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

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Agenda

- **Mission Operations Overview**
- **Discussion of Analysis and Discovery**
- **Sequence of Events**
- **Data Review and Analysis**
- **Root Cause**
- **Lessons Learned**

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NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)

LTAN:	21:55:00	**Inclination :**	99.1(Deg)	**Altitude:**	844(Km)
		Node Rate:	+2.4(min/month)	**Period:**	101.9(minutes)

International designator:	**1994 089A**		**SATELLITE WAS DECOMMISSIONED 23MAY07/JD143.**
Catalog Number:	23455	**Launch Date:**	**12/30/1994**
Spacecraft Letter :	**J**	**Operational Date:**	**04/10/1995**

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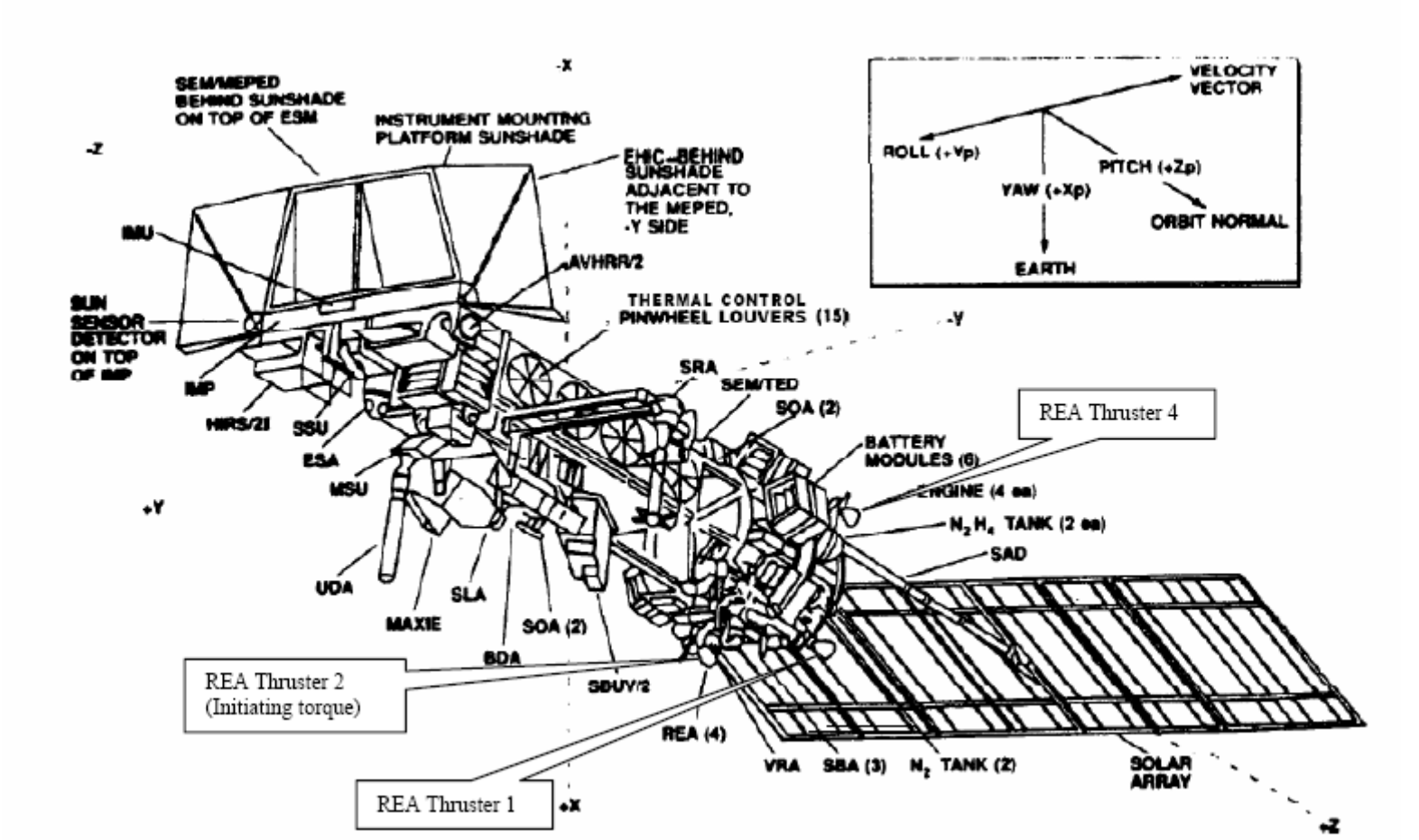
NOAA 14 Spacecraft Wire Diagram



Analysis and Discovery

- The explanation of the NOAA-14 anomaly depended directly on the understanding of the NOAA -17 DOY 324 and 342 anomalies
- The understanding of the NOAA-17 anomaly seemed almost accidental except for an understanding of how discovery in the operations environment can occur.
- Discovery occurs with a much higher probability when a team (in this case a mission support team) is motivated by a vision for the mission objective with a goal to understand systems to improve missions support.

Analysis and Discovery

- The NOAA-17 Anomaly Report Final Draft Delivery, was somewhat late, and within hours of delivery when the real cause of the anomaly was discovered.
- The discovery was made during an attempt by this analyst to explain to a colleague how a particle or debris hit could have cause 1 thermistor near a thruster to indicate a temperture rise of about 3 Lsb in a few update periods (~8 seconds per update)
- While doing this, I realized that my explanation was a reach, somewhat implausible, and that in the past for GOES IM we had written Contingency Plans on how to detect a bi-prop thruster leak by looking for sudden cooling at the thruster.

Analysis and Discovery

Summary of Three Impulsive Angular Momentum Events On NOAA 17 and NOAA 14

- **NOAA -17; 2005, DOY 324 (Nov. 20th); 10:30 UTC**
  - **Discovered in Trending Data**
  - **Angular Momentum Delta = 60 in-lbf-sec**
  - **Reported as Particle hit and later revised as Thruster leak.**

- **NOAA -17; 2005, DOY 342 (Dec. 8th); 01:20 UTC**
  - **Discovered in Trending Playback Data at 15:30 UTC**
  - **Angular Momentum Delta = 10 in-lbf-sec**
  - **Reported as Particle hit and later revised as Thruster leak.**

- **NOAA-14; 2006, DOY 271 (Sep. 28th) ; 14:47 UTC**
  - **Discovered in Scheduled Contact FCDA 20:23 UTC**
  - **Angular Momentum Delta = ~800 in-lbf-sec (12 rev per hour tumble)**
  - **Recovered by 03:00 UT DOY 271**
  - **Resolution of root cause based upon experience with NOAA – 17 and numerous supporting signatures in Solar Array and Thruster Temperature data**

The NOAA-14 Anomaly and Sequence of Events

- D271 2006 20:42 UTC Fairbanks AK CDA pass detects NOAA-14 had lost Earth lock and gyro rates were spurious.
  - Playback Data Analysis Reveals Recorded History
    a. 14:47 UTC Gyro Rates Saturate on pitch, roll, yaw, and skew gyros
    b. Solar Array encoder shows reverse slew of 140 degrees in 45 seconds
    c. 14:47:20 UTC Solar Array Drives Swapped by flight software (FSW)
    d. 14:47:40 UTC Data Bus Swapped
    e. 15:05:00 UTC Yaw RWA off Skew RWA on (FSW response)
    f. 20:42:00 UTC AOS Fairbanks Discovery of tumble state.
    g. 22:24:00 UTC AOS Emergency Fairbanks Call Up
    h. 22:29:57 UTC N_2 Gas Thrusters Enabled to initiate de-spin
    i. 00:04:00 UTC D272 AOS Fairbanks (call up) Earth Lock not acquired
    j. 01:28:00 UTC Wallops scheduled AOS YGC in ACQ phase
    k. 03:08:00 UTC Wallops scheduled inhibit N_2 thrusters, cmd Reduced YGC
    l. 06:40:00 UTC Wallops TIP to Normal Mode, Earth Lock confirmed

Data, Analytical Approach, and Results Summary

- During Recovery on Day 271 the cause of the tumble was not known
  - The focus was on satellite recovery to Earth Lock and normal Ops.
  - The most obvious data on this day were the responses of the fault detection logic in the flight software
- After recovery data analysis focused on the REA thrusters which were known to have caused attitude disturbances on NOAA-17 in 2005 on DOY 324 and DOY 342.
  - This analysis successfully revealed the cause
- After discovering the cause, the emphasis of the data analysis was:
  - To characterize and understand the propellant leak
  - To evaluate the evolution of the spacecraft attitude up until de-spin and Earth Lock recovery
  - After that, payload and bus components were evaluated for damage.

Data, Analytical Approach, and Results Summary (Continued)

- Attitude Dynamics is dominated by the high angular momentum impulse which saturated the Roll Reaction Wheel Assemblies (RWA) and initiated a body spin rate of about 13 Revolutions per hour.

- Additional motion due to the recovery of angular momentum stored in the deflected solar array and in the switching of the Yaw RWA “off” and the Skew RWA “on” is visible in the rate data but not a dominate feature of it.

- The degenerate Body Moments of Inertia results in a rapid rotation of the body spin vector across the separatrix from the +roll axis to –roll axis correlated with the replacement of the Yaw RWA with the Skew RWA

