



Recent On-Orbit Anomalies Affecting EOS Terra and Wilkinson- Microwave Anisotropy Probe (W-MAP) Missions

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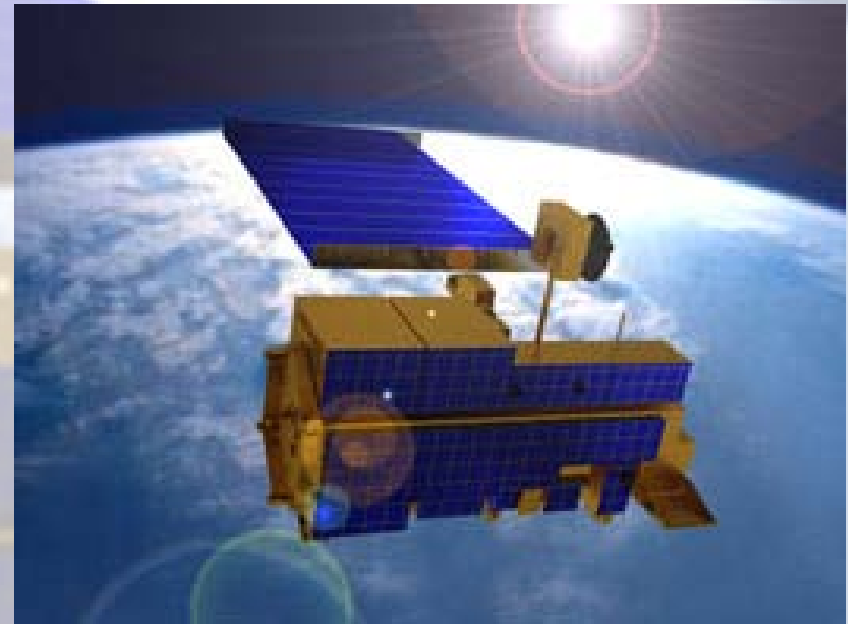
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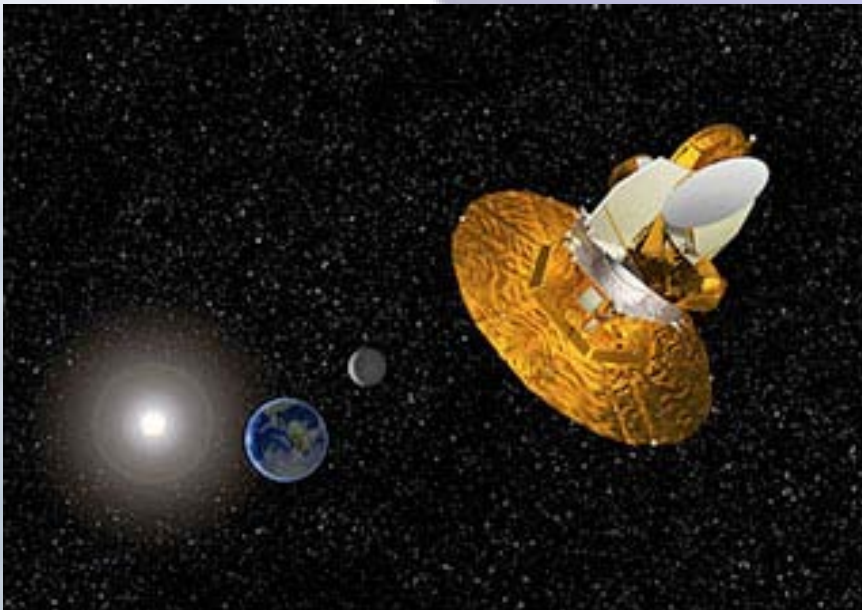
EOS Terra Background

- EOS Terra observatory launched in December, 1999.
- Low Earth Orbit Polar Mission, 98 degree inclination (99 minute orbit).
- Baseline Mission Duration 5 years, Goal 7 years.
- Power System Architecture: 2500W, 120V dc regulated bus.
- Solar array: Deployable flexible array utilizing single junction GaAs solar cells.
- Energy Storage: Two 54 series NiH2 50 amp-hr IPV cell batteries.

