

Status GRACE Mission Operations



Mona Witkowski, JPL
Operations Mission Manager

Franz-Heinrich Massmann, GFZ
Deputy Operations Mission Manager

Jet Propulsion Laboratory

© California Institute of Technology. Government Sponsorship Acknowledged



GSTM – Austin, Texas 10 – 12 October 2017

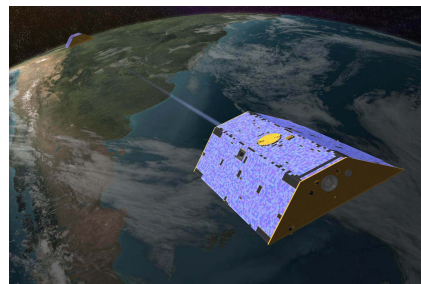
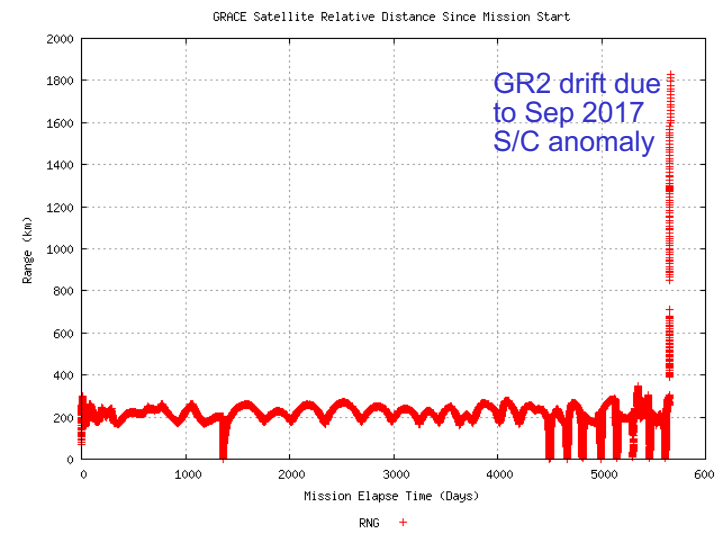
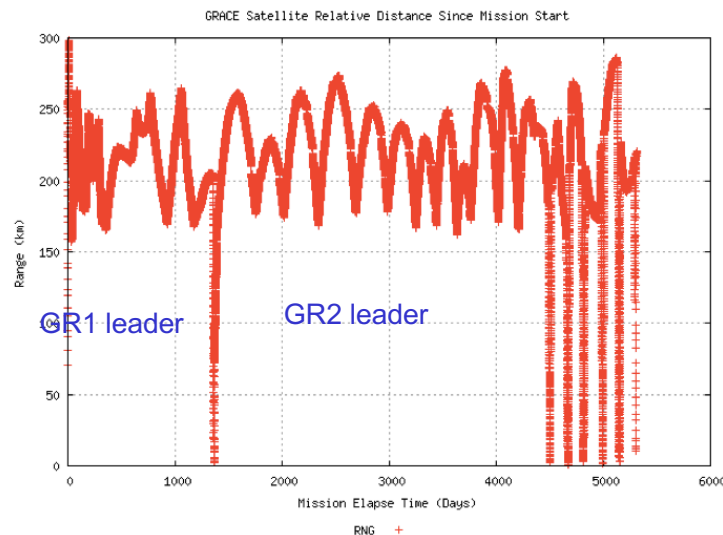




Orbit Status 30 – Sep 2017

15 Years in Orbit - 17 March 2017!!

- Semi-major axis (GR-2): 6691 km, 313 km above 6378 km
- Altitude decrease (GR-2): ~ 339 m/day
- Inter-satellite Distance: 220 km ($\pm$ 50 km)
(currently ~570km & decreasing)
- Satellite Swap Maneuver: 25 Jul <flyby 30 Jul> 09 Aug 2017



