The Efficacy of Battery Management Strategies to Extend Life on the Grace Project

By

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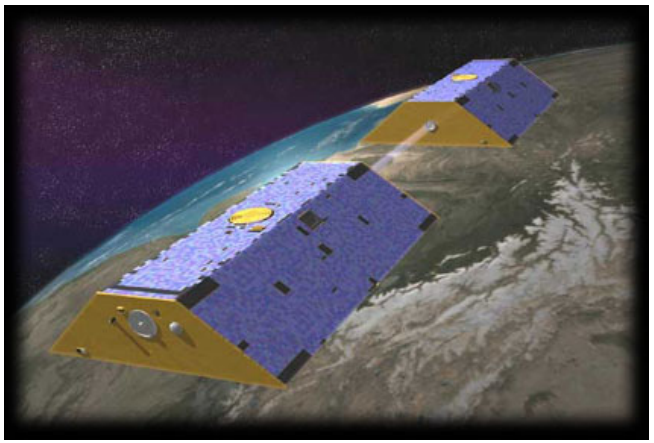
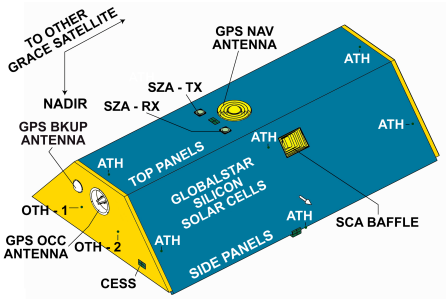
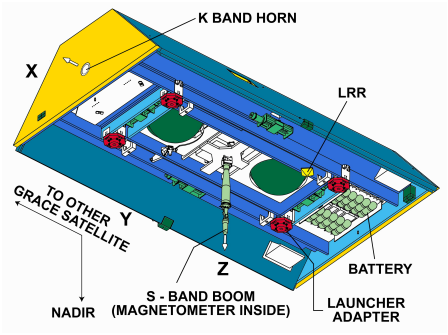
Discussion Outline

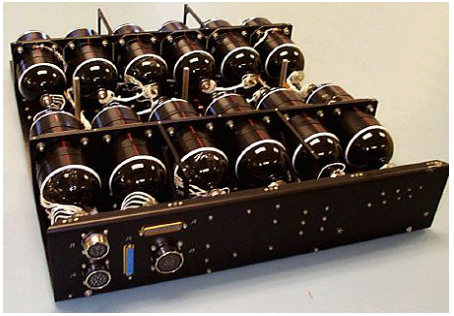
- Mission & Operational Background
- Action #1: Refine control of battery operating temperatures.
- Action #2: Implement partial reconditioning protocols during full-sun periods.
- Action #3: Optimization on charge control management based on temperature and charge return.
- Conclusions

Grace Mission Background









Launch: March 17, 2002
Orbit: retrograde precessing Polar Orbit
Attitude: initially 500 km, currently 450 km
Distance Separation: 220 ± 50 km
Operations: German Space Operation Center (DLR-GSOC)
Solar Array : Body-fixed with string switching controller
Battery Design:

- **Ni-H2, 16-Ahr nameplate,**
- **10 CPV (20 cells total),**
- **No backup cell**

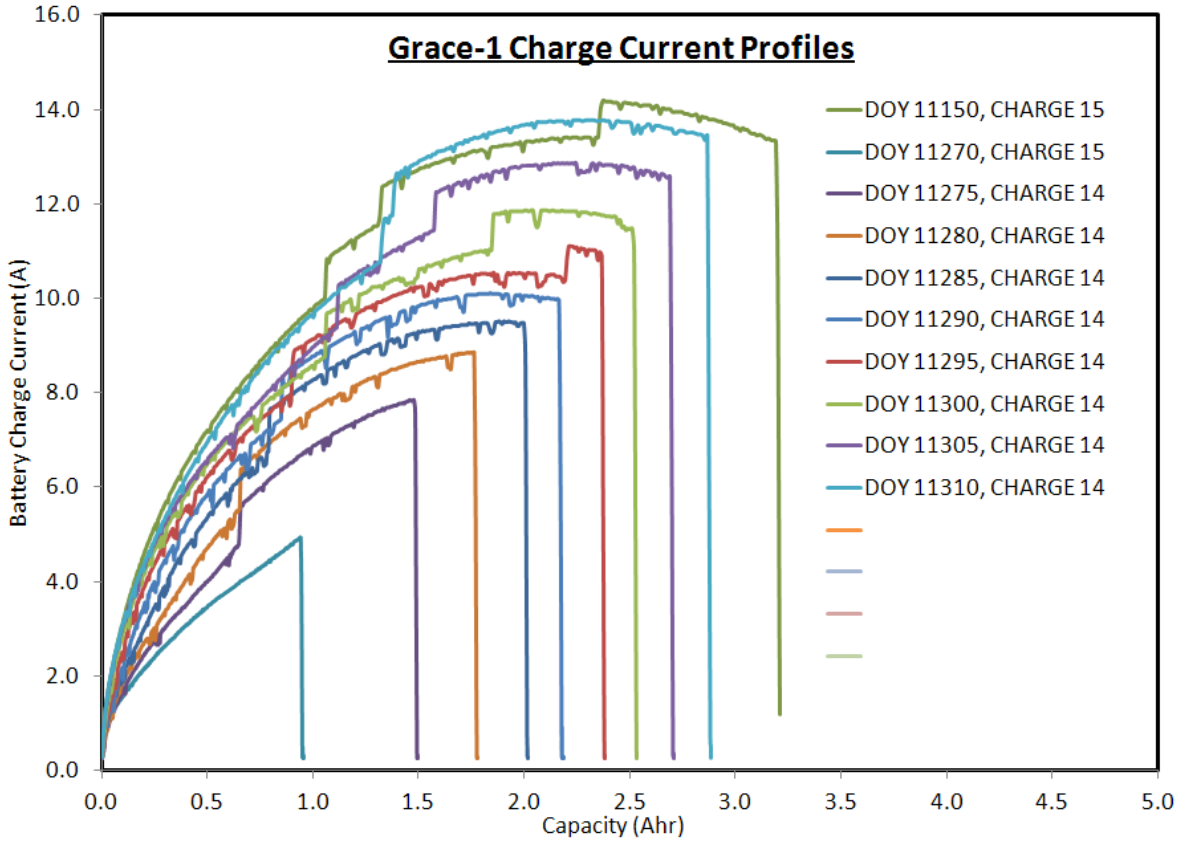
Grace Battery Operational State

- Over 40,000 cycles
- Grace-1 has18 cells remaining:
  - 1st cell voltage collapsed in Aug. 2009.
  - 2nd cell voltage collapsed in Apr. 2011.
- Grace-2 has19 cells remaining:
  - 1st cell voltage collapsed in Jul. 2007.
- Estimate remaining capacity: <20% of BOL
  - Based on minimum operational battery voltage limit.

Operational Constraints & Guidelines

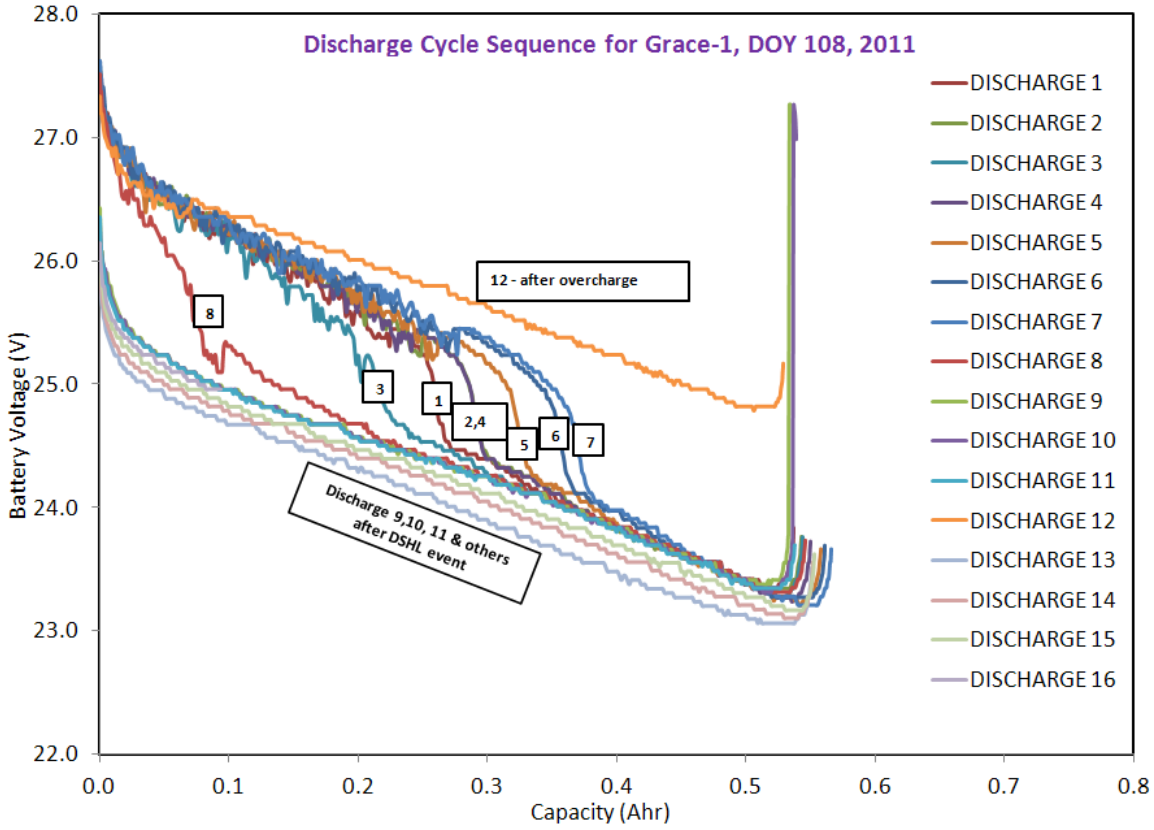
- No control on trickle charge (fixed at 0.28 amp) or high rate charge current
- Limited thermal control
  - Heaters and thermostat controller limits minimum battery temp.
  - Spacecraft orientation determines the charge current profile for the battery.
  - Operators have control over the amount of overcharge (C/D ratio) the battery gets each orbit using VT levels.
- Limited battery/cell telemetry
  - No cell voltage monitoring. Only ½ battery voltage
  - 2 battery temperatures — main and redundant on baseplate
  - Pressure is measured on two CPV's —main and redundant
- The charge control algorithm compensates for Current and Temperature
  - V_eoc= 27.05 +0.3*EOC+0.2*(I-I_o)-.09*(T-T_o)
  - Coefficients are hardwired, EOC control has 0 to 15 level setpoints
  - Shorted cells are compensated for by lowering the EOC value.