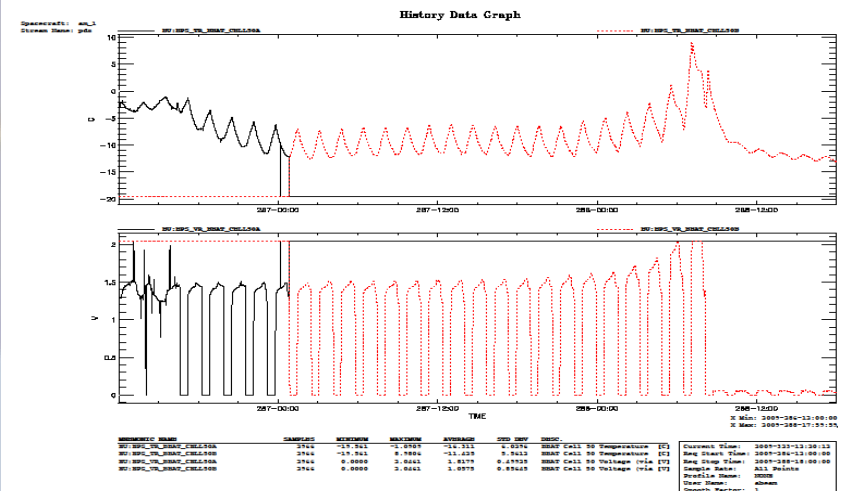
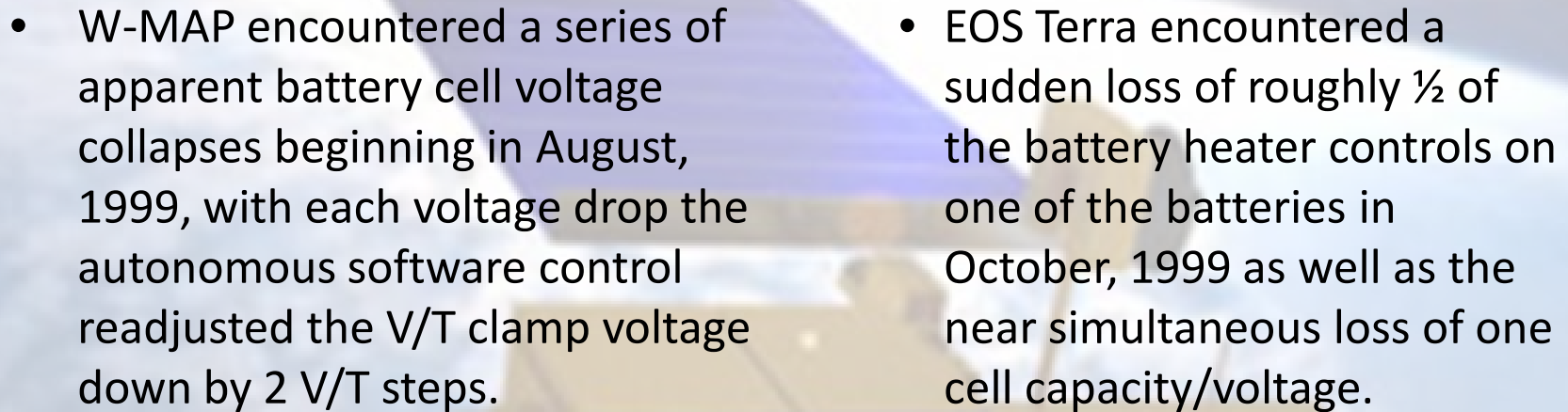
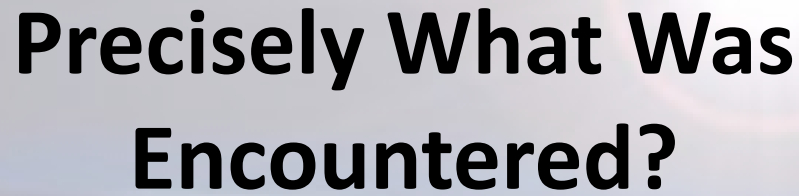




W-MAP Background

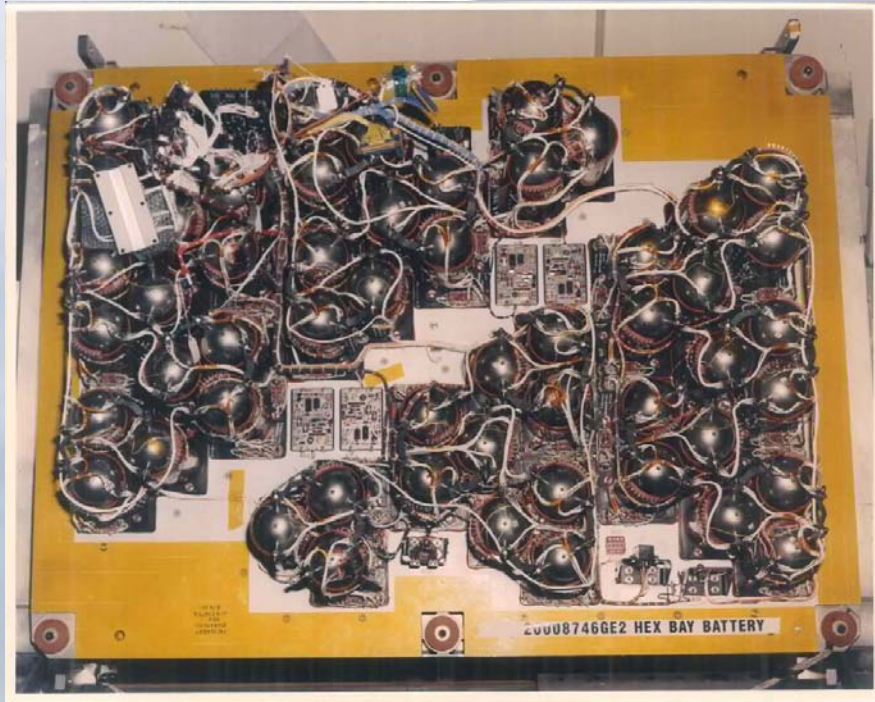


- W-MAP observatory launched in June, 2001.
- Orbit: L-2
- Baseline Mission Duration 2 years.
- Power System Architecture: 400W average power, 28V dc DET unregulated bus.
- Solar array: Deployable flexible array utilizing single junction GaAs solar cells.
- Energy Storage: One 11 CPV series connected NiH2 23 amp-hr battery.





What Was Affected?