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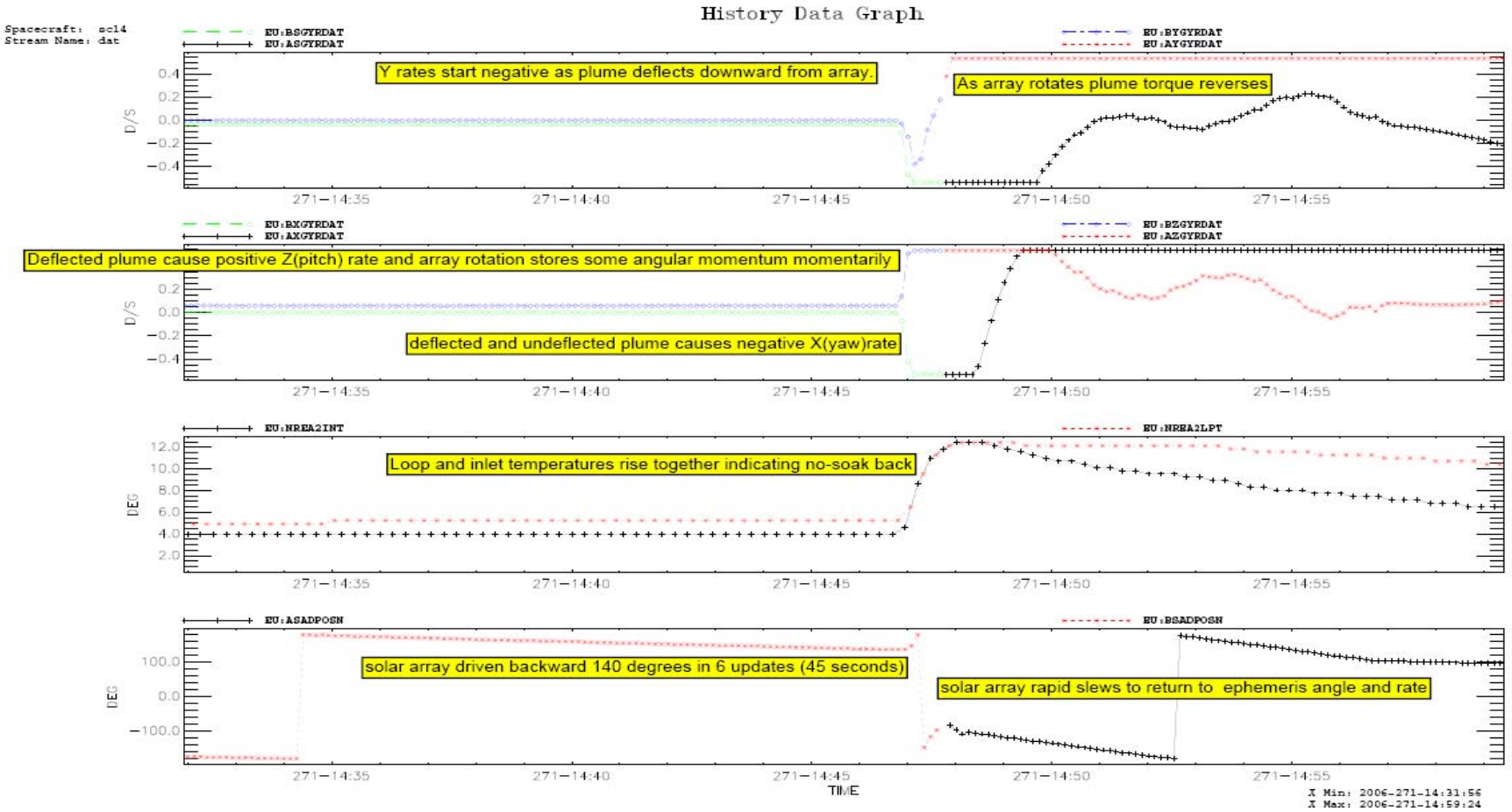
Discovery
Solar Array Angle, Body Rates, and REA 2 Line Temperatures



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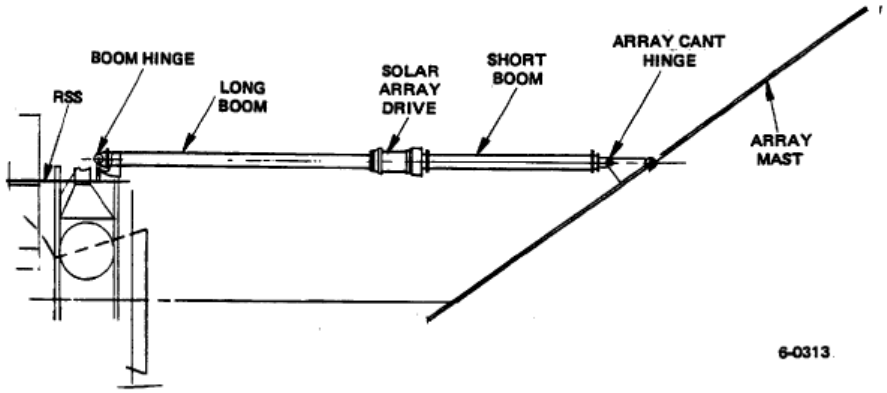
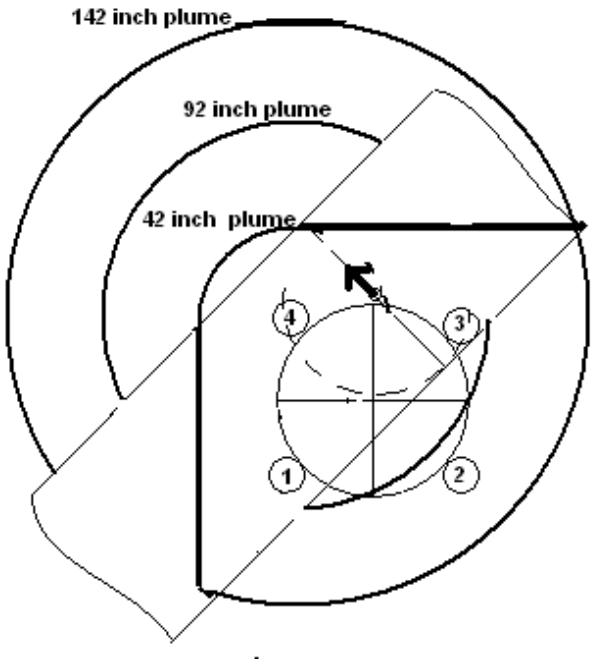
NOAA 14 Spacecraft Solar Array Assembly Side View and Plume Geometry for Thruster 4





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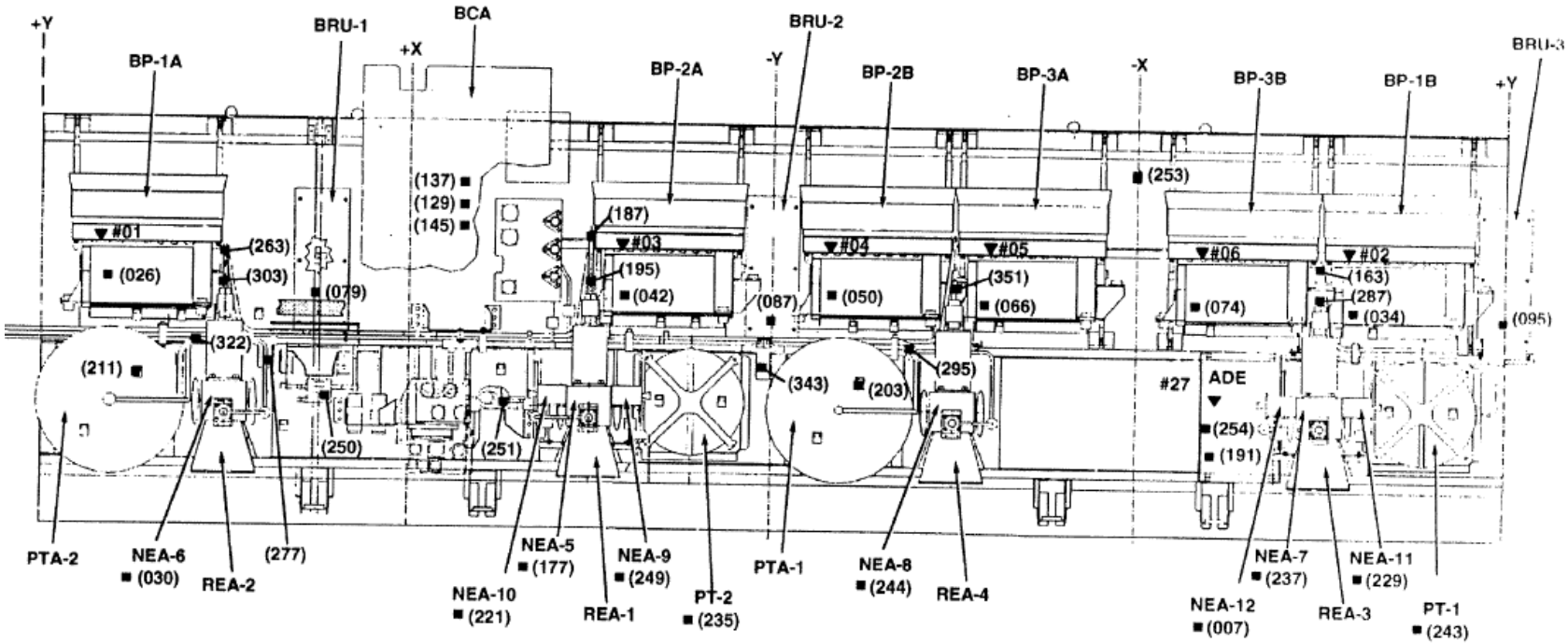
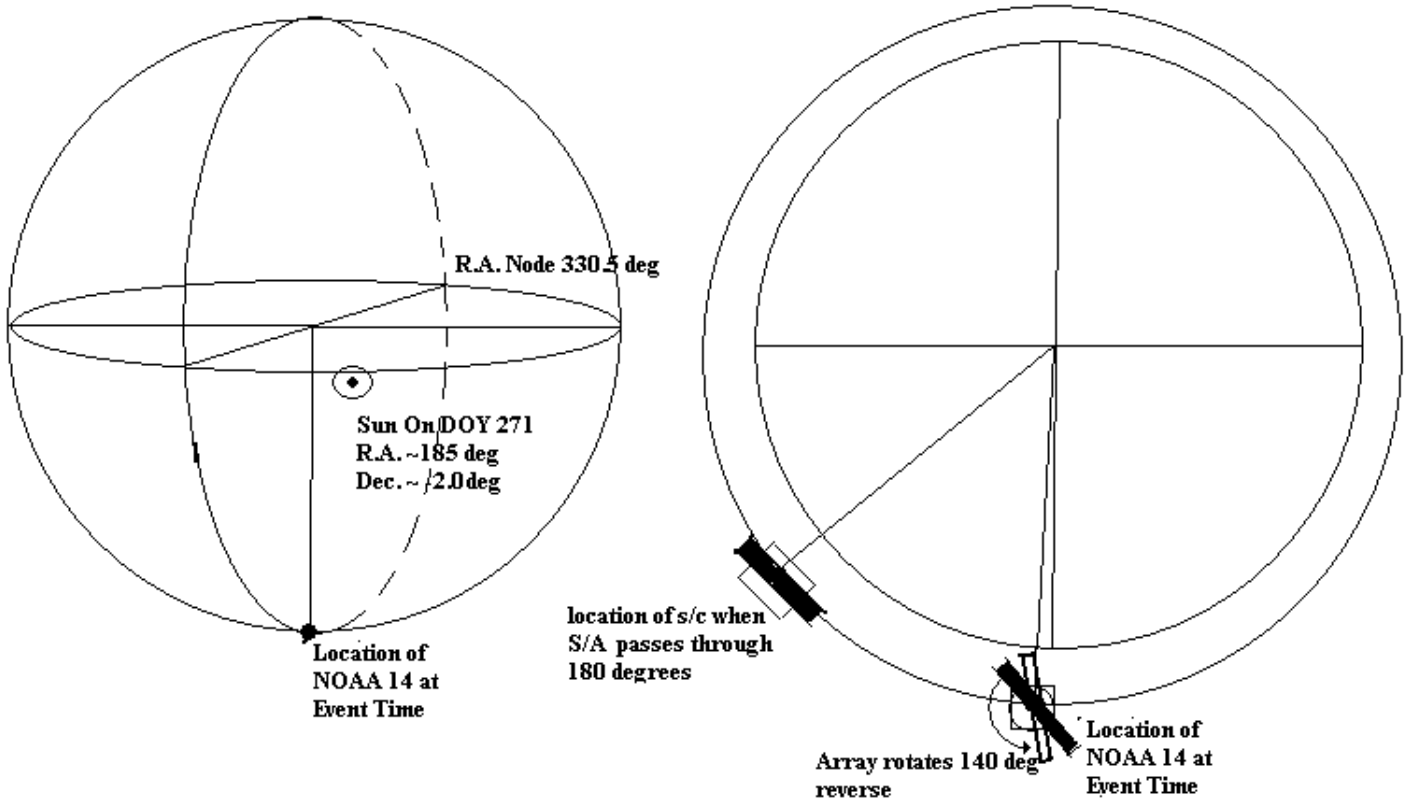
Note: THIS FIGURE DEPICTS 26.5 Ah BATTERY PACKS. THE NEW Ah BATTERY PACKS OCCUPY THE SAME LOCATIONS. THE NEW PACKS HAVE FIXED-AREA RADIATOR AND NOT LOUVER/RADIATOR ASSEMBLIES AS SHOWN.