Grace charge current profiles



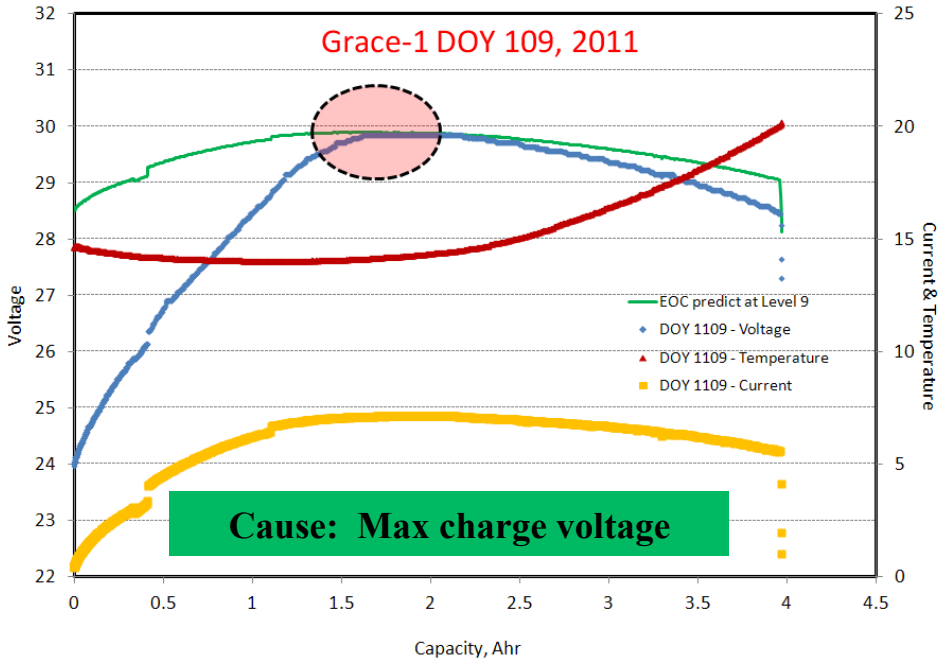
Battery charge rates are dependent on S/C to sun orientation, and dynamic w.r.t state-of-charge and DOY. No operator control.

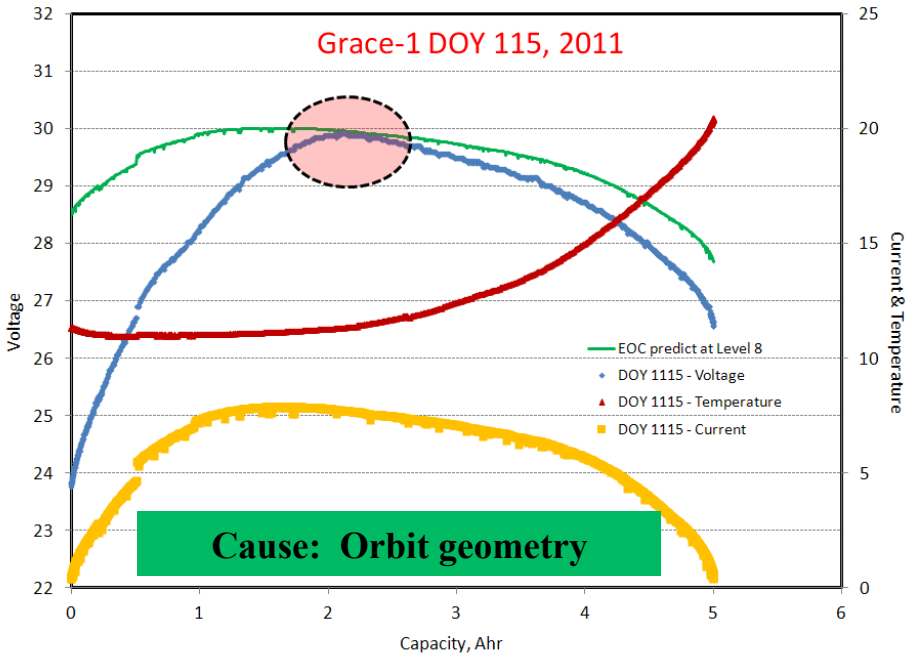
Operational Impact: Cell Voltage Collapse Events, April 18th of 2011



Weak cell rapid decrease in capacity. After cell voltage collapse, weak cell could not be recovered even after "extreme" overcharge.

Operational Impact: Battery Charge Runaway Events





Operator error in EOC setting attributed to unreliability of VT-control due to lower operating battery voltage range.

Chemistry

Negative electrode: $\frac{1}{2}H_2 + OH^- \Leftrightarrow H_2O + e^-$

Positive electrode: $NiOOH + H_2O + e^- \Leftrightarrow Ni(OH)_2 + OH^-$

Net Reaction: $\frac{1}{2}H_2 + NiOOH \Leftrightarrow Ni(OH)_2$

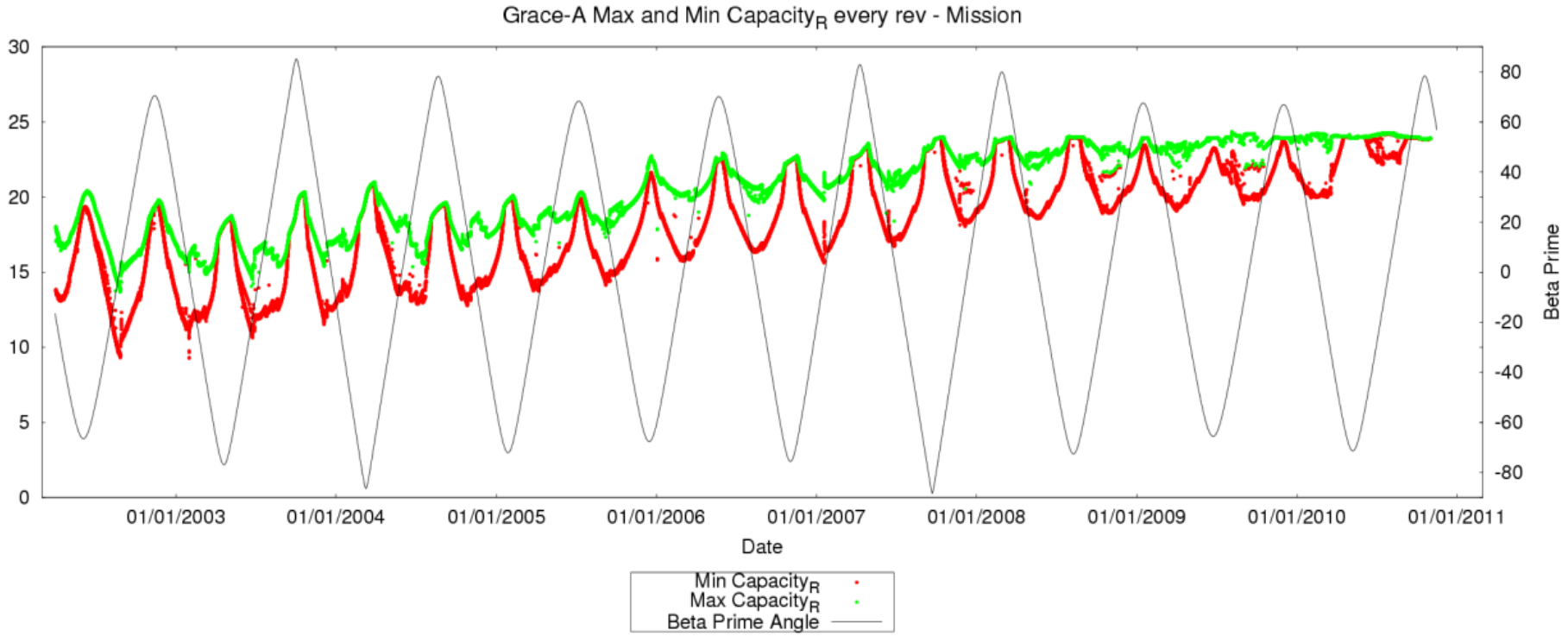
Overcharge chemistry:

Negative electrode: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$

Positive electrode: $2(OH^-) \rightarrow 2e^- + \frac{1}{2}O_2 + H_2O$

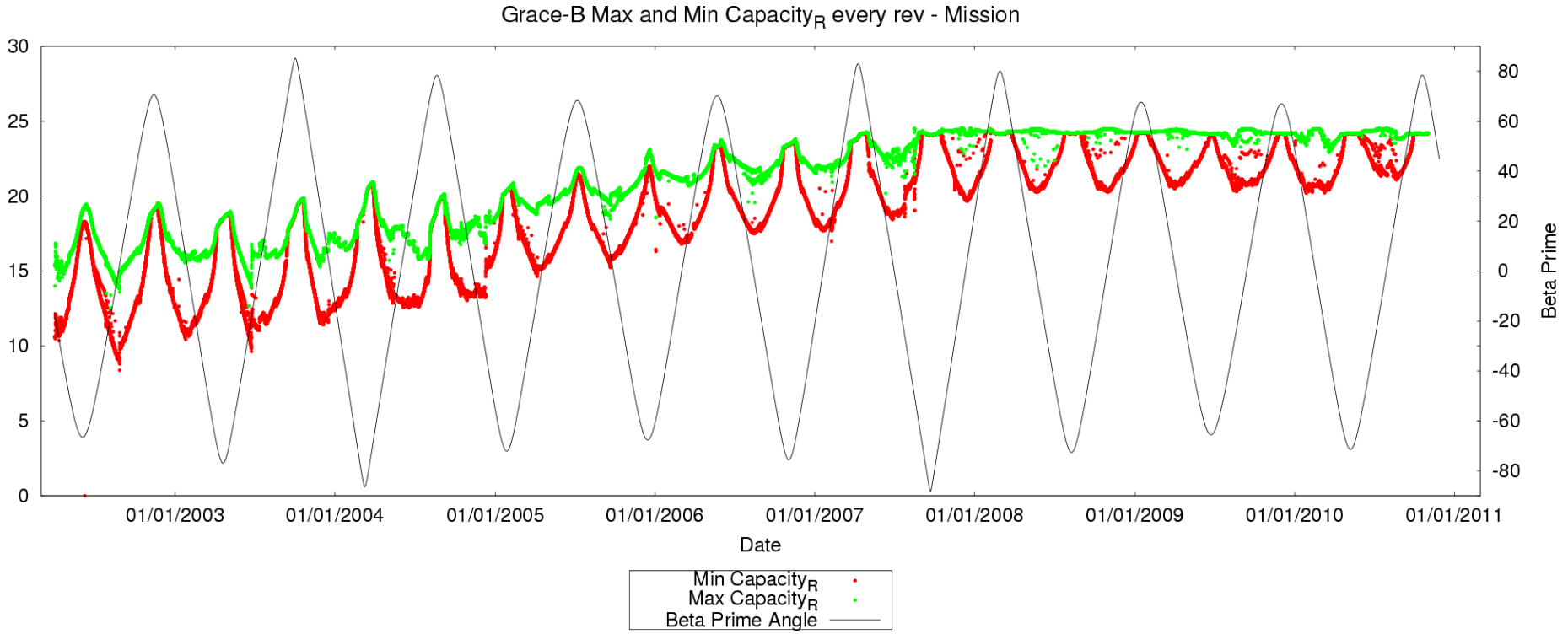
The overall reduction in charge efficiency is directly proportional to the percentage of current going into production of oxygen.

Mission Life Max/Min Capacity, Grace-1



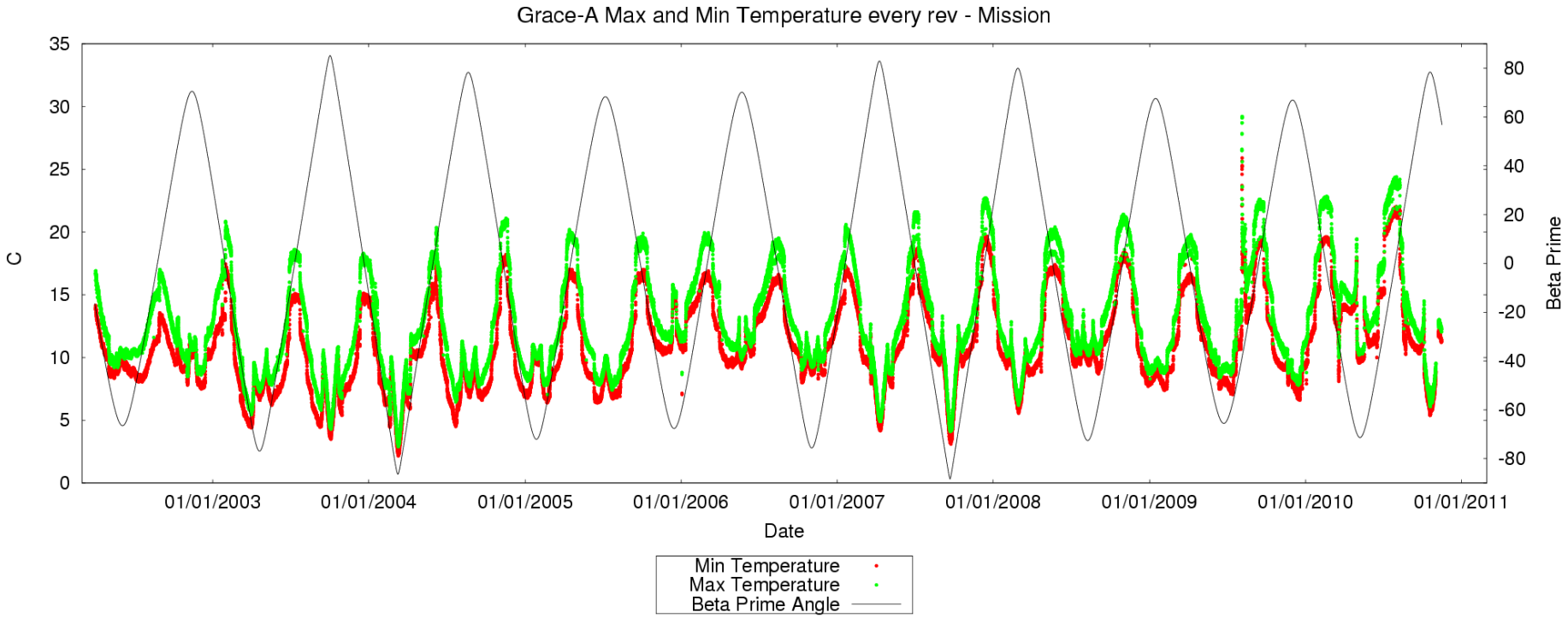
Life-time operating pressure (capacity) maxed-out!

Mission Life Max/Min Capacity, Grace-2



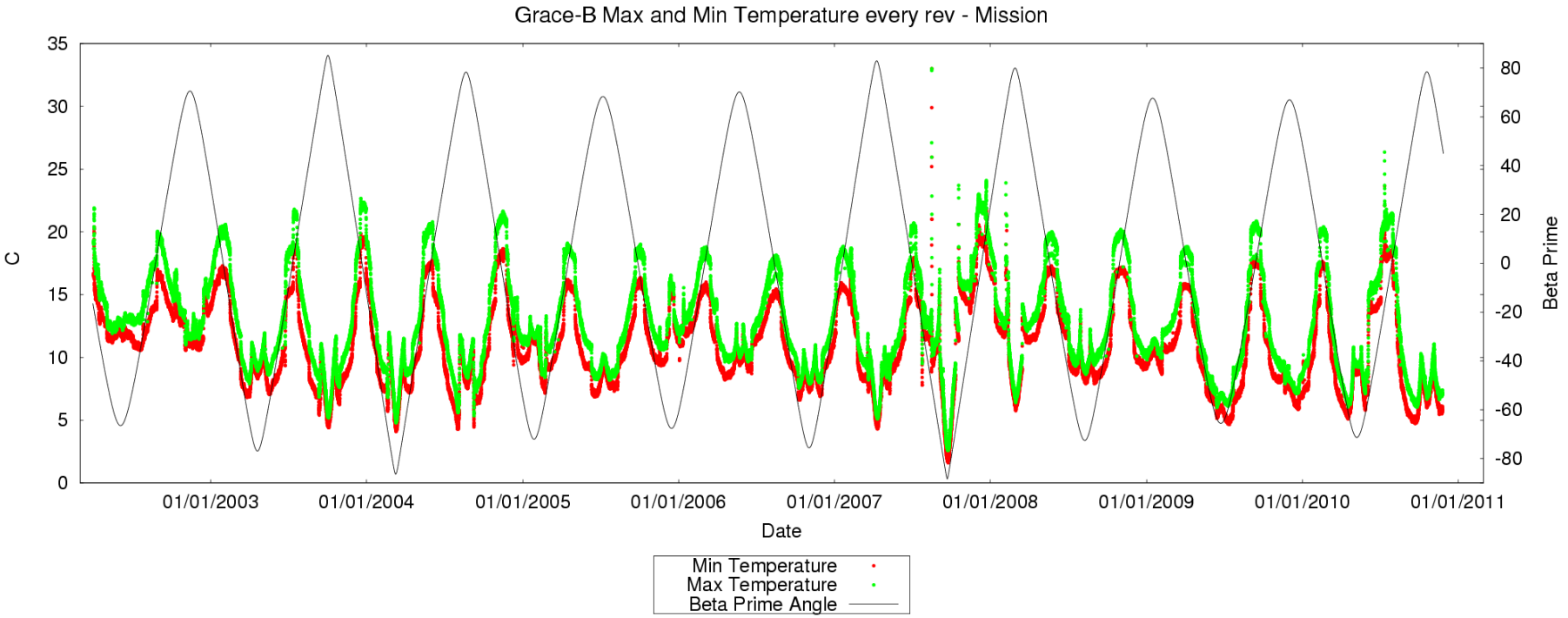
Life-time operating pressure (capacity) maxed-out!