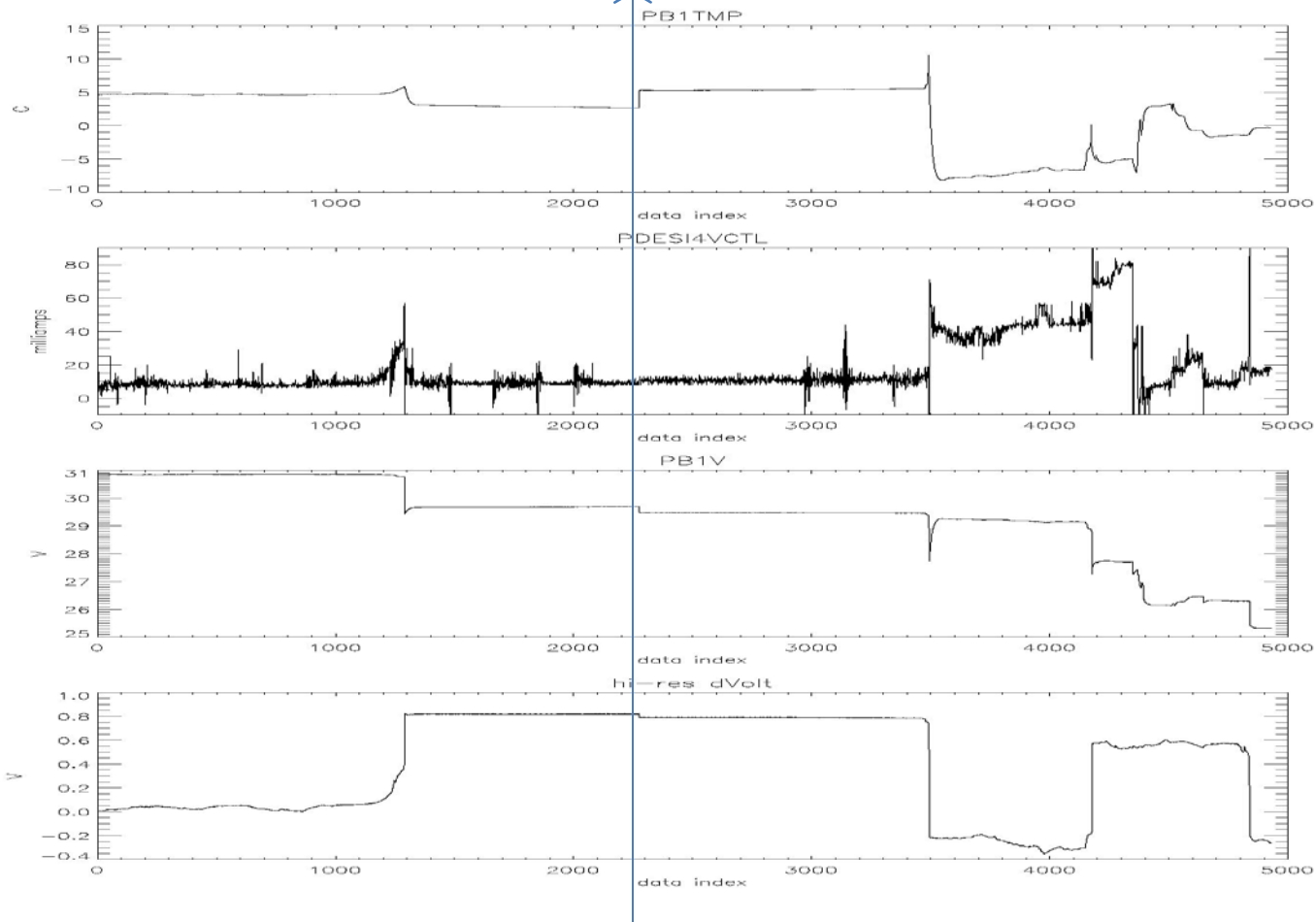


EOS Terra Battery (left) – W-MAP Battery (right)



Details on W-MAP Anomaly

Roughly 7 year data span not shown between arrows



Temperature/Voltage/Current data from June, 2001 to October, 2009, of note battery voltage drops near end of plot.



OK, So What Happened?

- After examining the telemetry that was available from W-MAP, there were two basic theories as to why the battery voltage was collapsing:
 - One theory was that the cells were overcharged for an extended period and O₂ was being generated and degrading the performance of the cell plates (concern over potential “popping” issues and subsequent damage/blistering).
 - The second theory was that the cells were severely undercharged and merely required some form of boost charging to recover and resume nominal operations (with a higher constant trickle charge rate required).