▼ TCE CONTROL THERMISTOR; DENOTES TCE #.
■ TEMPERATURE TELEMETRY POINT
(...) = TIP ADC

Solar Array and Orbital Geometry



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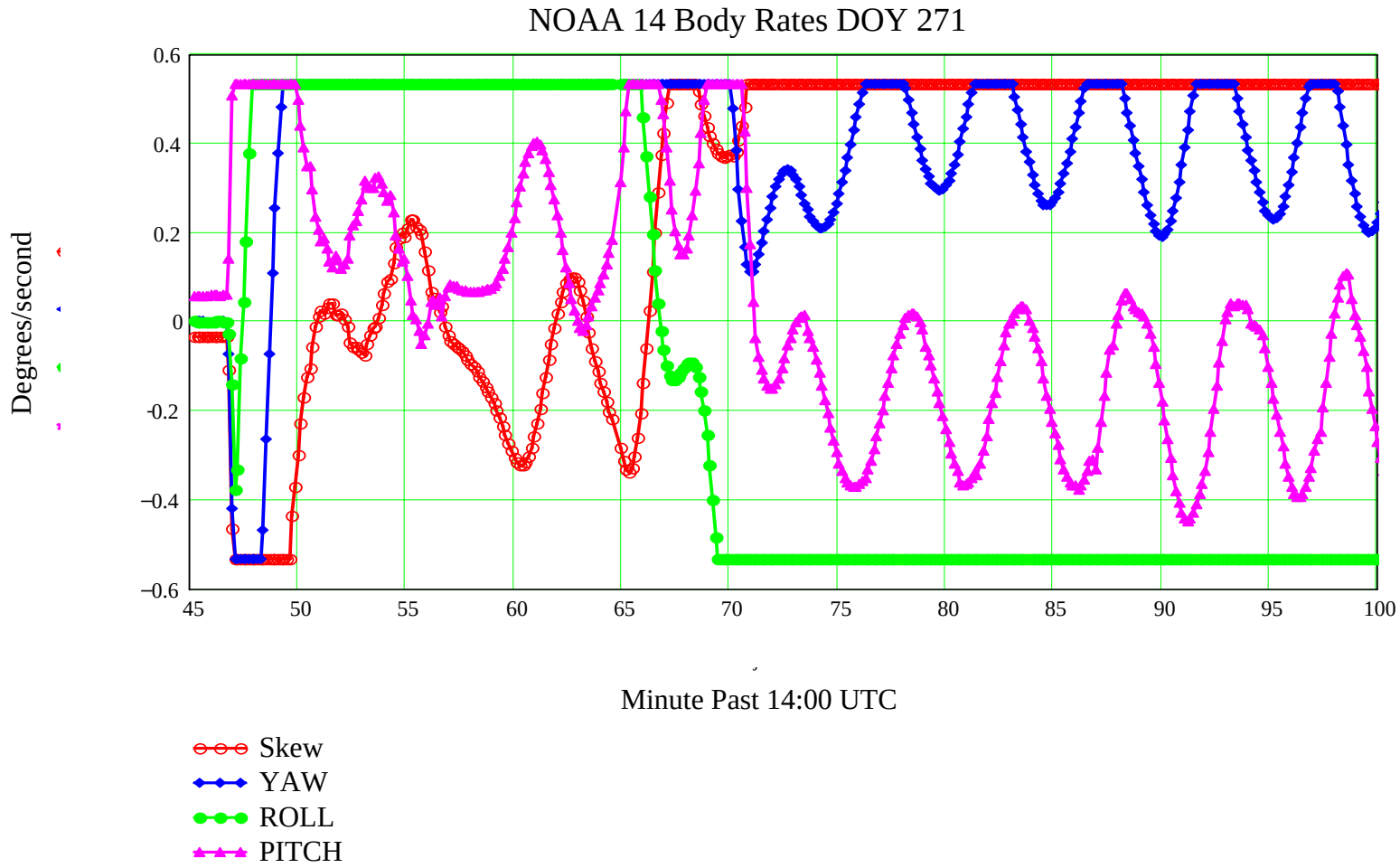
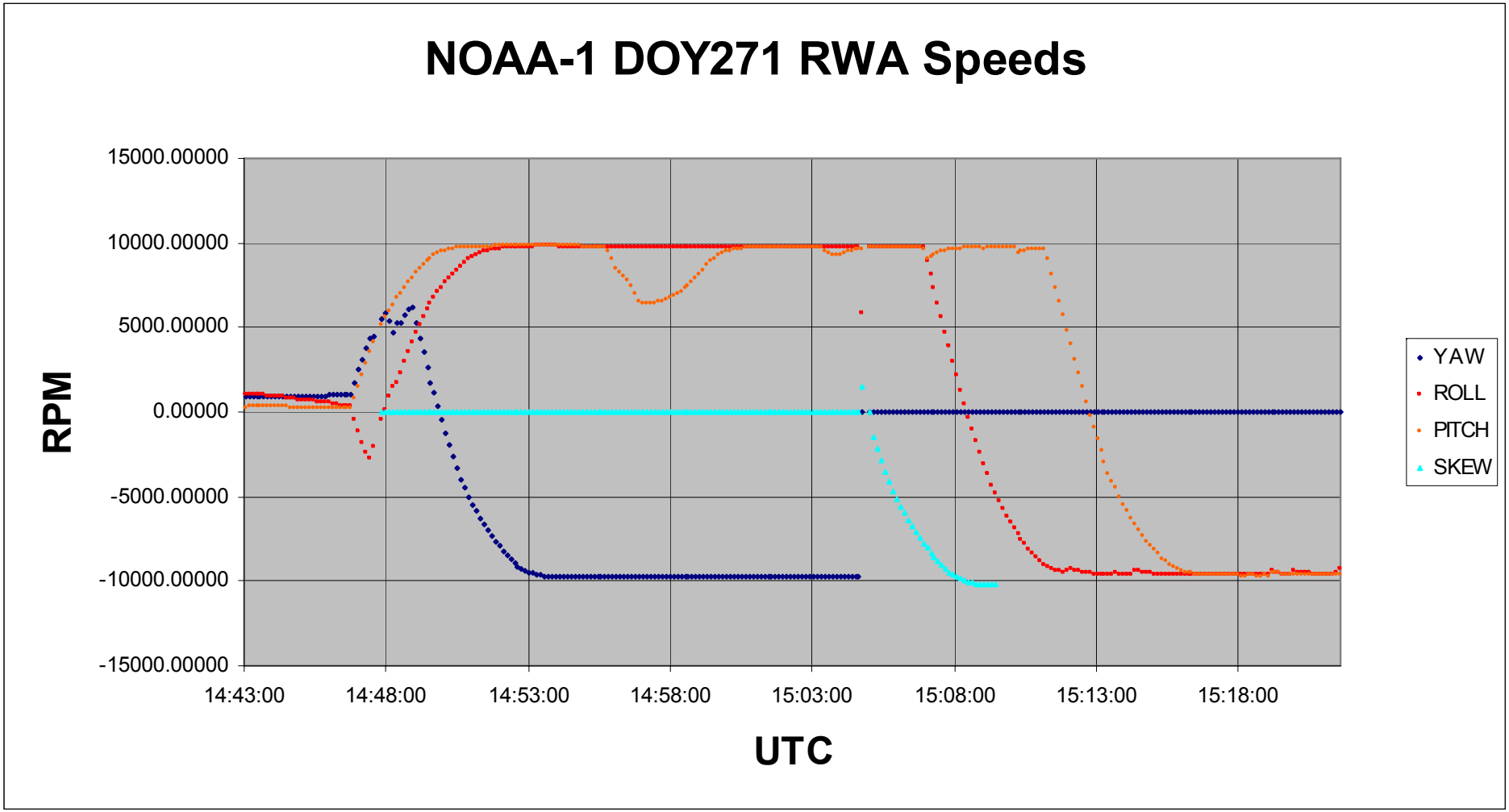
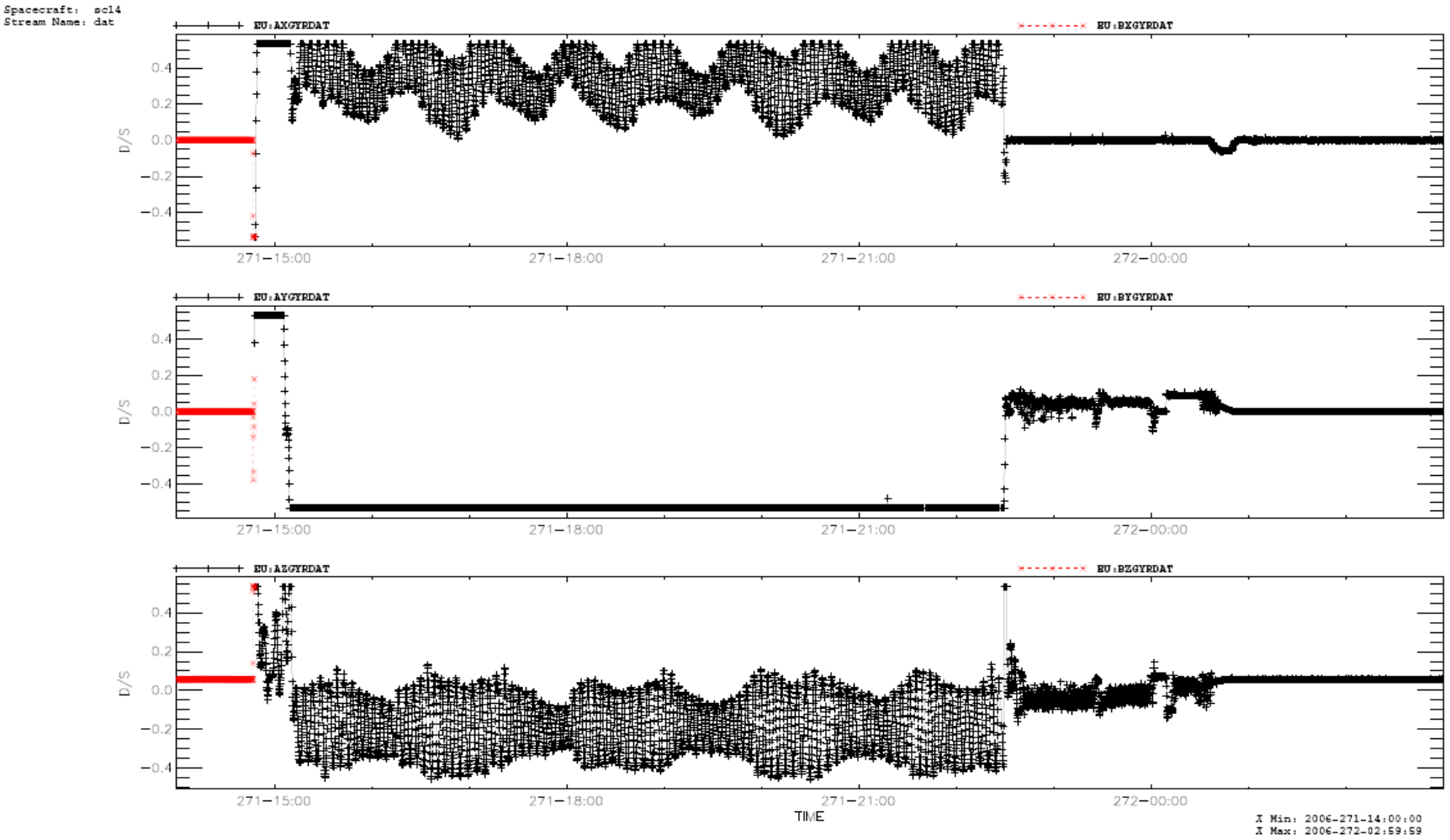