Mission Life Max/Min Temperatures, Grace-1



Life-time operating battery temperature too high (> 20°C)

Mission Life Max/Min Temperatures, Grace-2



Life-time operating battery temperature too high (> 20°C)

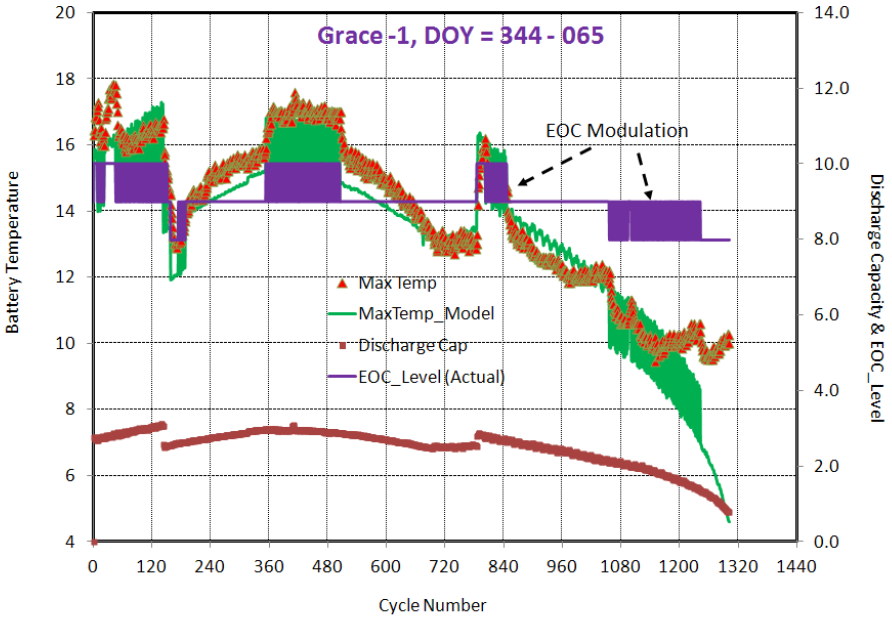
Action #1: Adapt protocols to control battery operating temperatures

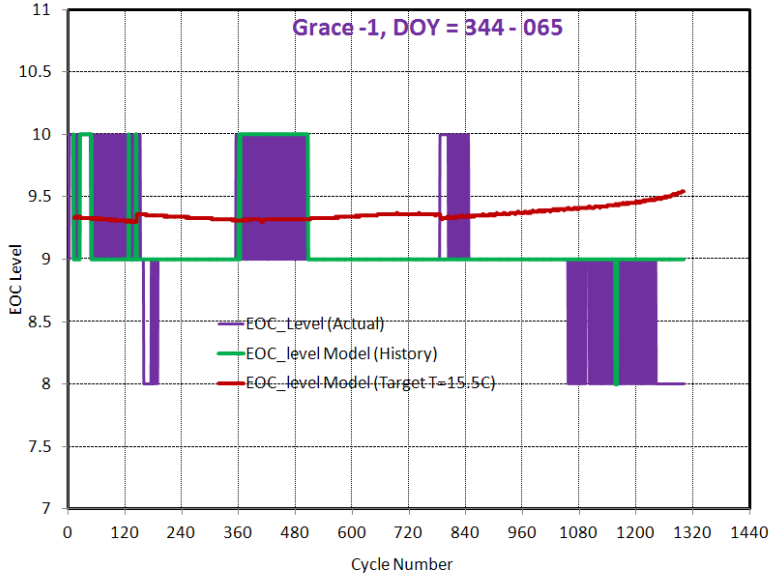
- Battery temperatures dictated by environment and thermal dissipation.
  - Assume overcharge amount and discharge duration as dominate contributors.
- EOC Modulation Protocols
  - Maintain VT-control and maximum battery management autonomy with minimum additional operator workloads.
  - Implemented during Fall Eclipse Season, 2010

EOC modulation results

Regression Model:

$$BattTemp = A * Dchg\_cap + B * EOC\_level + C$$



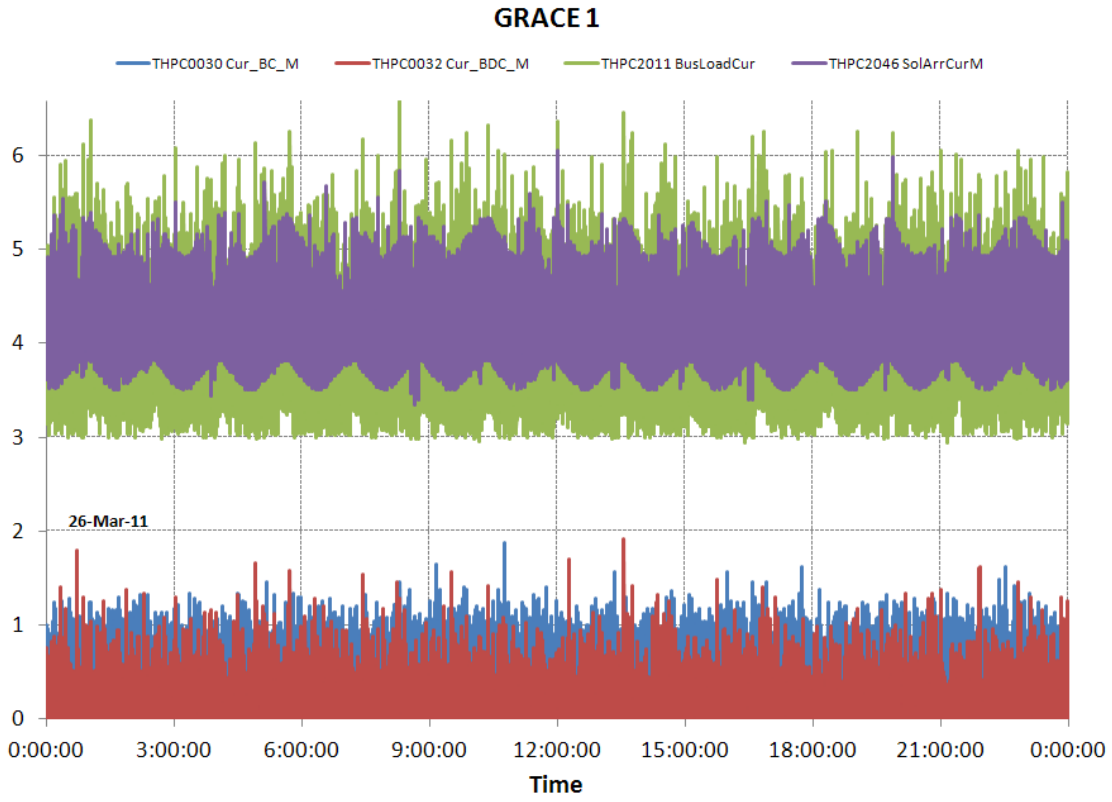


Overall, EOC modulation proved insignificant on battery state-of-health. Battery temperature still too high.

Action #2: Adapt protocols to monitor battery state-of-health during full-sun periods

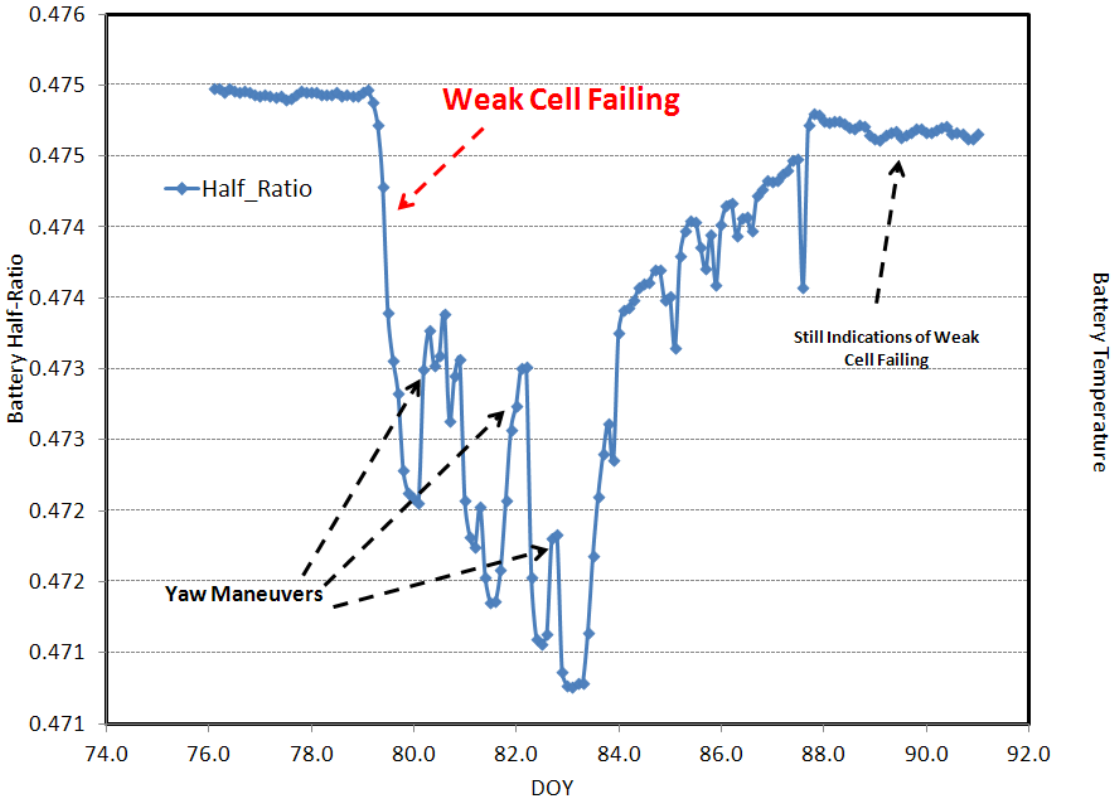
- No trickle-charge rate control.
- Limited cell voltage/pressure monitoring.
- Partial reconditioning of battery.
- Initiated weekly maneuvers during summer full-sun period.
  - Provides proactive approach to maintain battery state-of-health and performance.