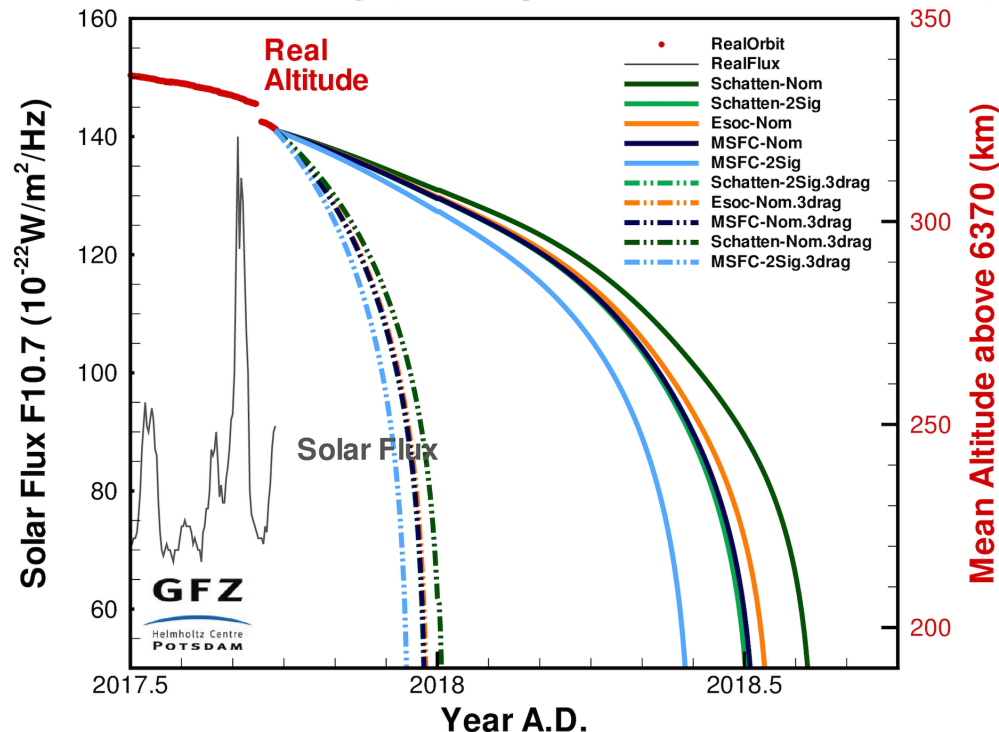
- 5,676 days in orbit
- 87,417 revolutions
- 9 Satellite Swaps
(1 planned for the mission)

Status GRACE Mission Operations

Mission Lifetime Predictions



GRACE-1 Decay (26-Sep-2017, NRLMSIS2000)



End Of Mission

GR-1: Orbit Decay: Jun-2018/Aug-2018
(In the case of uncontrolled decay: Dec-2017)

**** Based on Decay Predictions 1700926 (Massmann)**

GR-2: Battery & Propellant: Nov/Dec-2017

Usable Propellant:

- GR-1: 1.30 kg
- GR-2: 0.59 kg

Additional cell failures on both satellites have shortened remaining lifetime

- > GR-1 experienced a 3rd cell loss in Jul 2017
- > GR-2 experienced a 7th cell loss in Aug 2017 & 8th cell* loss in Sep 2017