NOAA-1 DOY271 RWA Speeds
15000.00000
10000.00000
5000.00000
0.00000
-5000.00000
-10000.00000
-15000.00000
RPM
14:43:00
14:48:00
14:53:00
14:58:00
15:03:00
15:08:00
15:13:00
15:18:00
UTC
YAW
ROLL
PITCH
SKEW

Flat Spin Stabilization



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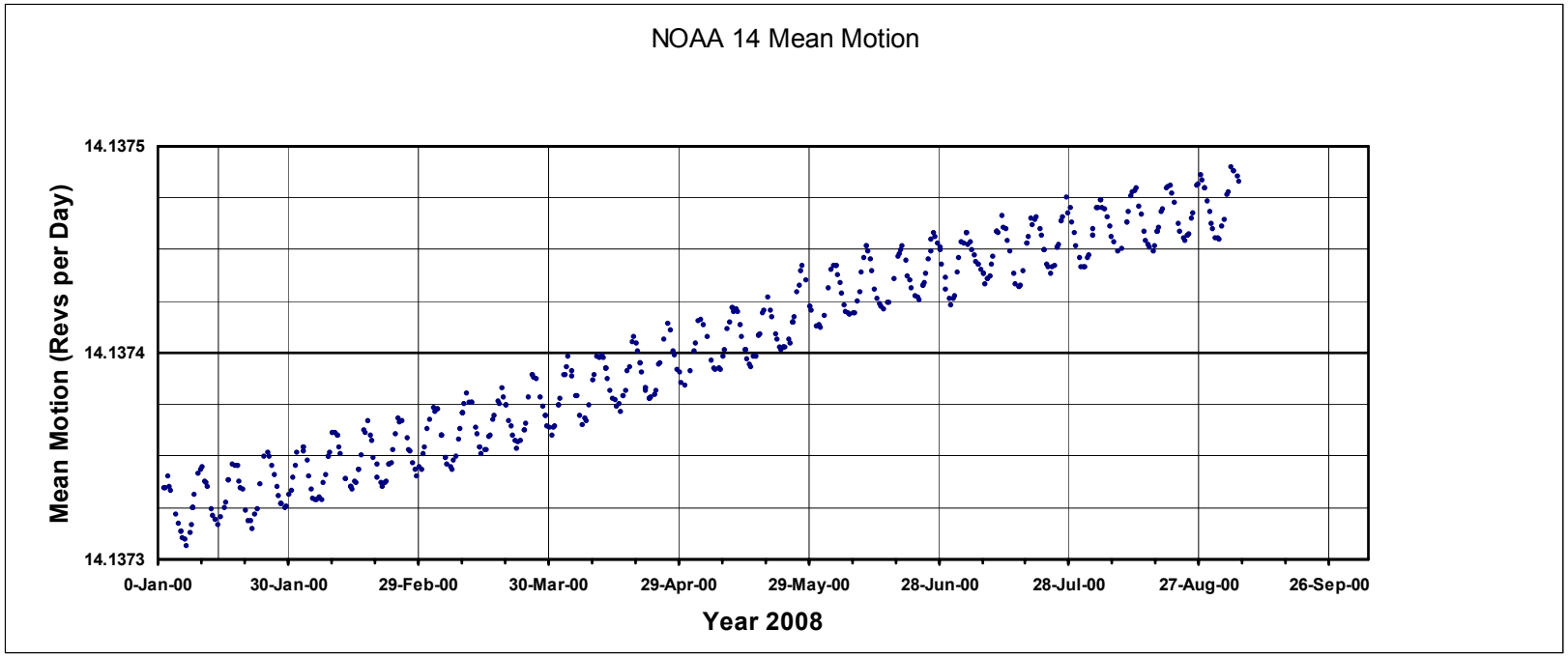

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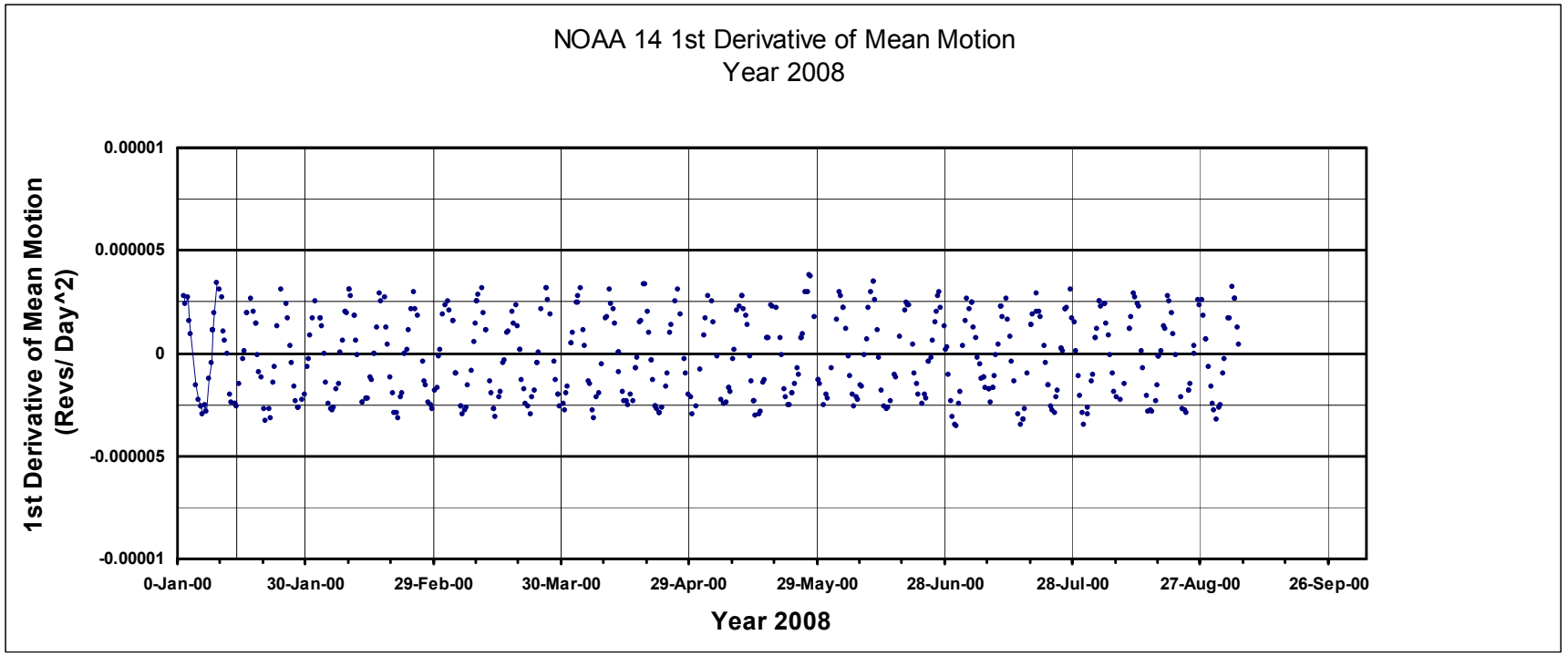
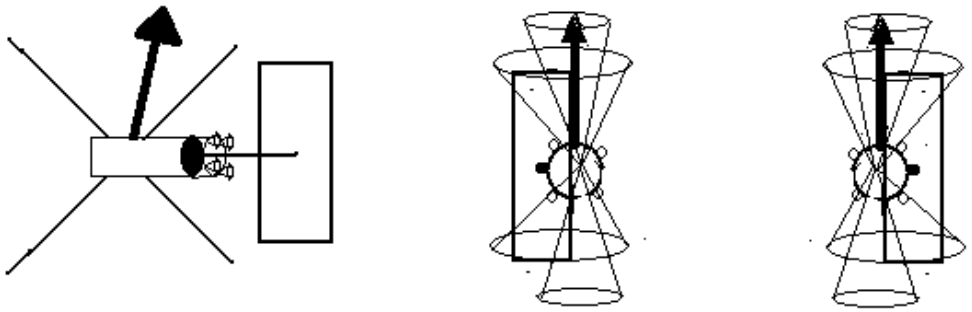


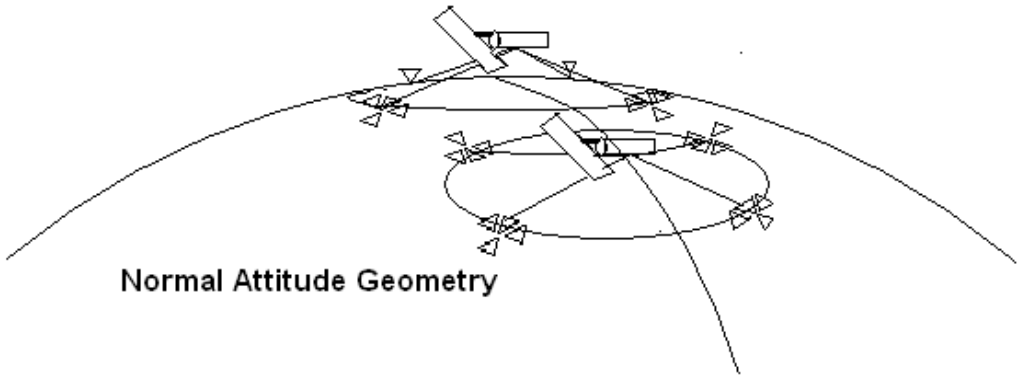
Analysis of the Earth Sensors and Their Data

- The Earth Sensor is the Barnes Earth Sensor Assembly (ESA)
- Nominally, 4 quadrants of the ESA sense the IR Horizon 45 degrees from the flight path fore and aft of the spacecraft sub-satellite point and 63◦ from the nadir vector.
- When spinning at 12 RPM along the roll axis these sensors become Earth IR Scanners with cone angles of; 116◦ , 132◦ , 53◦ , 35◦ for Q2, Q3, Q4, and Q1 (B-sensors) respectively.
- Thus after flat spin stabilization, periods of Earth sensor data with all space and all Earth are clues to the approximately inertial spin axis attitude, (remembering that the Earth angular radius is about 63◦ .

