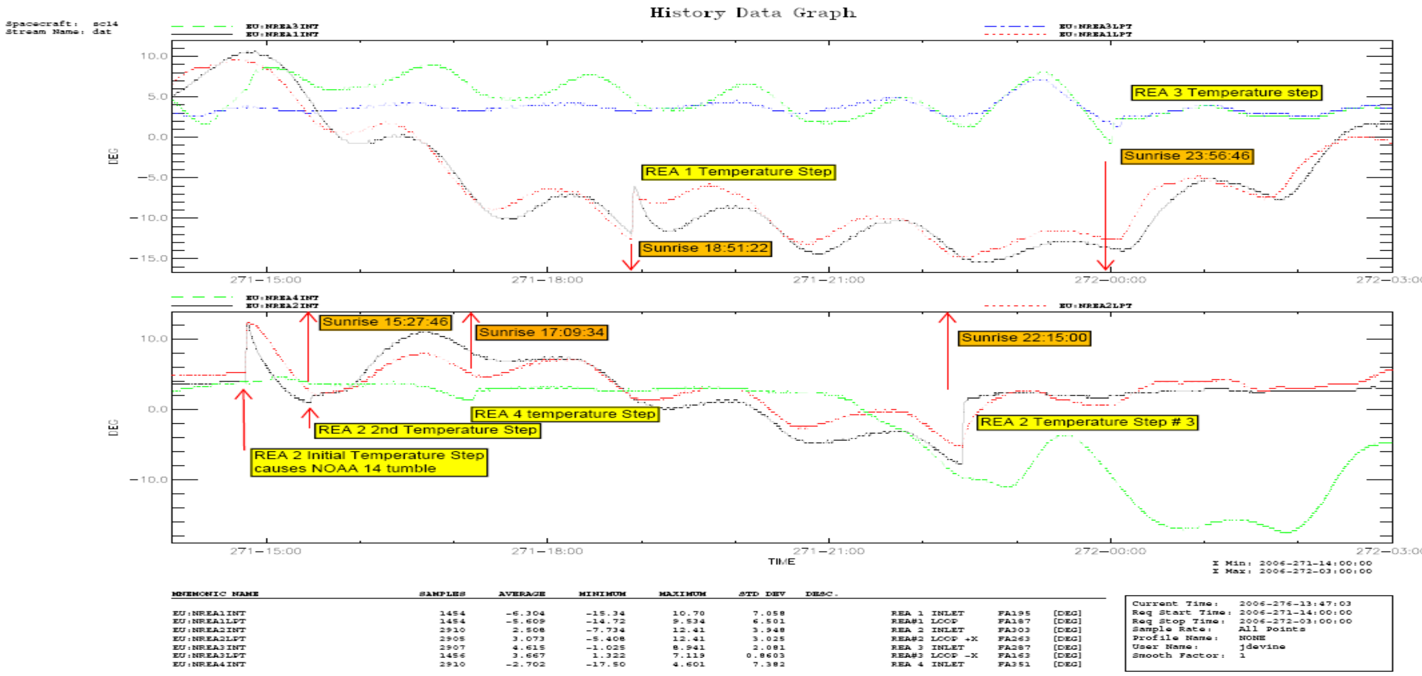

Figure 4. REA Thruster Temperatures For 13 Hours During the Event

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. 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 6 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