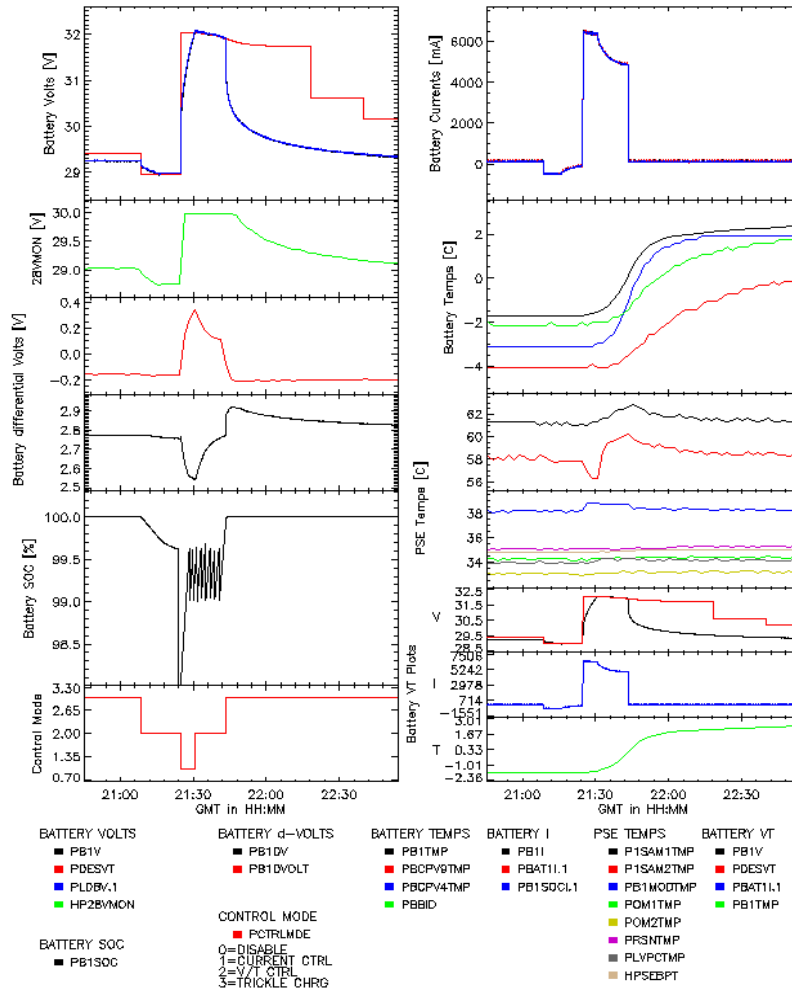
Which Was It?

- After the initial discharge/charge cycle was performed on the W-MAP battery, it became evident that the charge portion of the cycle resulted in a significant cooling effect on the battery (endothermic reaction).
- Considering that endothermic charge characteristics are normally associated with battery state of charge values well below fully charged, the theory of undercharged cells became the dominant favorite theory for addressing the continuation of operations of the mission.



And Then What?

SC PWR SYSTEM STATUS (1) for period ending 2009308 (November 04) 22:53 GMT

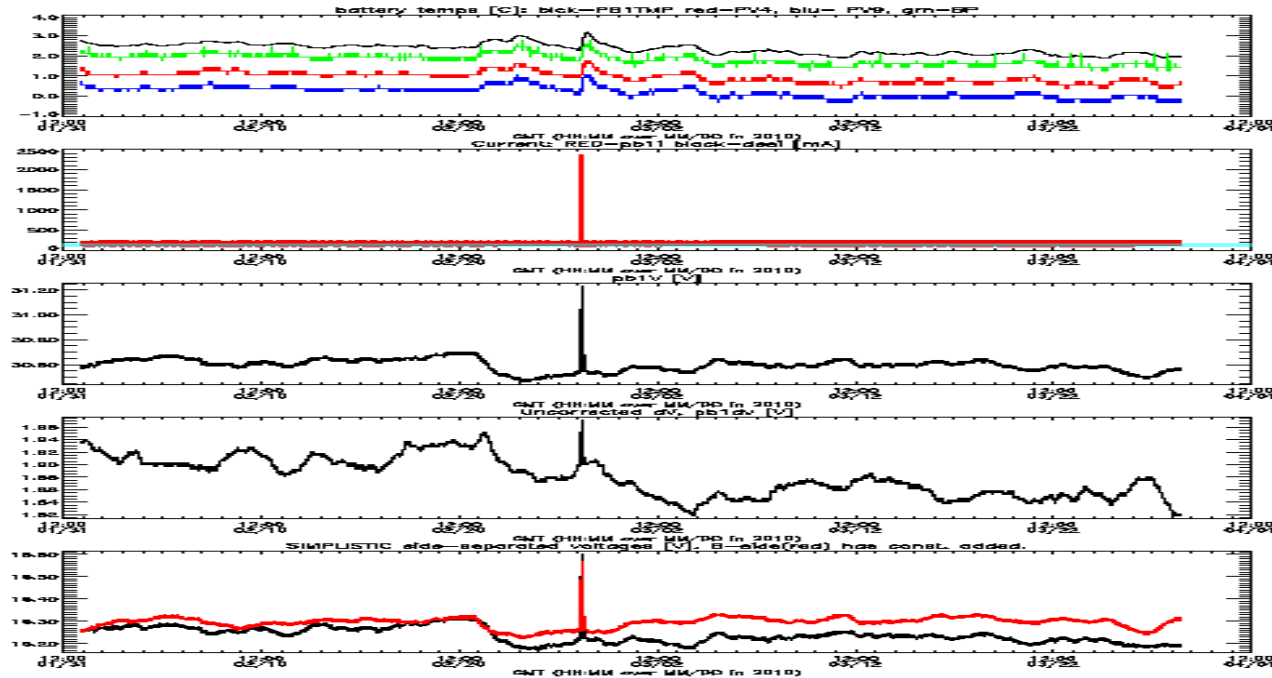


Plot generation date: Nov 04 2009 22:54:03 GMT

- Despite performing multiple charge cycles on the cells (and increasing the theorized state of charge well above the low state of charge associated with the knee of the voltage curve), cells would again collapse soon after charging.
- The prevailing theory was now forced to consider additional internal chemistry disorders that might explain the apparent inability to retain capacity.



How Does This W-MAP Story End?



- Repeated charge cycles have provided some stability to the W-MAP Battery characteristics although voltage stability is still somewhat elusive.
- Testing is underway on spare flight battery and old Ni-H2 cells to mimic conditions experienced by the flight battery in hopes of shedding some light on chemistry mechanism experienced.