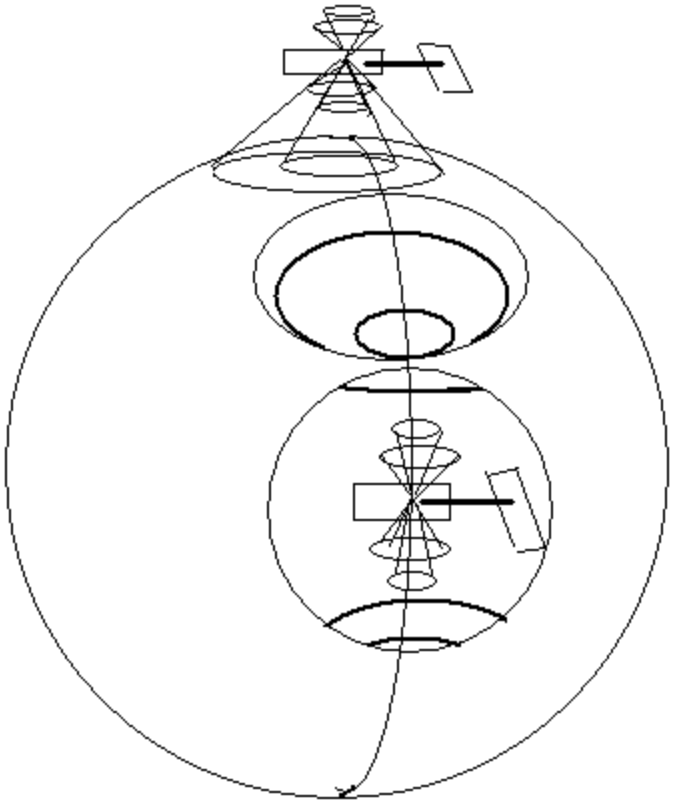
Earth Sensor Geometry Orbital View



Spin Attitude for Three Phase Angles

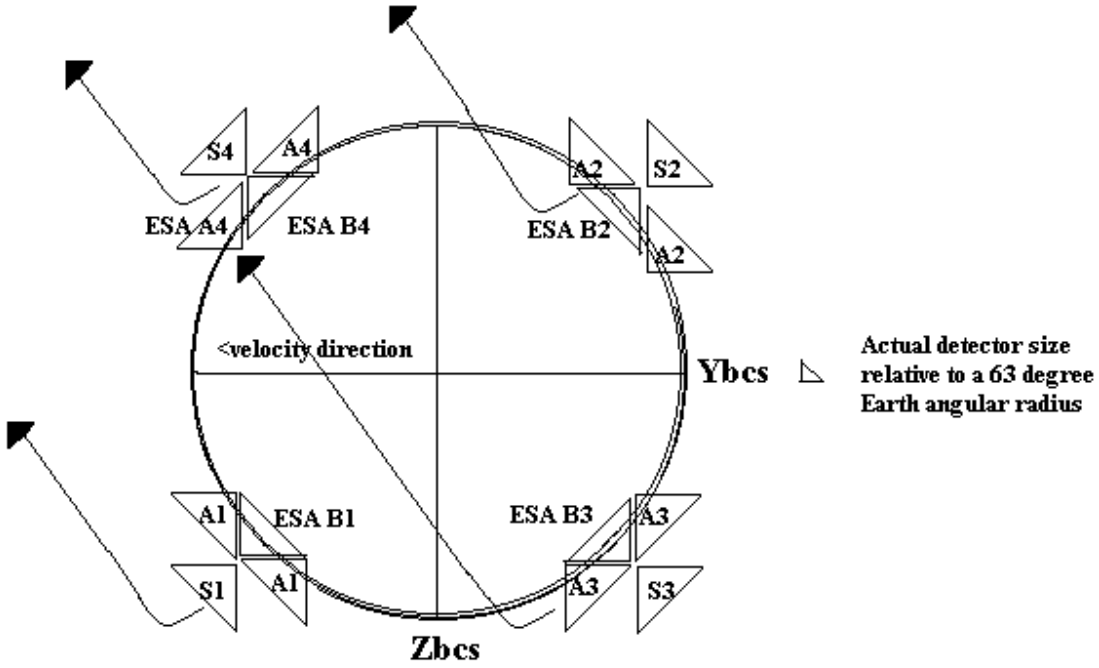


Normal Attitude Geometry



ESA Earth Cuts versus Orbit Angle

Earth Sensor Geometry Showing the Initial Disturbance Effect (not to scale)



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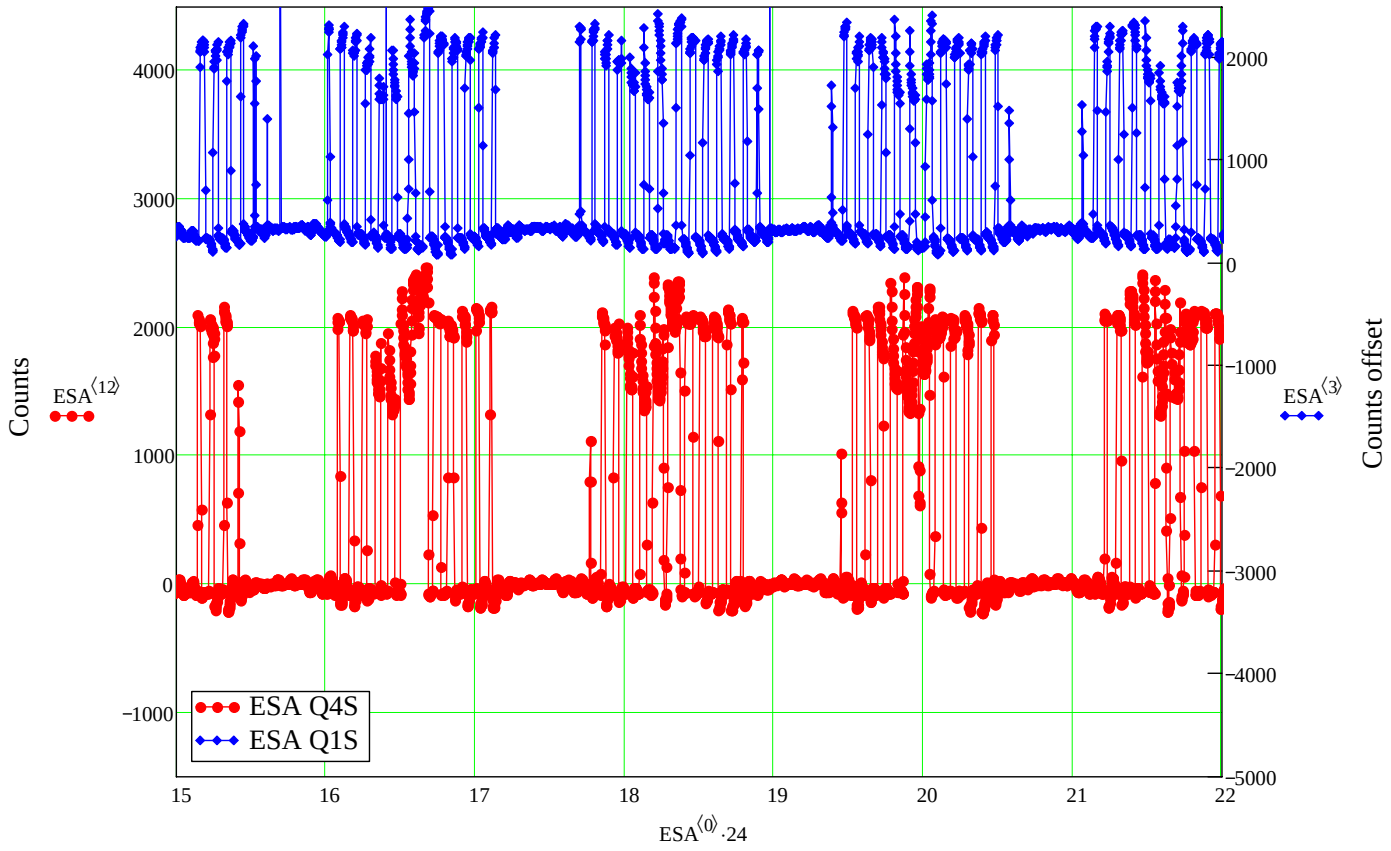
ESA Space Sensor Quadrants 1 and 4 (Forward)