Grace current distribution profile during full-sun



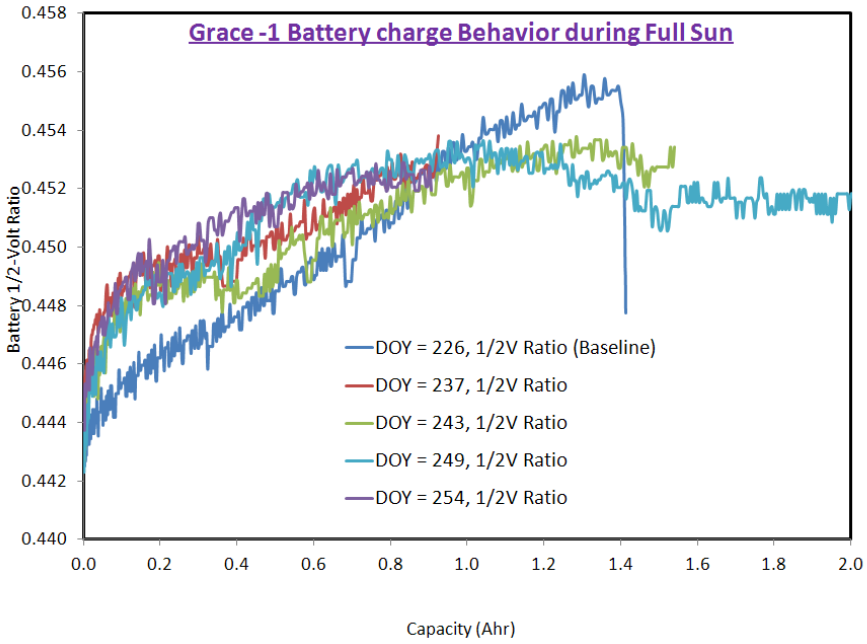
Variable trickle-charge and capacitive discharge.

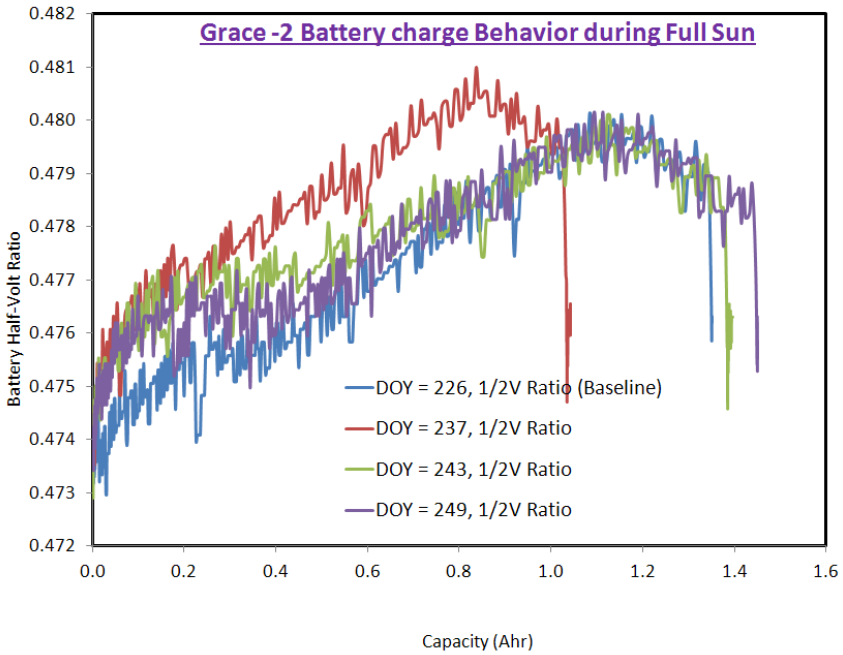
Failing Weak Cell during full-sun



Weak cell recovery is possible by inducing discharge/charge cycle and adequate overcharge amount.

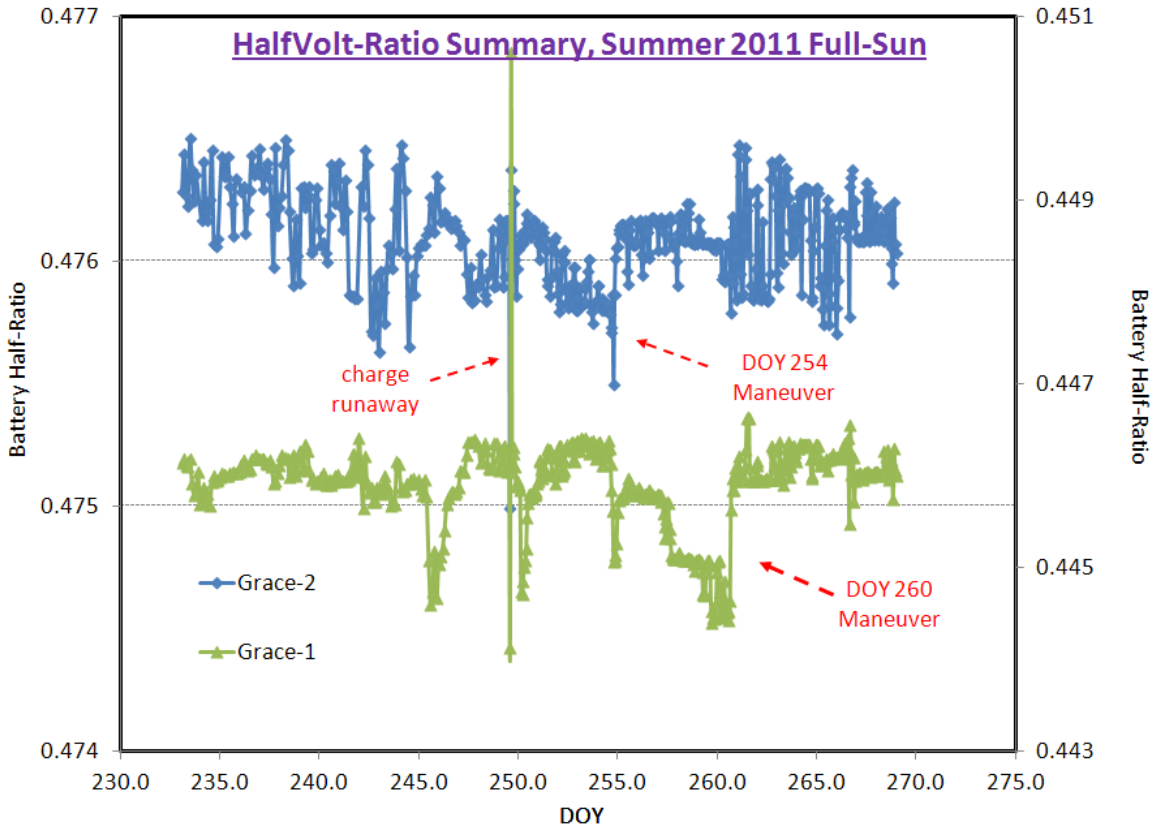
Half Voltage Ratio Profile





Half voltage provides indications of optimal charge and cell uniformity .

Grace HalfV_Ratio Summary

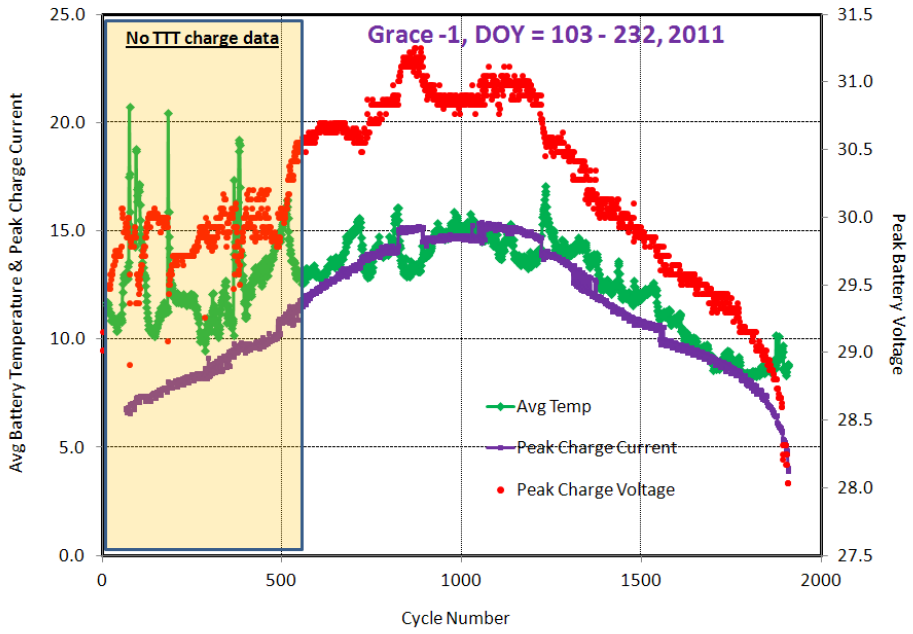


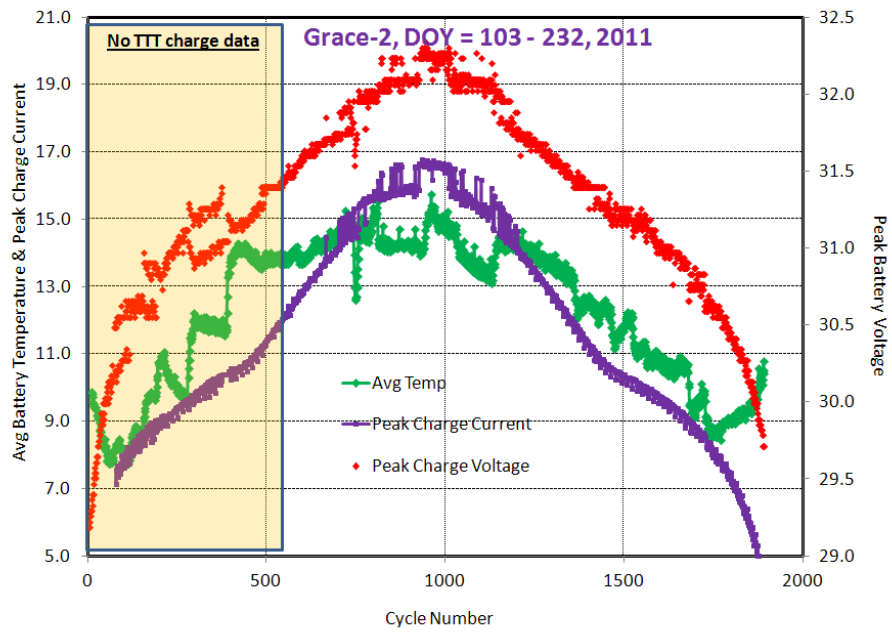
Satellite attitude maneuvers are used to modulate power from the solar array. The maneuvers induce controlled discharge/charge cycles monitor battery performance and maintain adequate overcharge amount for weak cells.