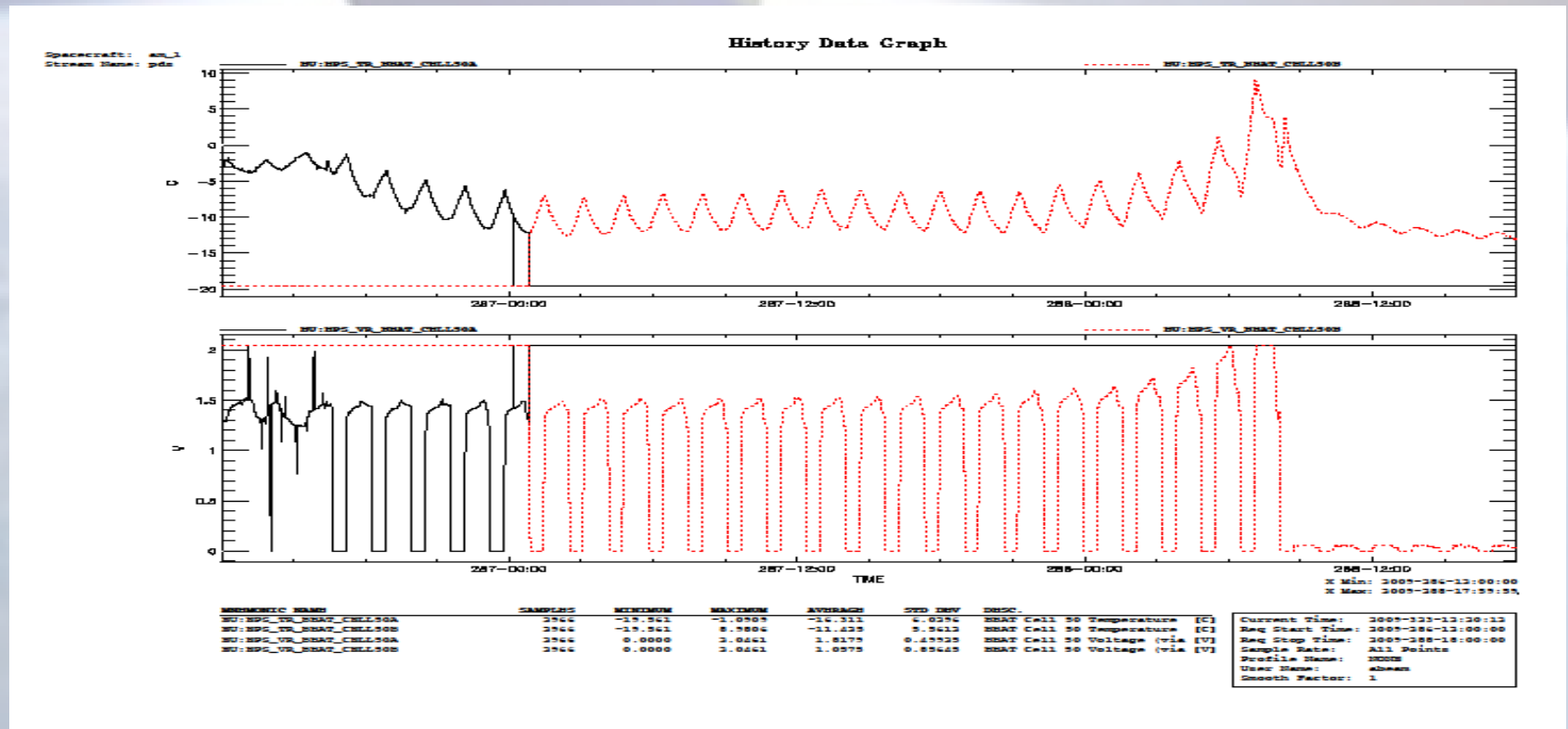
OK, What Happened to EOS Terra?



- During Day 286 (2009), the temperature control on one of the EOS Terra batteries indicated significant cooling (outside of control parameters) of multiple cells within the Hex Bay Battery.
- Flight Operations attempted both soft and hard resets of the Heater Control hardware without any change in temperature trend.
- Decision was finally made to switch sides to the redundant heater control, no significant change in thermal control occurred.



Details on EOS Terra Anomaly



Temperature and voltage data for EOS Terra Hex Bay Battery Cell #50 for period covering on-orbit anomaly.