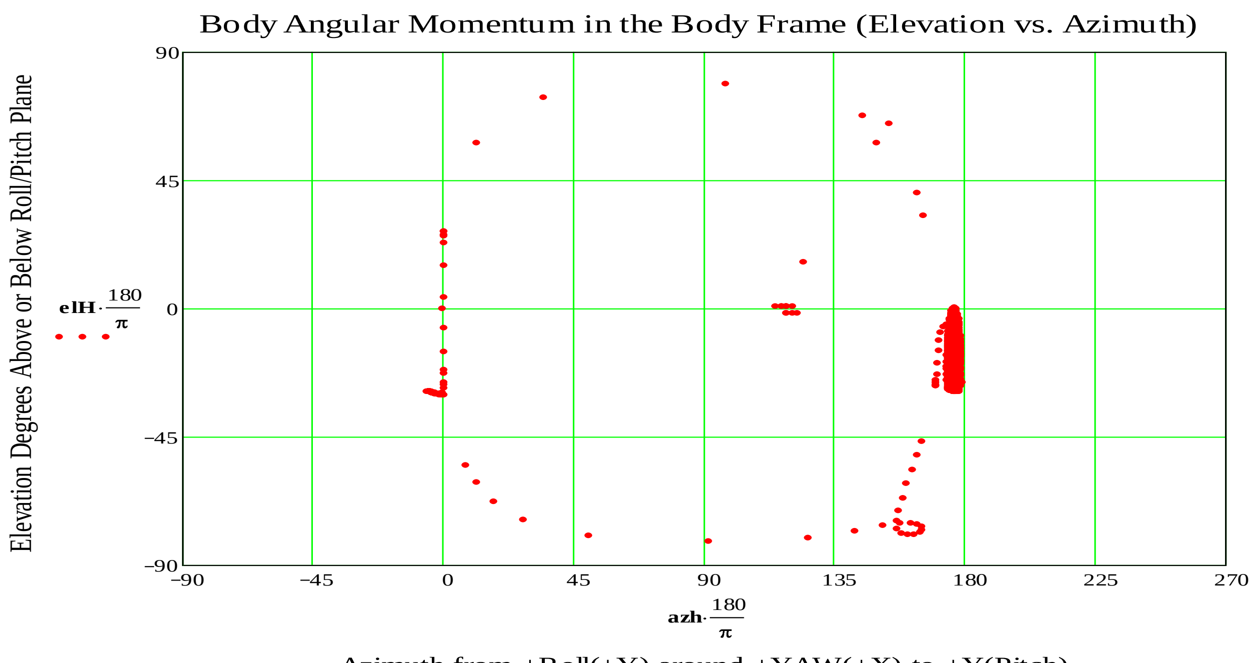

Figure 5. Total Spacecraft Angular Momentum in the Body Frame From 14:47 to 22:30 UTC