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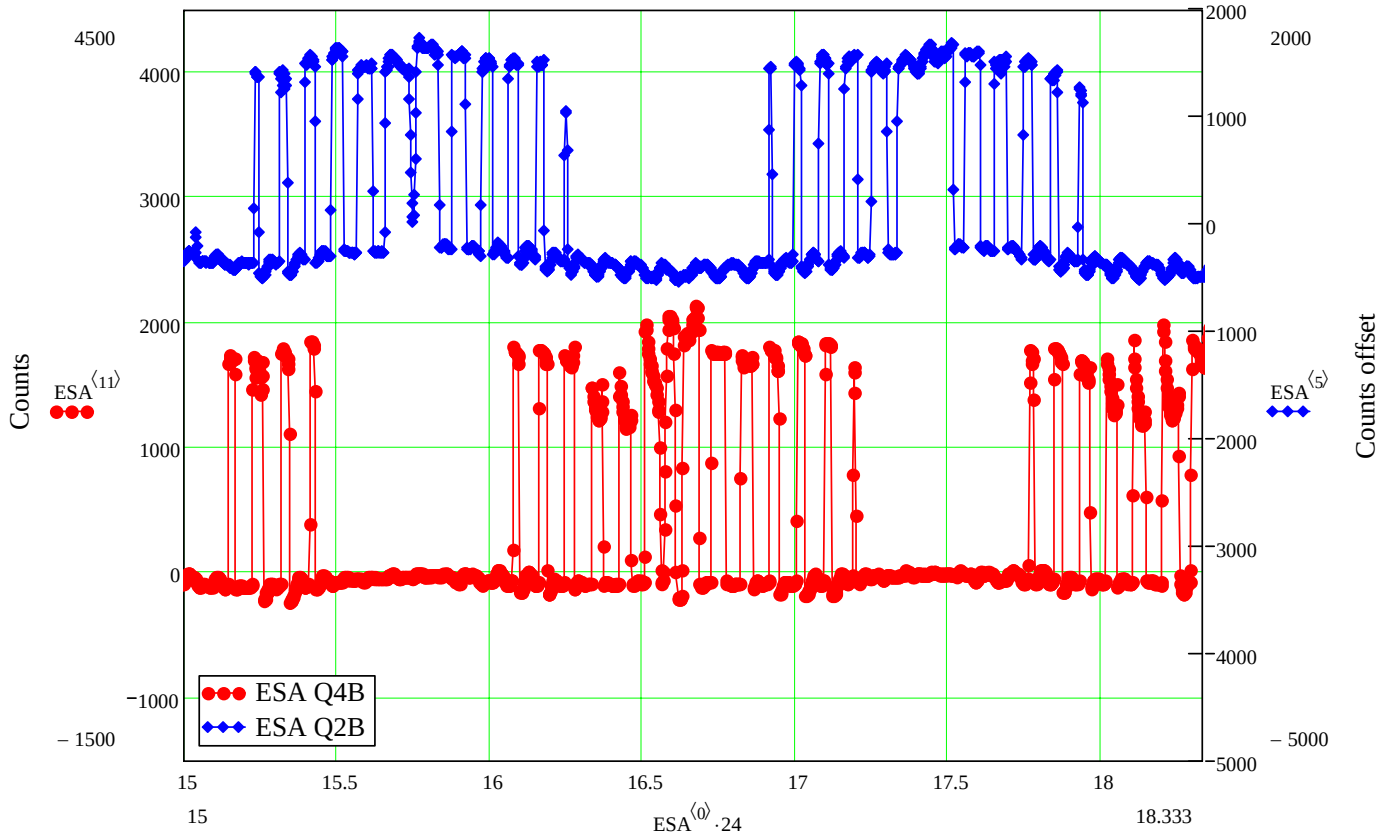
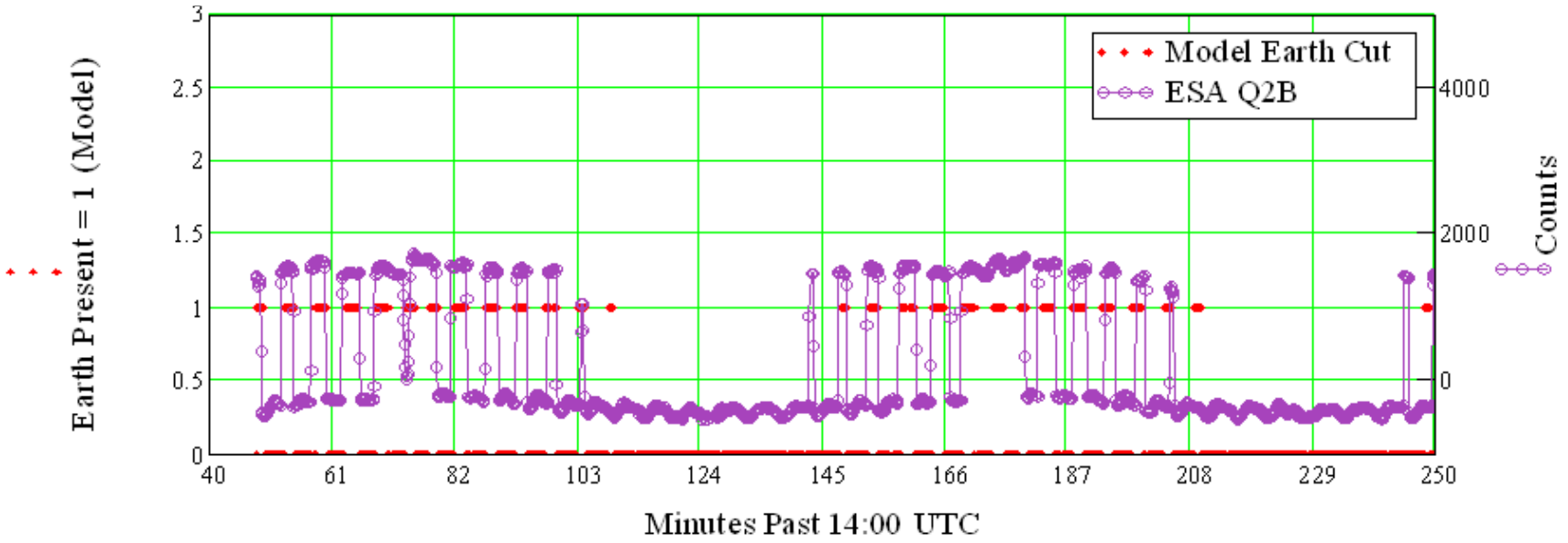
The ESA as and IR Earth Scanner Quadrants 2B (aft) and 4B (forward)



Modeling the ESA Data to Assure Understanding

- The ESA Model:
  - Reconstructed Spin Rate Vectors in the body frame measure motion about an approximated inertial angular momentum vector.
  - Point sensor located at the center of the triangular shaped space sensor for each quadrant.
  - Only the space sensor was consider for this representative case.
  - Because of this, the model does not exactly track the data when the space quadrant sensor is tracing complete circles on the Earth.

Earth Sensors Earth Cuts Modeled for Spin Vector Attitude



The Analysis of the Total Angular Momentum

- Total angular momentum could not be determined from RWA spin rate and gyro rate data because the roll gyro rate was saturated.
- The body roll rate was computed approximately using solar array current sensor data.
- A crude reconstruction of all saturated gyro rate data was performed to reconstruct the body rate vector.
- Using the reconstructed body rate, the total angular momentum vector is traced in the body frame.
- The inverse of this is the motion of the body in the inertial frame

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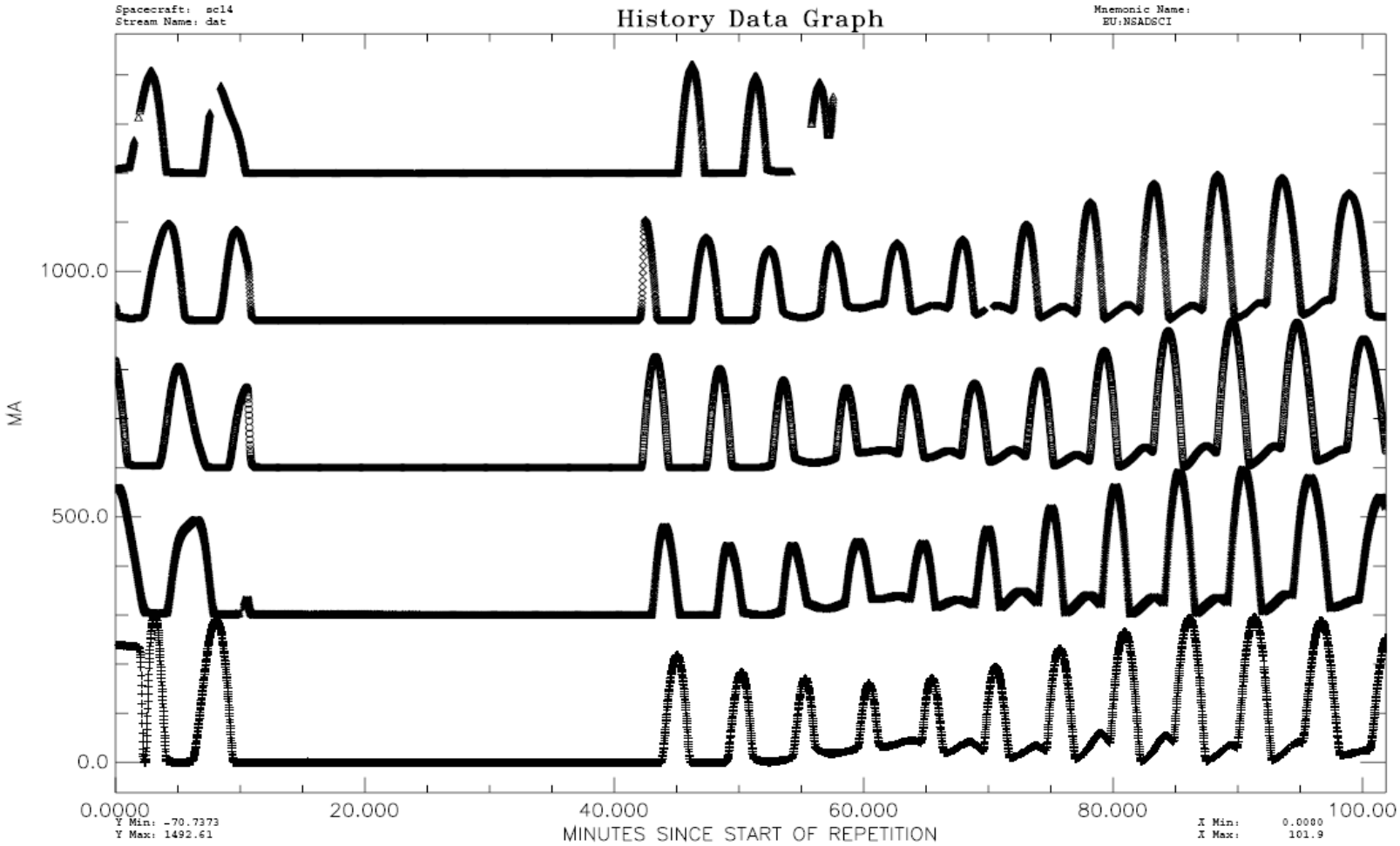
Solar Array Current Determines Spin Rate