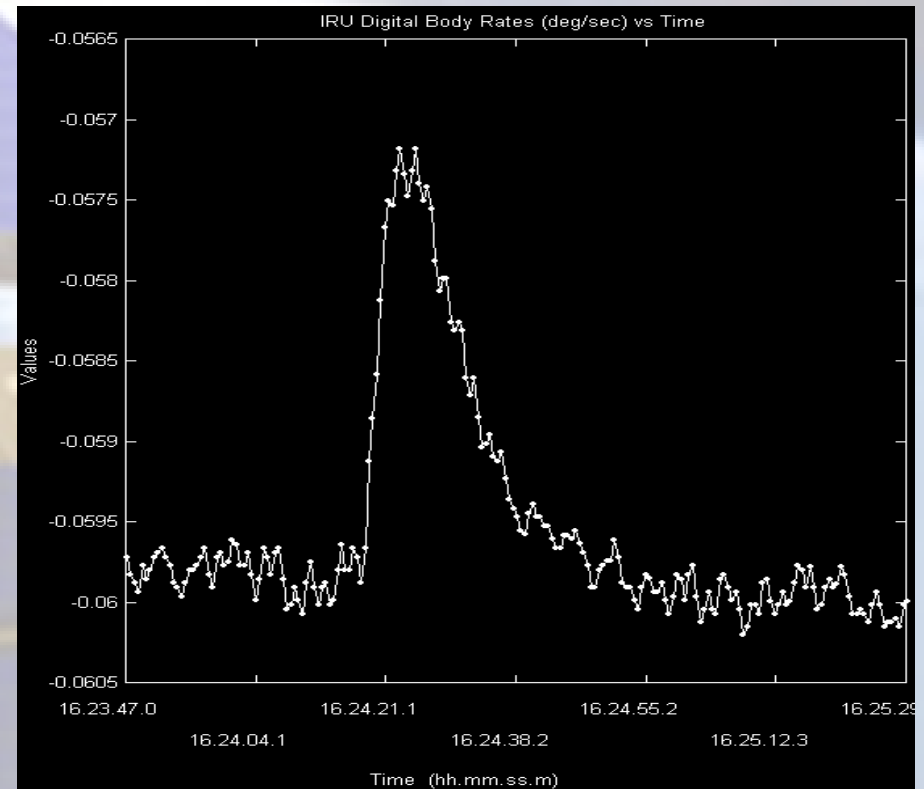
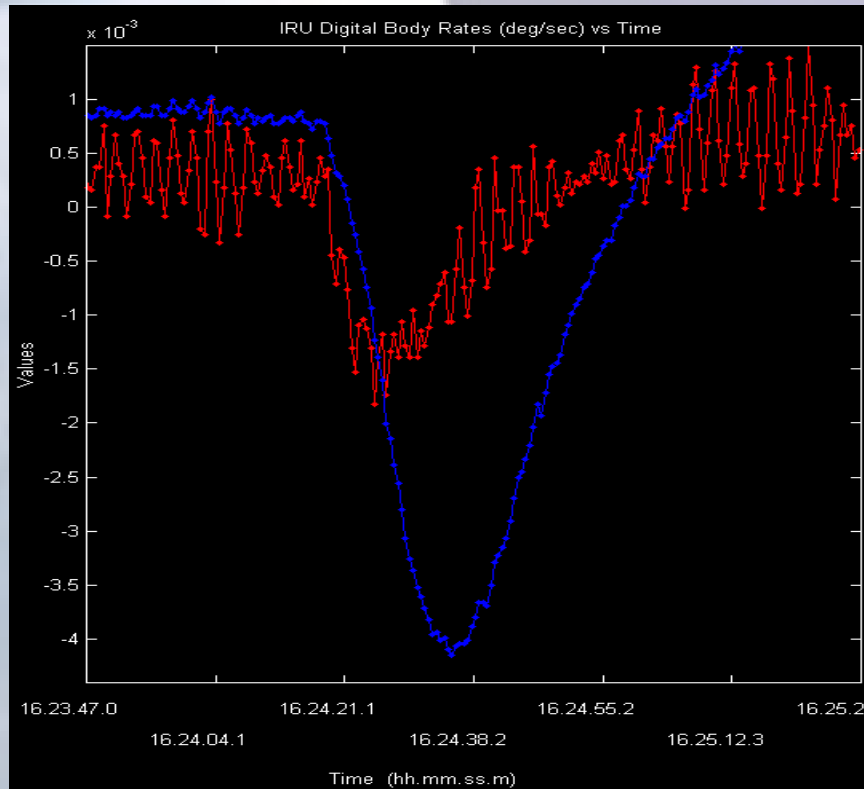


And Then What?

- Within two days Cell #50 ultimately appeared to reach a high enough internal resistance to trip the cell bypass switch.
- The only plausible explanation for an open circuit cell condition was loss of internal pressure, FOT asked to examine observatory 3-axis rate information for timeframe of anomaly.
- Working theory now involved possibility of debris/MMOD strike that could explain loss of heater control and cell response characteristics.



What Did The S/C IRU Rate Information Display?



Low and behold, IRU data confirmed unexpected 3-axis movement at time of anomaly.



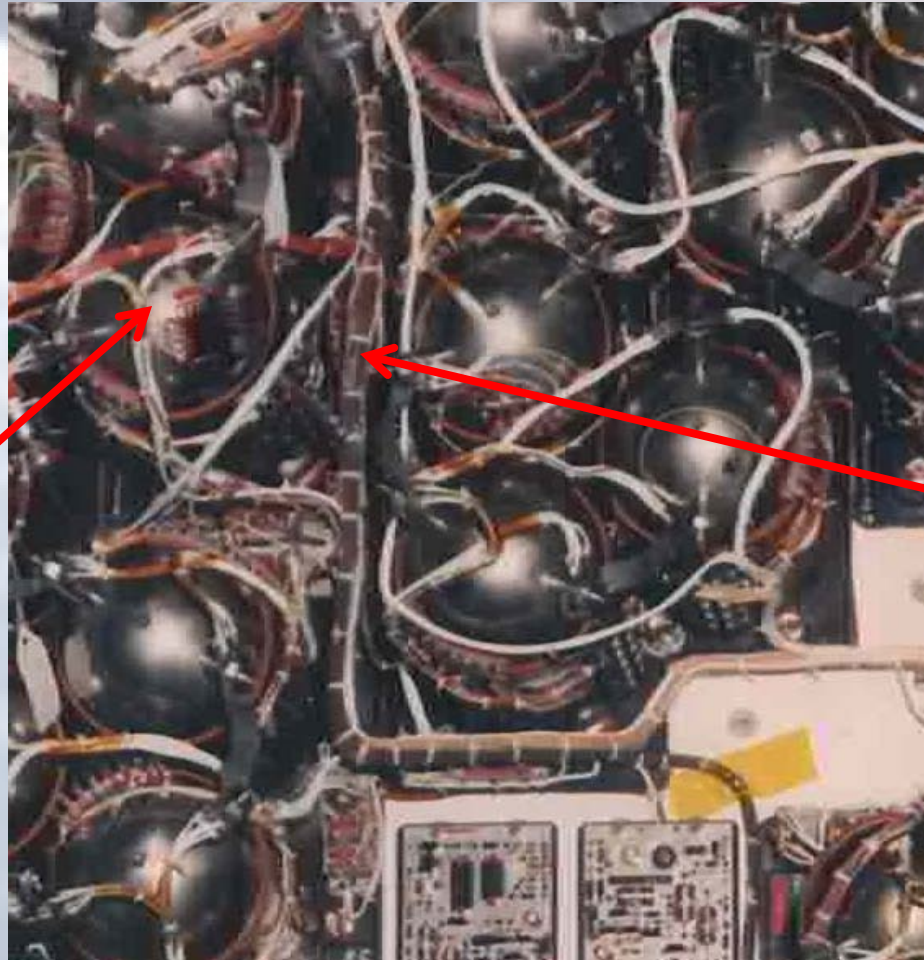
How Is That Possibly Related To Heater Control Loss?