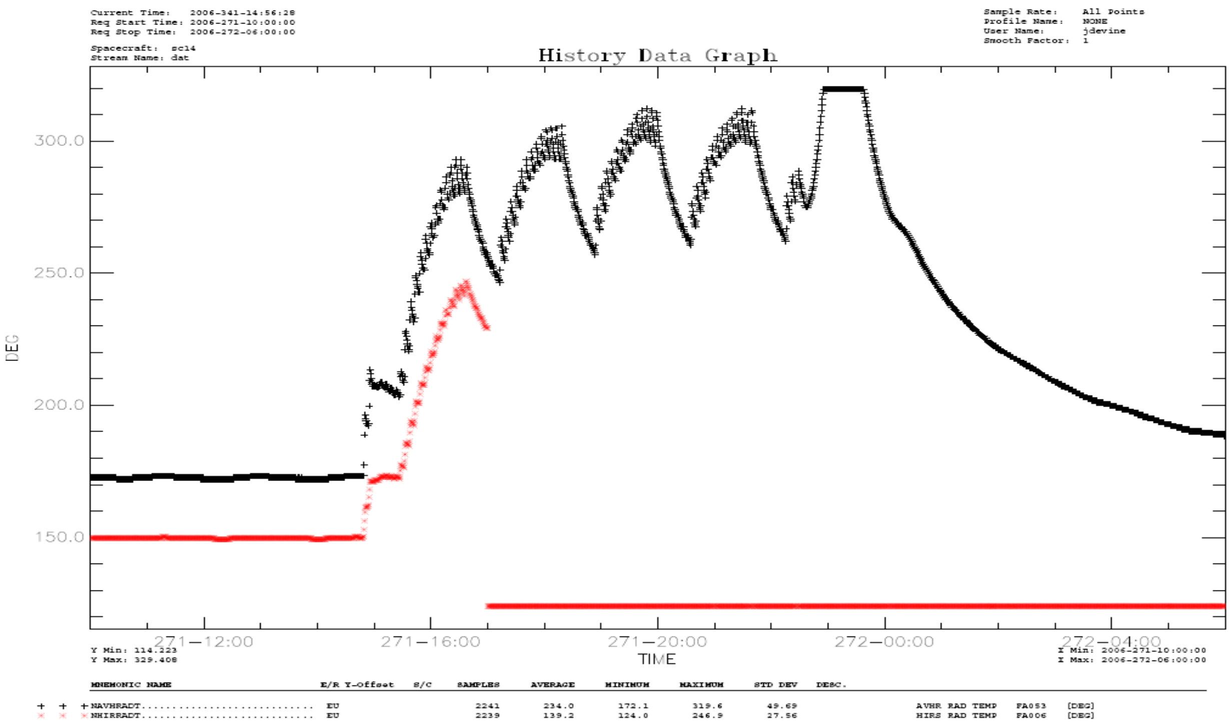

Figure 6. AVHRR Radiator Temperatures for 20 Hours Spanning the Event

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.

D. 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 7 and 8 show 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.

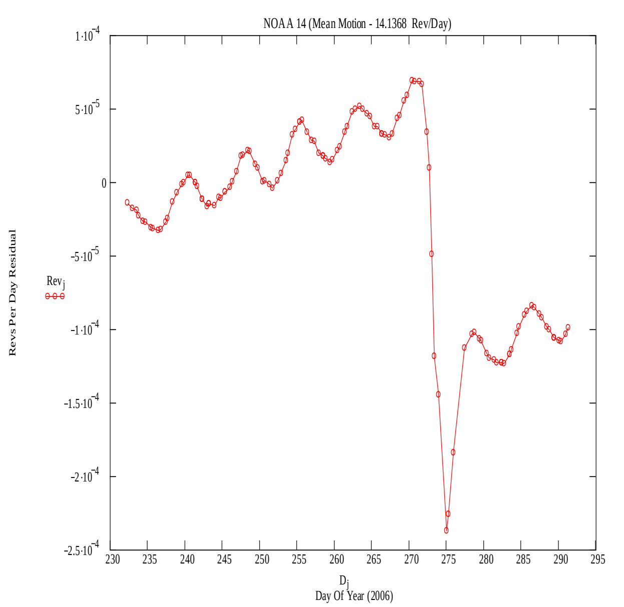

Figure 7. NORAD Two Line Elements for Mean Motion minus 14.1368 Revs per Day.

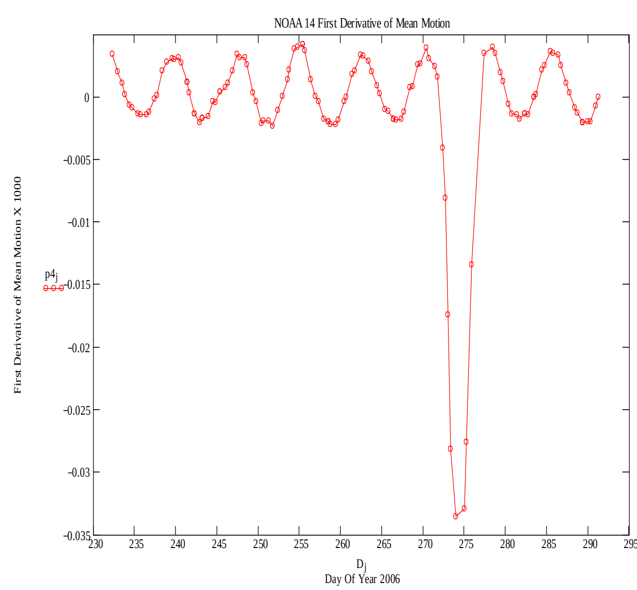

Figure 8. NORAD Two Line Elements for First Derivative of Mean Motion Showing Acceleration Impulse. The duration is dependent upon the length of the tracking arc.

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 lesson 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 (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 a 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 state 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 that 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 de-spin initiation and to reserve real time commanding to mitigate the thermal power hazards should they occur after de-spin. c) With this 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.

Acknowledgments

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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.**
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