Action #3: Optimization of charge control

- Battery temperatures dictated by environment and thermal dissipation.
  - High dissipation stems from charge inefficiency and overcharge amount.
- VT charge control with 0.3-volt steps have proven to be too coarse for optimum battery management.
  - One step results in a 3°C increase in battery temp.
  - An increase of 0.3 volts can lead to thermal runaway near the max charge capacity of the battery.
- Implemented time-tagged charge control during Spring, 2011.
  - Has enabled "Fine" control of the amount of overcharge.
  - Time-tagged commands reduce the EoC voltage at a specific time in the charge cycle to terminate the charging at a desired level of overcharge.

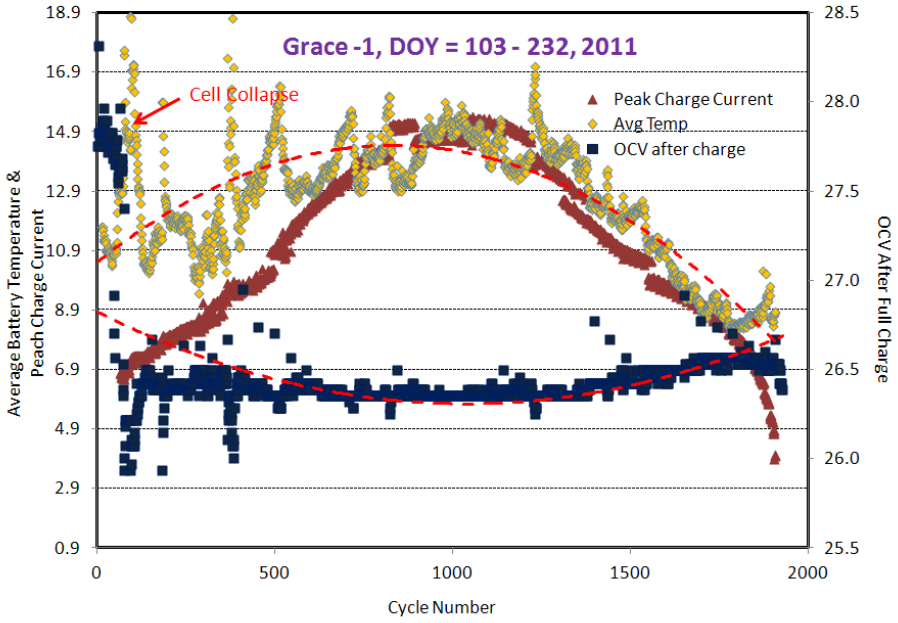
Charge results from Time-Tagged commanding protocols

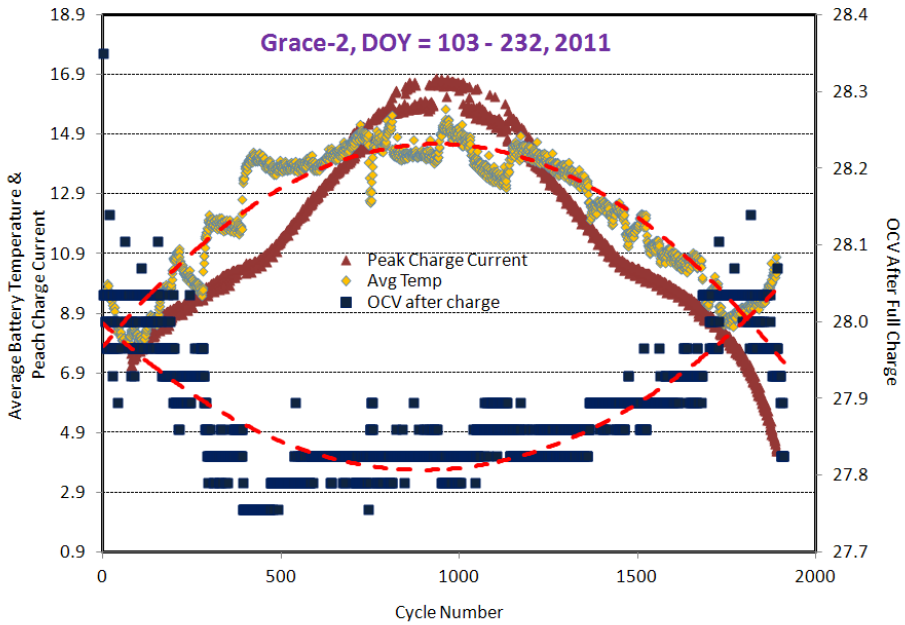




Fine control of overcharge amount optimized science capabilities and improved battery performance.

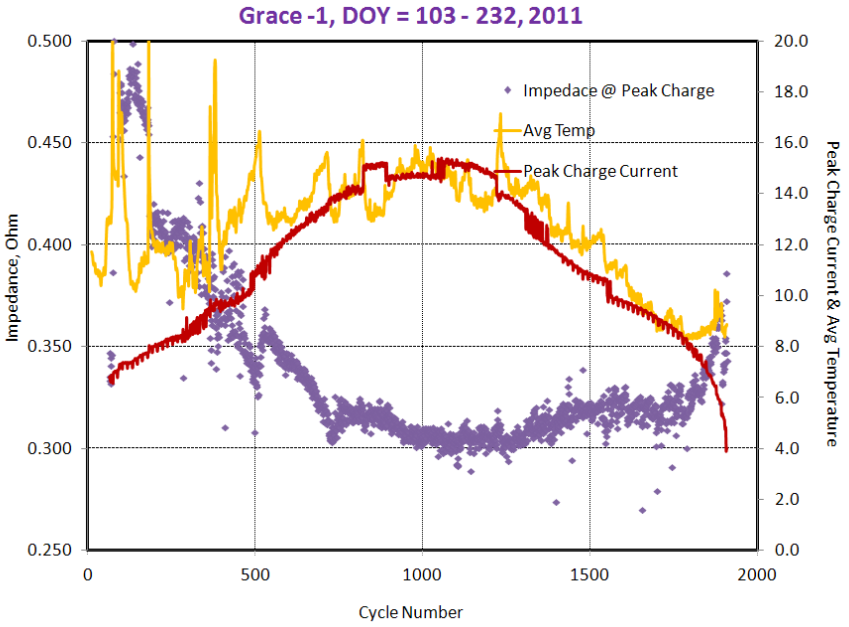
Charge results from Time-Tagged commanding protocols

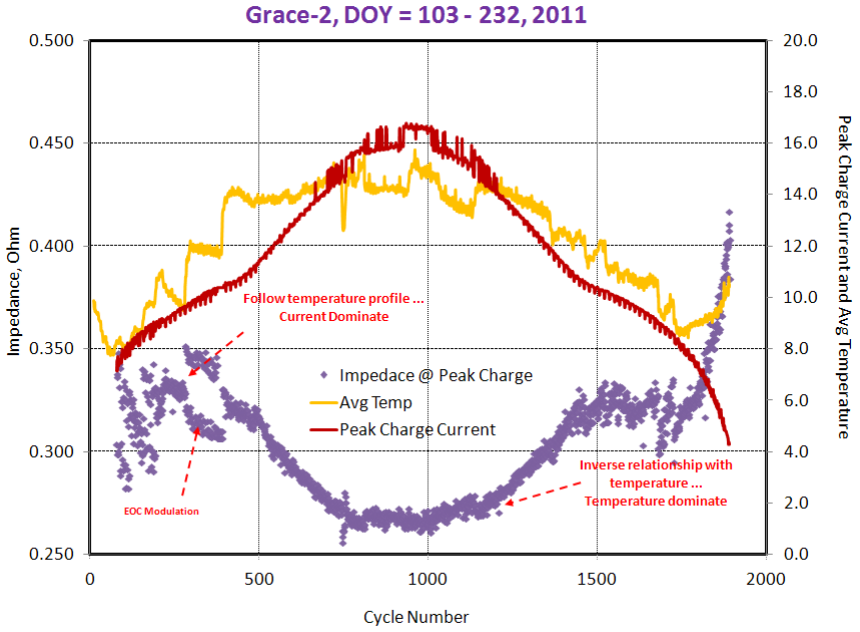




Battery voltage prior to eclipse discharge suggest lower charged capacity despite higher charge rate and end-of-charge voltage.