- Heater power provided to cell heater groups by way of heater harness bundles throughout the batteries.
- Close-up examination of battery close out photographs reveal the possibility of collateral damage as a result of MMOD strike.
- Although documentation found to date indicates Cell #50 located in area without harness bundles adjacent to cell, working theory is that numbering scheme for cell identification was changed.



Close-Up View of Affected Area?



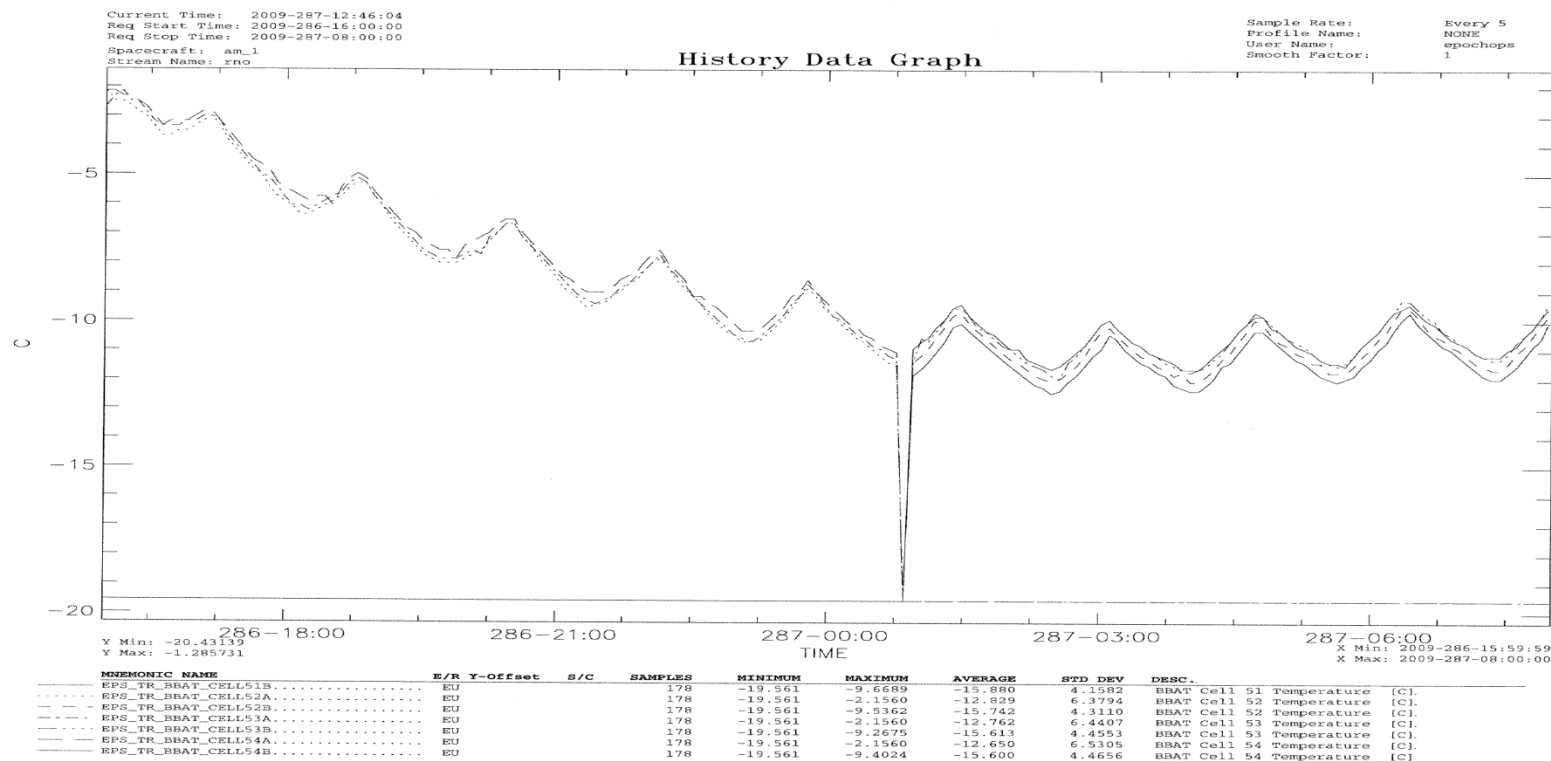
Cell #50

Heater harness bundle

With harness bundle so close to affected cell, likely collateral damage could have resulted in loss of partial heater control.