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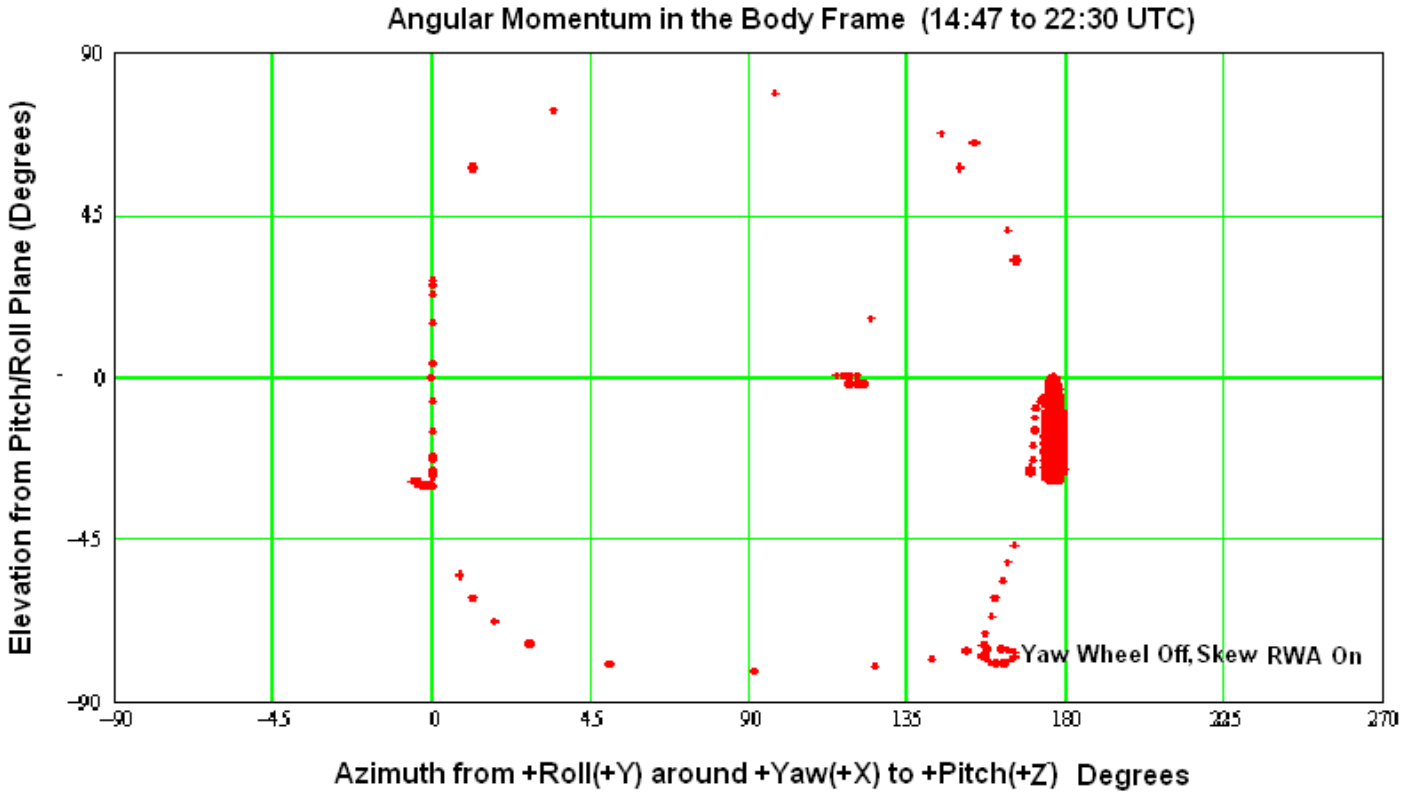

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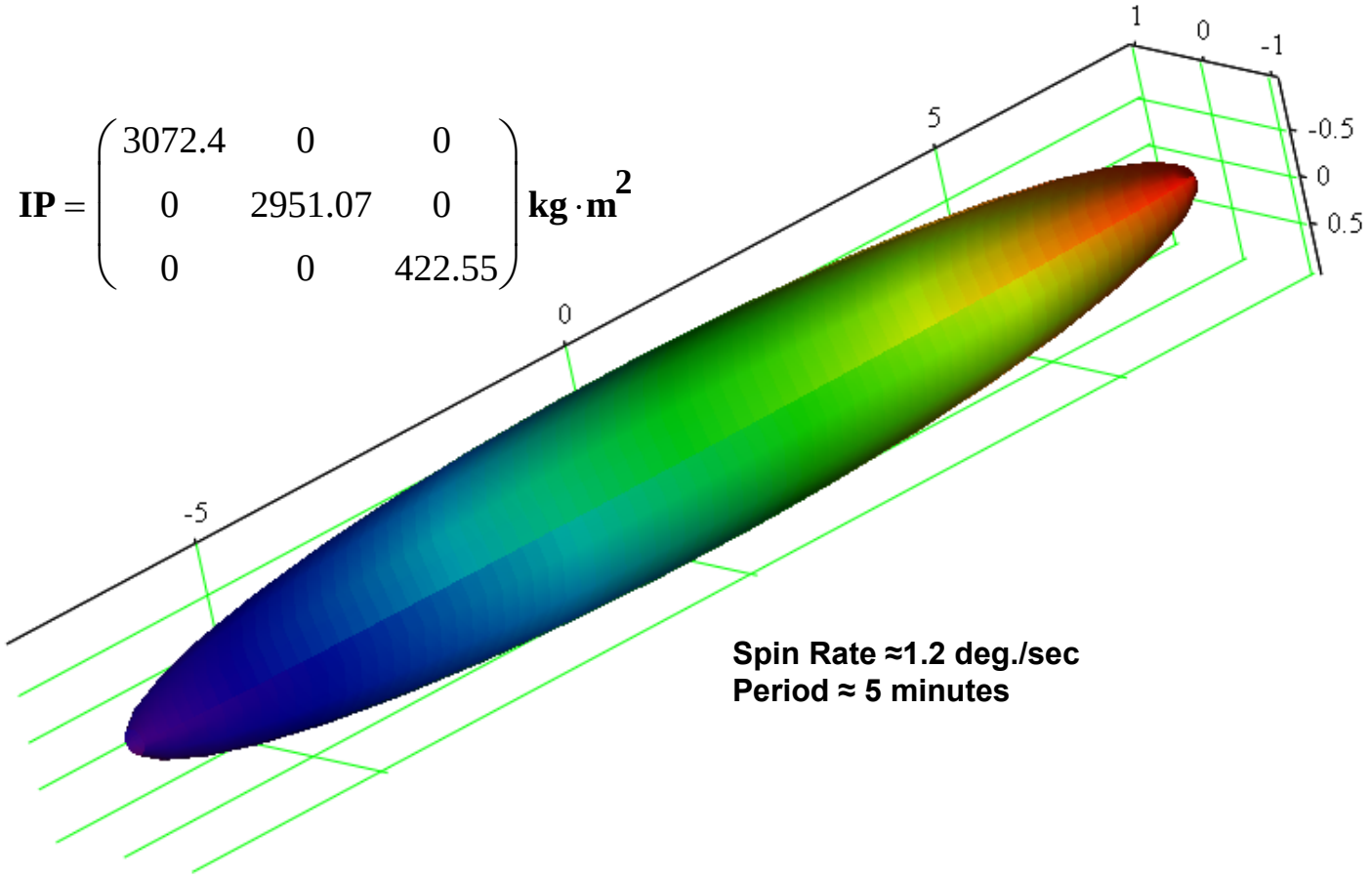
NOAA 14 Principal Moment Of Inertia Ellipsoid

$$\mathbf{IP} = \begin{pmatrix} 3072.4 & 0 & 0 \\ 0 & 2951.07 & 0 \\ 0 & 0 & 422.55 \end{pmatrix} \mathbf{kg \cdot m^2}$$



Spin Rate ≈1.2 deg./sec
Period ≈ 5 minutes

Payload and Bus Effects

- The NOAA 14 has remote sensing payloads susceptible to damage from extended periods of exposure to the Sun:
  - The High Resolution Infrared Sounder (HIRS) with radiative cooling of IR sensor
  - The Advanced Visual High Resolution Radiometer (AVHRR) with similar radiative cooling for fewer IR channel detectors.
- Data shows:
  - The HIRS was immediately “safed” to assure no IR detector damage from sunlight in the cooler radiator causing the early loss off telemetry.
  - The AVHRR remained “ON” to illustrate that extreme temperature were not reached until the de-spin recovery achieved Earth lock.
- Computed Battery Depth of discharge indicated the batteries reached negative DOD (a calibration error that probably means the actual capacity was over estimated) *No data for this is available*