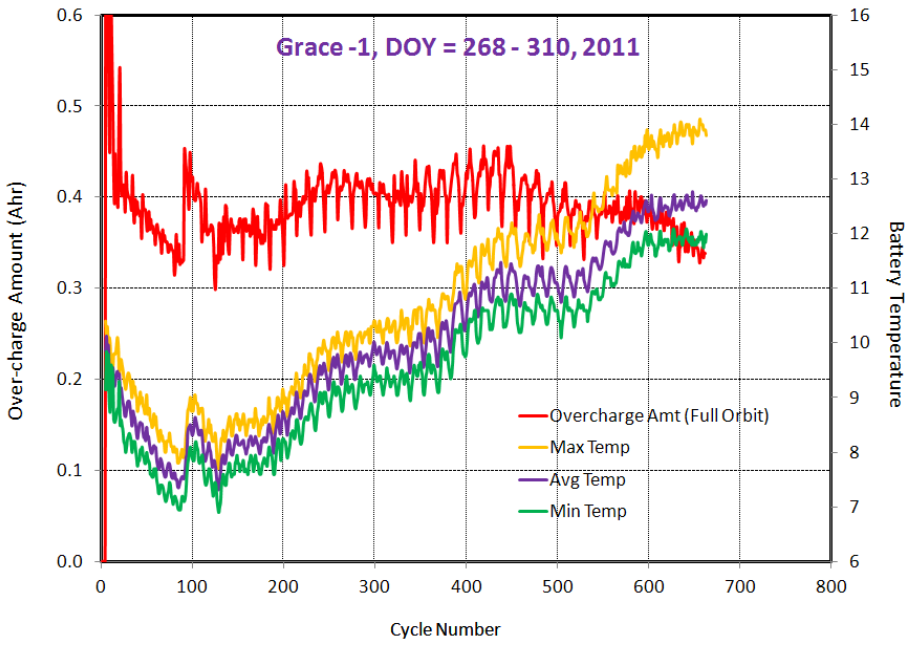
Charge results from Time-Tagged commanding protocols

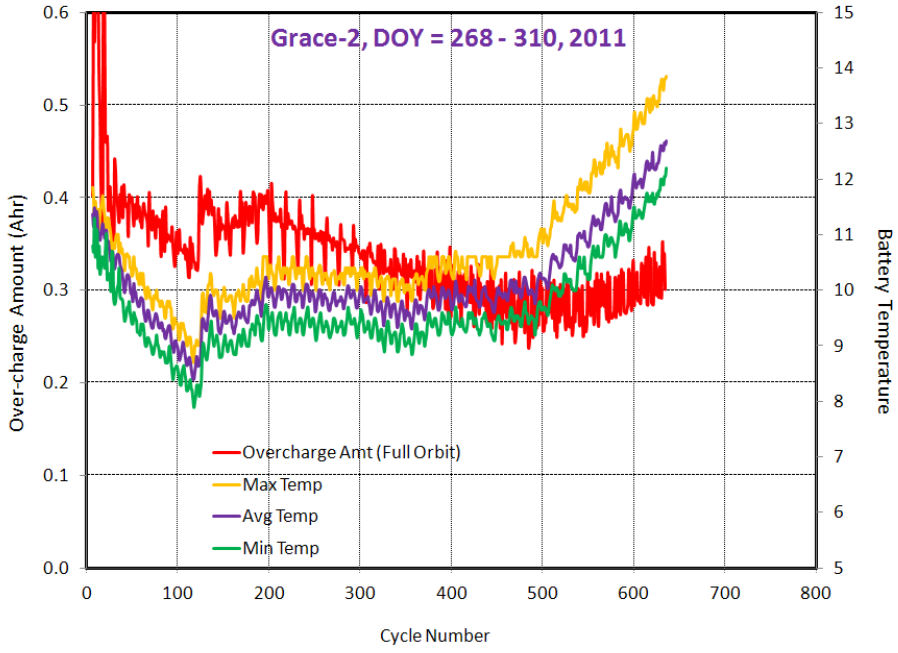




Peak charge impedance indicated poor charge efficiency at higher charge rate and higher operating temperature.

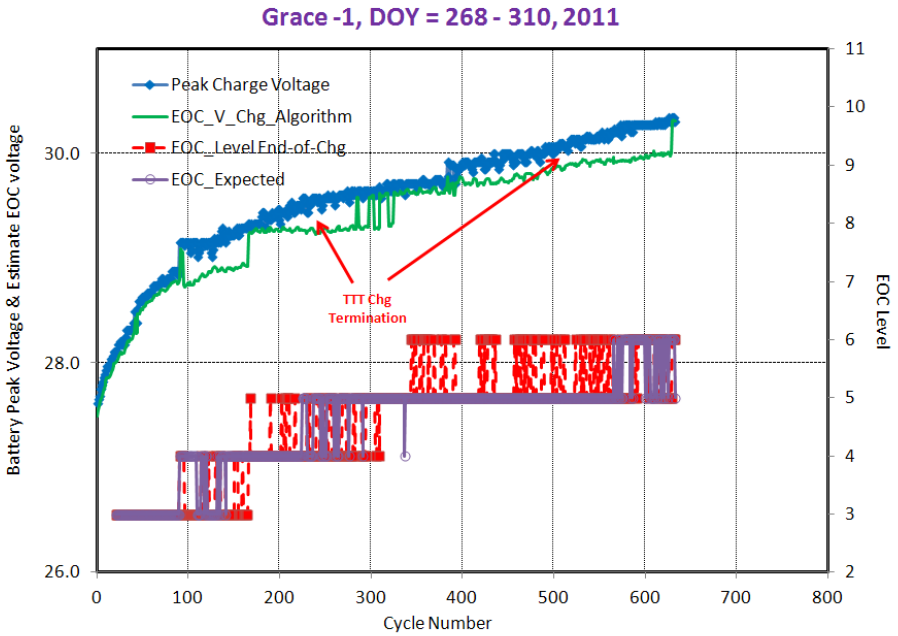
Summary of battery Performance, Temperature & Overcharge Amount

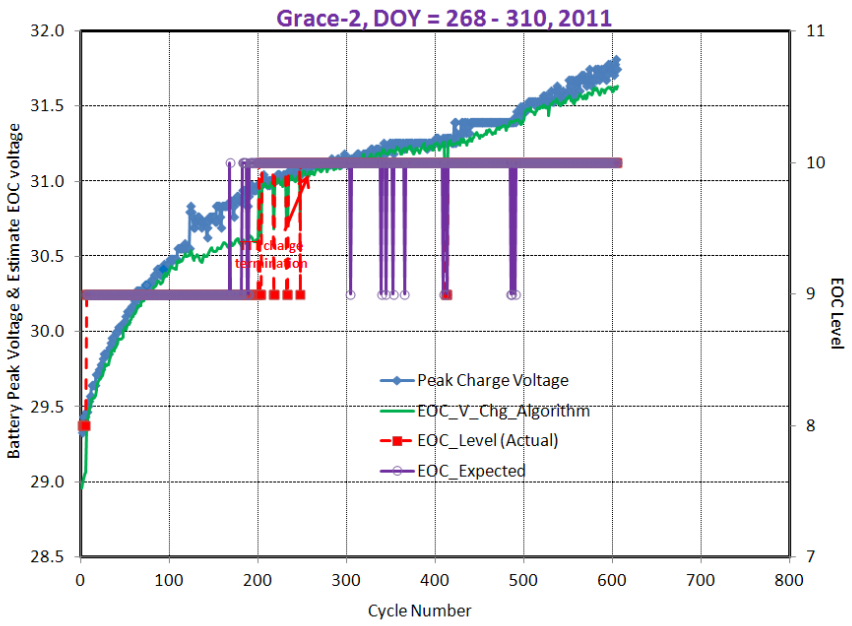




- **Temperature and overcharge amount are actively monitored to maintain optimum charge conditions.**

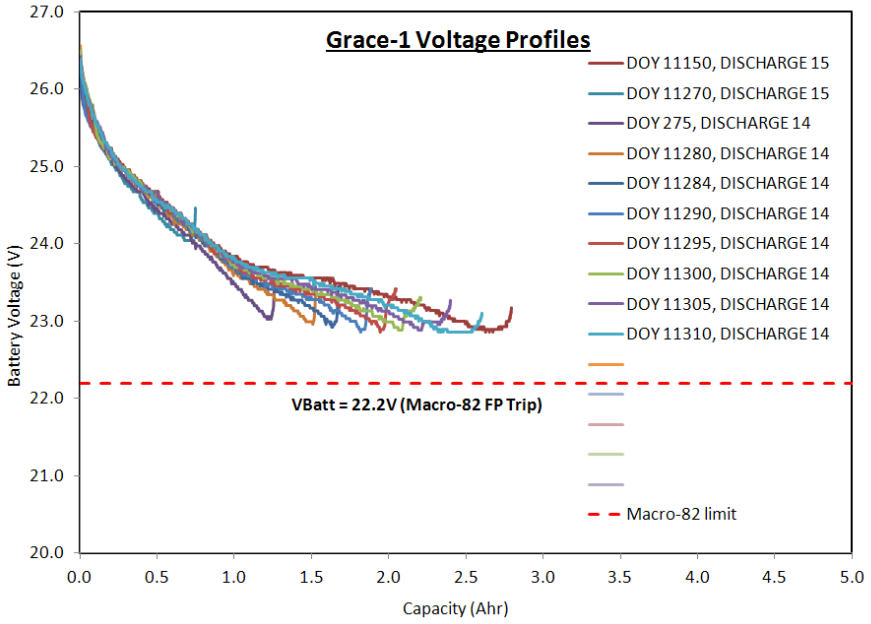
Summary of battery performance, VT vs Time-Tag Charge control