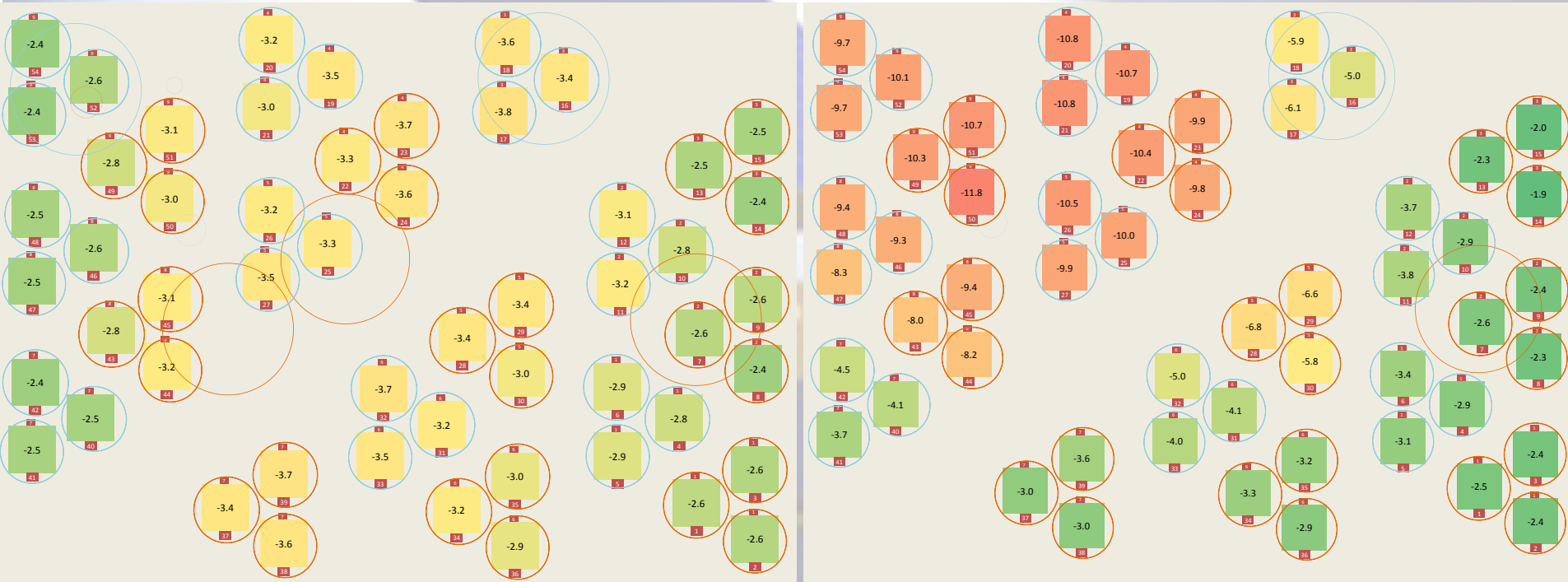
What Heater Control Impacts?



Temperature response (similar) encountered on 4 out of 9 heater groups on the EOS Terra BBAT – Group 9 shown, impact same on both prime and redundant sides.



Map of Cell Temperature Spread Before and After Anomaly



Left: Pre-anomaly typical thermal profile (1.43°C max spread).
Right: Post-anomaly thermal profile (8.93°C max spread).



How Does the EOS Terra Story End?



- After examining all potentially affected hardware and implementing a series of modifications to various heater group set point changes, thermal spread remained in the 10°C range with no physical configuration means identified to correct for loss of heater groups.
- Considering the exhaustion of options available for hardware correction to the thermal gradient issue, final decision to increase c/d ratio sufficiently to raise unheated cells to an acceptable range and reduce thermal gradient to within 3°C max cell-to-cell is being considered for implementation.



In The End, What Did We Learn?



- Several significant and obvious lessons result from these investigations:
 - On-board instrumentation is critical when investigating anomalous behavior (more is better!)
 - Routing of redundant power/signals in a single bundle may (or will) get you in trouble.
 - Whenever utilizing Ni-H₂ batteries for spacecraft, some means of cell bypass is needed to avoid potential loss of mission due to MMOD strikes.



Thanks and Acknowledgements



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 - Joseph Cavaluzzi, Noah Williams, and Janet Weiland (MAP FOT)



Acronyms

- BBAT : Hex Bay Battery
- °C : degrees centigrade
- c/d : charge/discharge ratio
- CPV : Common Pressure Vessel
- dc : direct current
- DET : Direct Energy Transfer
- EOS : Earth Observing System
- FOT : Flight Operations Team
- GaAs : Gallium Arsenide
- IPV : Individual Pressure Vessel
- IRU : Inertial Reference Unit
- MMOD :
Micrometeoroid/Orbital Debris
- NASA : National Aeronautics and Space Administration
- NESC : NASA Engineering and Safety Center
- Ni-H₂ : Nickel-Hydrogen
- O₂ : Oxygen
- S/C : Spacecraft
- V : Volts
- V/T : Temperature compensated Voltage
- W : Watts
- W-MAP : Wilkinson Microwave Anisotropy Probe