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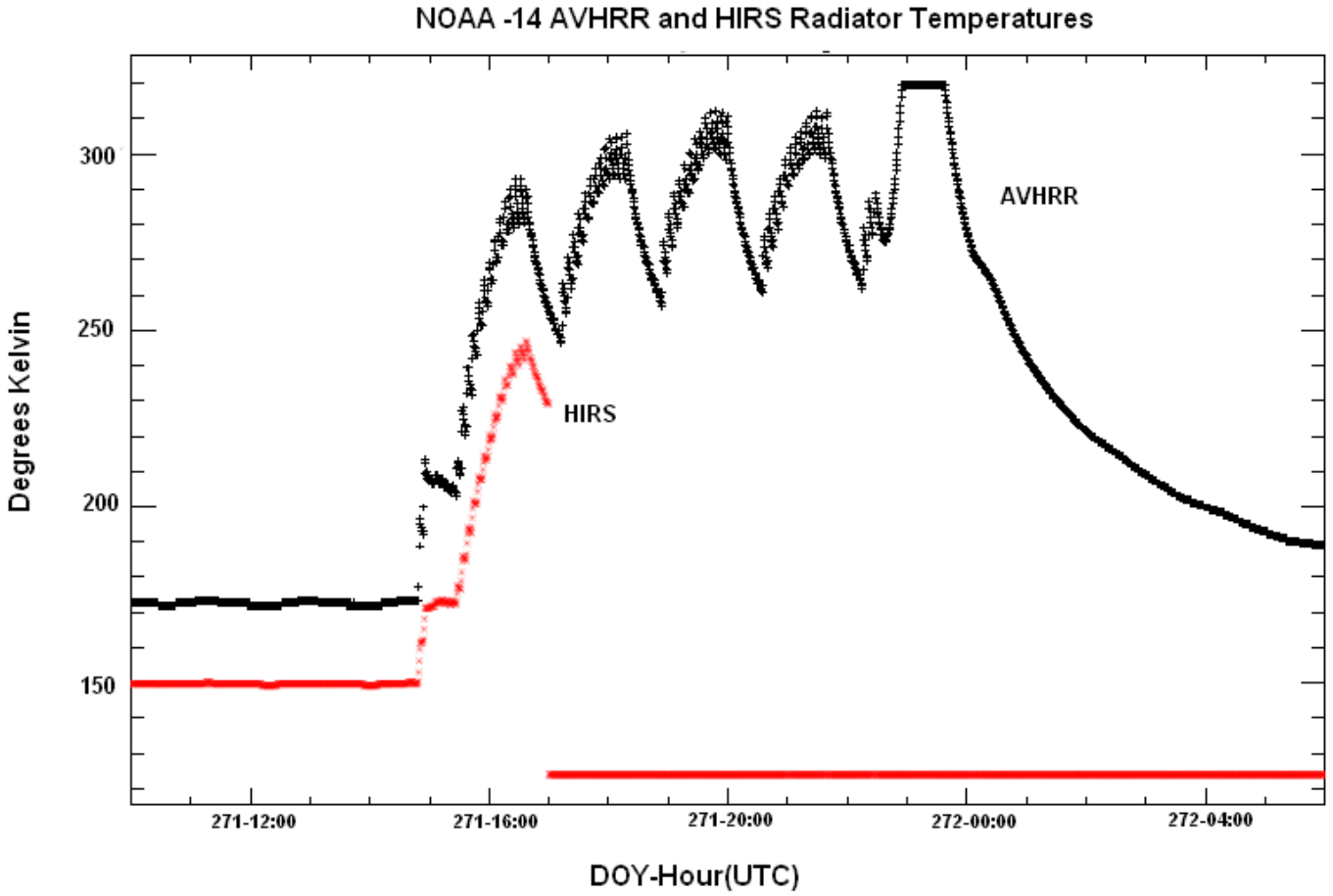
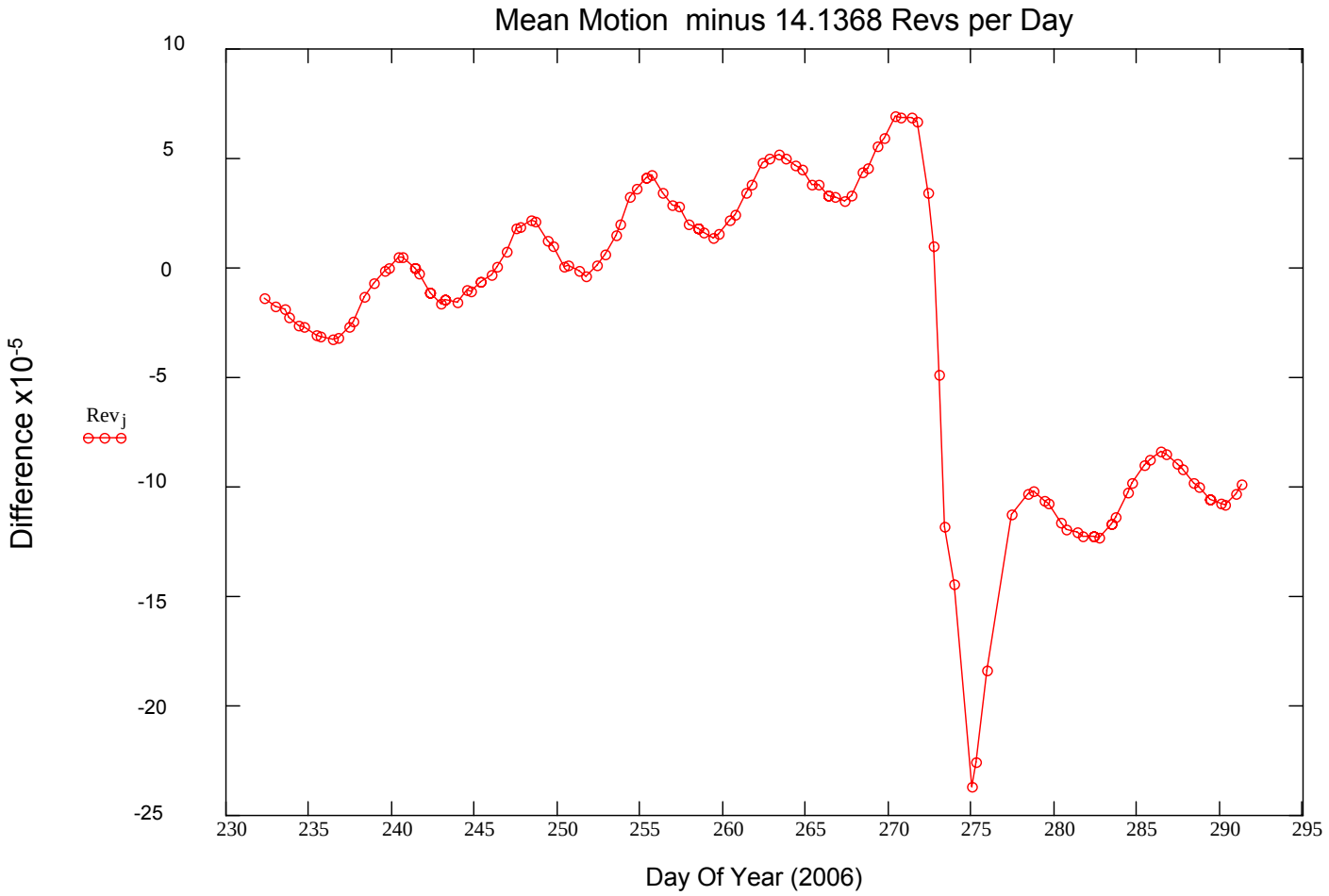


NORAD Two Line Elements Provide Additional Evidence



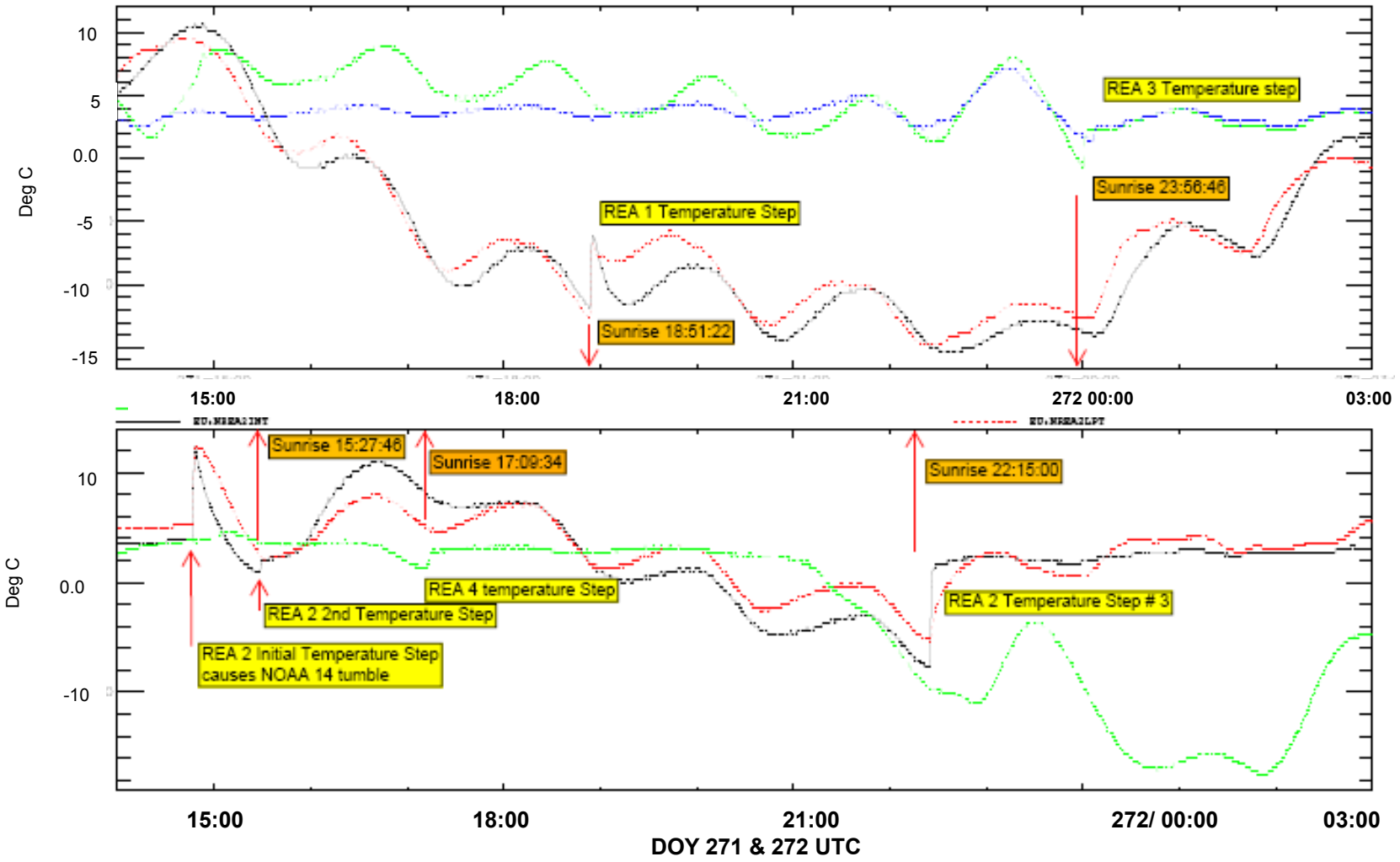
Root Cause

- The large angular momentum impulse and solar array spin back of 140 degrees in 45 seconds was caused by the release and ignition of hydrazine propellant from the REA # 2 and deflection of the plume from the canted solar array causing a windmill torque.

- This phenomena had been experienced on NOAA -17 twice in 2005 when manageable angular momentum impulse were thought to be debris hits but were subsequently determined to be ignition of hydrazine from leaks on REA #2 and #4 on DOY 324 and 342 respectively.

- This root cause points to another much earlier source of the problem. That is hydrazine venting and isolation procedures just after orbit insertion at the beginning of the mission were insufficient.
  - Propellant venting was incomplete or did not occur.
  - Subsequent thermal management of isolated hydrazine remnant was not planned
  - Thermal modulation of this propellant by Day/Night transitions and solar array occultation may have contributed to the failure of the thruster valve seals.

The Propellant System Response to the Hydrazine Leak Ignition



Lessons Learned

Spacecraft Propulsion Systems Isolation

- Initial propellant isolation and venting procedure failed to vent the hydrazine remaining in the manifold after it was isolated.

Mission Operations Contingency Planning

- The potential for this anomaly exists on NOAA- 17 and -15 which have the same REA system. NOAA -18 did not require this system to achieve mission orbit and thus does not have an isolated hydrazine system.
- The most dangerous period to the spacecraft and payload was after the de-spin to acquire the Earth.
- Thus if initial analysis, (in this case from real time data) shows that the spacecraft was power and thermally safe and that the payloads were also safe, a more relaxed approach to the schedule for recovery should be considered.
- The onboard autonomy was ineffective in this case.
- Consideration should be given to include in onboard protection logic the possibility that no components have failed and the sensors are consistent and that a propulsion system anomaly has occurred.