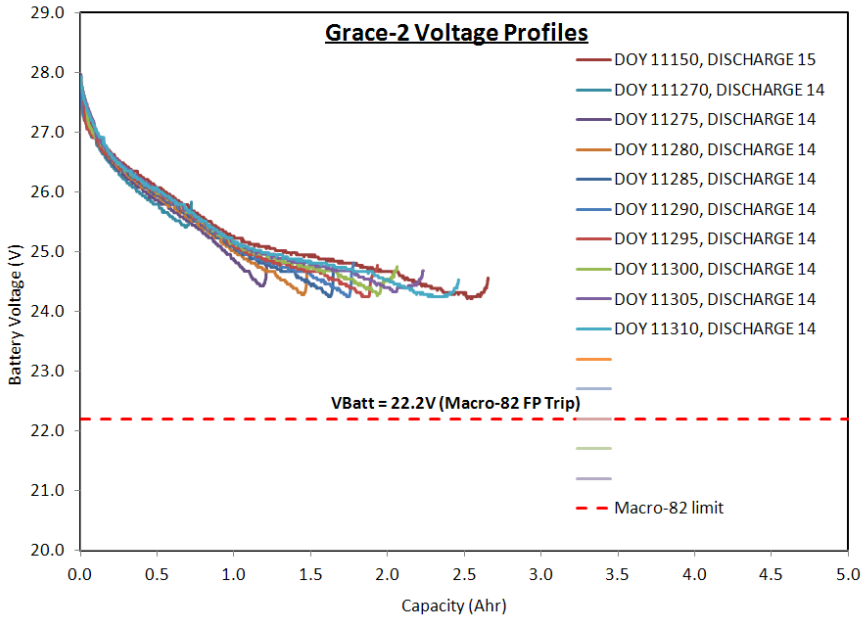




- **Time-tag charge control is complimentary to VT charge control.**
  - **Grace-1 VT control is more unreliable than Grace-2.**

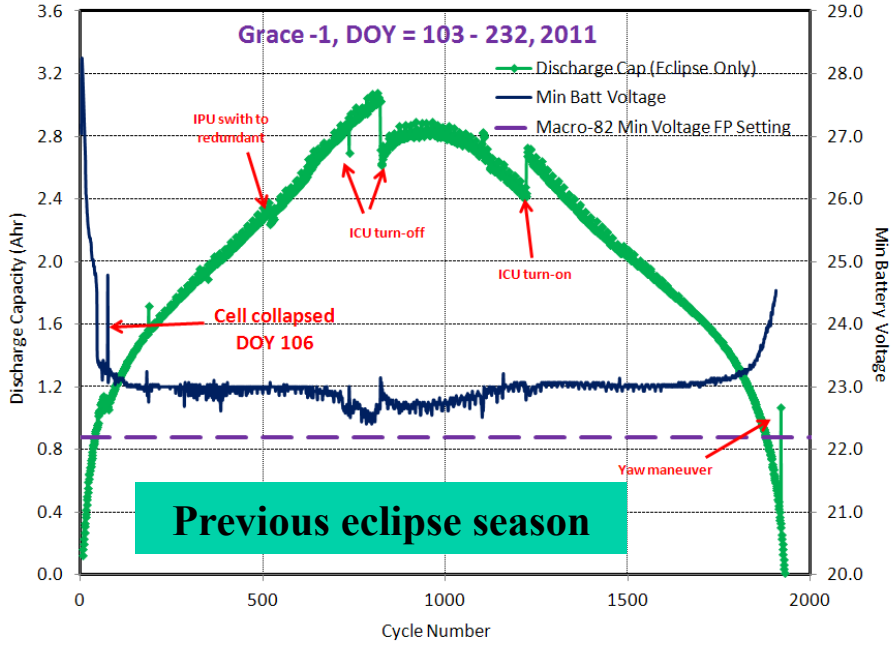
Summary of battery performance, Discharge Voltage Profiles

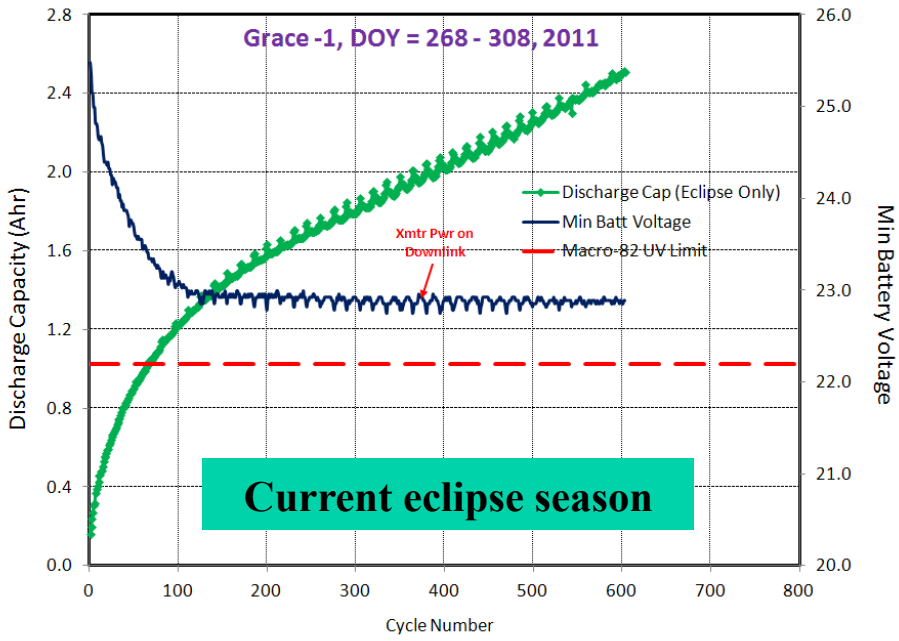




- **Battery discharge voltage profiles improved with increasing discharge capacity.**
- **Secondary plateau observed near 2 Ahr discharge capacity.**

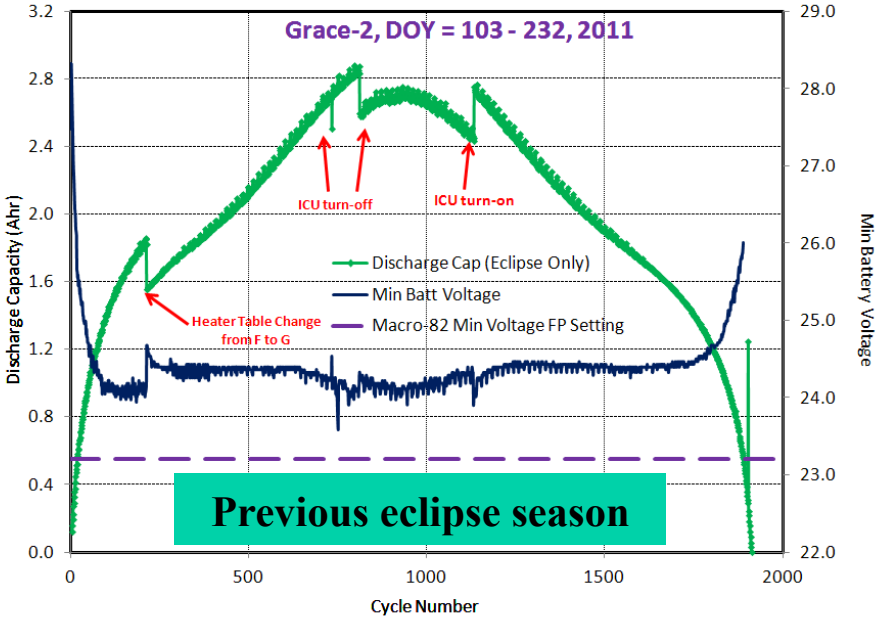
Summary of battery performance, Grace-1

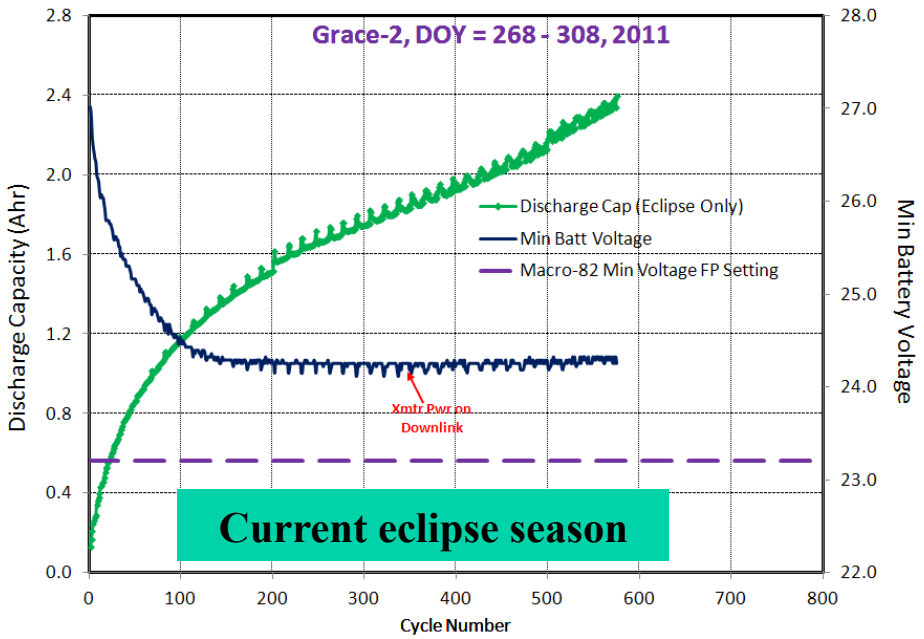




- **Eclipse battery minimum voltage performance is improved with discharge capacity.**

Summary of battery performance, Grace-2





- **Eclipse battery minimum voltage performance is improved with discharge capacity.**

Conclusions

- Controlling charge of degraded batteries on GRACE satellite is labor intensive
  - Daily monitoring and control of the amount of overcharge
  - Daily management of charge termination by ground command.
  - Modest success in forecasting charge control parameters for 3 days.
- Operator rapid response to VT-control management is critical with presence of weak cell and imminent cell voltage collapse.
- The project has enhanced its telemetry data management information system to extract the essential information needed to manually over-ride the satellites' autonomous charge-control algorithm.
- Sustaining adequate overcharge is needed even in full-sun orbits when battery not used for periods as long as 5 weeks.
  - Mitigates electrolyte bridging effects in the battery.
- Weekly characterization of the battery (e.g., peak charge impedance and voltage, minimum discharge voltage, etc.) has shown that adopted procedures are effective in maintaining battery health.

Acknowledgement

- Excellent operational cooperation & teamwork!
- Mona Witkowski – JPL
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  - Jaap Herman
  - Markus Kinzler
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