** 8th cell appears to have recovered a week later*

Mean fuel expenditure on GR-2 increased dramatically due to repeated mode drops

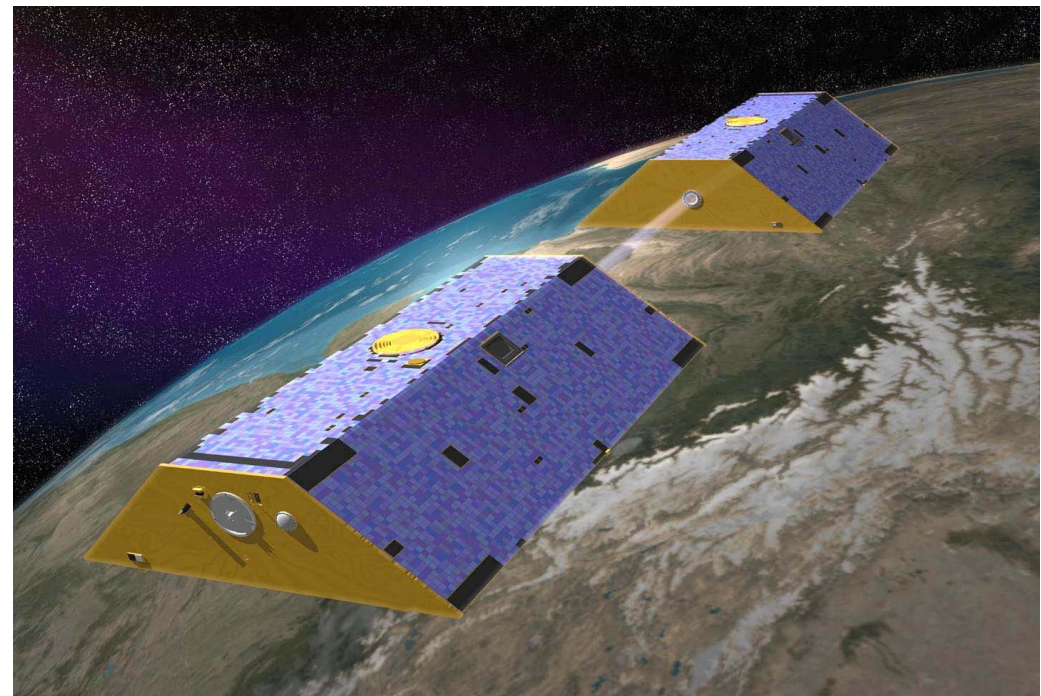
- > Anticipated need for 300g to complete last science observations

Satellite Status



H/W	Satellite	Status
Battery	GR1	17 of 20 cells (3 failed)
	GR2	13 of 20 cells (7 failed)
ICU	GR1	Single string
	GR2	Back-up unit may be operable
IPU	GR1	Back-up unit may be operable
	GR2	Single String
OBDH	GR1	Fully Redundant
	GR2	Fully Redundant
PCDU	GR1	Fully Redundant
	GR2	Fully Redundant
SCA	GR1	Fully Redundant
	GR2	Fully Redundant
TXR	GR1	Full Redundant
	GR2	Single Sting
USO/MWA	GR1	Single String
	GR2	Fully Redundant

- Nearing exhaustion of propellant
- One additional cell lost on GR-1
- 13 July 2017
- Two additional cells lost on GR-2
- 17 August 2017
- 04 September 2017 (RECOVERED!)



Battery Status



Battery Specifications:

- NiH2 Common Pressure Vessel (CPV) configuration; 16 Ahr capacity at BOL
- 10 CPVs with 2 cells in each CPV (total of 20 cells)
- Lifetime: 5 years on-orbit; minimum of 22,000 cycles at 35% DoD

Present Status:

- 15.5 years in operation
- GRACE 1:
 - 17 of 20 cells functioning
 - 3rd cell was lost in July 2017
- GRACE 2:
 - 13 of 20 cells currently functioning
 - Two additional cells have been lost since 2016 Science Team Meeting
 - 7th cell was lost in Aug 2017 & 8th cell was lost in Sep 2017
 - 1 of these 2 cells recovered during the “Hibernation” event in September 2017
 - Voltage drops below 16 V during discharge
 - S-band communication (up and down links) is unreliable below 16 V
 - IPU shuts down below 16 V and OBDH at 13.5V
 - Final science data collection period is expected to be possible during full sun orbits from 9 October – 5 November 2017

Outlook for GRACE 2



Battery Performance:

- Operating temperature is expected to remain very high due to necessary overcharge
 - Temperature saturates at 36°
- Voltage performance is not predictable

Flight System Operation:

- Stable operation of the satellite should be possible in the upcoming full sun period
 - Microwave Assembly (MWA) will be powered back on
 - Propellant has been conserved for the October science data collection
 - Estimated to need 300g for science mode operations in full sun

Instrument Operation:

- MWA can be operated in sunlight at any Beta' angle
 - Will be operated continuously during full sun period
- ICU-Red is currently in "safe mode" and may be recoverable
 - Will require a reload of instrument software
 - May or may not attempt to recover during the full sun period



Satellite Events since Last GSTM - 1

GRACE Mission Operations Review at GSOC: 3 – 4 May 2017

Hardware Swaps: *Several (temporary)*

- GR-2: Switch to OBDH-R & back to OBDH-M during Sep 2017 low voltage situations

Software Uploads: *None*

Parameter Updates:

- 15 Feb 2017: Update Persistencies for SCA Outages
 - AHM from 1600 -> 800s & SM from 1500 -> 1350s
- 29 Mar 2017: Set Pitch Bias = $+1^\circ$ (both satellites)
- 04 Apr 2017: Set Pitch Bias = $+1.12$ (GR-1) & $+0.52$ (GR-2)
- 07 Apr 2017: Set Pitch Bias = $+0.805$ (GR-1) & $+0.737$ (GR-2)
- 12 Apr 2017: Set Pitch Bias = $+0.762$ (GR-1) & $+0.672$ (GR-2)
<*> Pitch Bias to be updated ~ 1/week going forward <*>
- 17 Aug 2017: Refine Monitors for triggering faults & adjust as necessary
 - Relaxes entry in to Coarse Pointing Mode (to conserve fuel)
 - ✓ Mon 34 – Star Camera Fault
 - ✓ Mon 37 – Reference Attitude
 - ✓ Mon 67 – Allowable entries into CMCPM

Solar Eclipse by the Moon (2)

- 26 Feb 2017 & 21 Aug 2017





Satellite Events since Last GSTM - 2

Orbit Control / Maintenance Maneuvers - All performed on GR-1 now

- 08 Nov 2016: Over performance due to calculation error (drift rate too high)
- 30 Nov 2016: Required to reduce drift rate imparted by 08 Nov maneuver
- 02 May 2017: To reverse drift rate between satellites
- 23 Aug 2017: To reverse drift rate between satellites
- 11 Sep 2017: Series of 22 maneuvers over 2 days to re-align the satellites
 - > To drop GR-1 ~4km in altitude to align with GR-2 for science ops
- 18 Sep 2017: Begin flying with Pitch Bias to increase drag
 - > 18 Sep: -10° / 20 Sep: -20° / 21 Sep: -25°
- 25 Sep 2017: Series of 2 more maneuvers to continue re-alignment

Satellite Swap Maneuvers (2)

- 15-Feb 2017 Drift Start Maneuver (GR-1)
- 27-Feb 2017 Satellite Fly-By (GR-1 Leader)
- 13-Mar 2017 Drift Stop Maneuver (GR-1)
 - Activate Occultation Measurements on GR-2 (stop on GR-1)
- 17-Jul 2017 Reduce load on GR-2 battery by switching OCC to GR-1 earlier
 - Activate Occultation Measurements on GR-1 (stop on GR-2)
- 25-Jul 2017 Drift Start Maneuver (GR-1)
- 30-Jul 2017 Satellite Fly-By (GR-2 Leader)
- 08-Aug 2017 Drift Stop Maneuver (GR-1)



Satellite Events since Last GSTM - 3

GR-2 Mode Drops

- 26-Oct 2016 GR-2: Drop to CICPM / CMCPM (low voltage)
- 11-Nov 2016 GR-2: Attitude Anomaly / SC Emergency Declared (IPU outage)
- 15-Feb 2017 Drop to CPM (both satellites – IPU outage)
- 25-Feb 2017 GR-2: Attitude Anomaly / Drop to CPM (low voltage)
 - Also Caused OBDH Boot & Closed HPLV String 1
- 15-Aug 2017 GR-2: Drop to CMCPM (IPU Outage)
- 16-Aug 2017 GR-2: Drop to CMCMP (IPU Outage)
- 17-Aug 2017 GR-2: Repeated drops to CMCPM (7th Cell Loss)
- 18-Aug 2017 GR-2: Attitude Errors / CMCPM / SC Emergency Declared
- 19-Aug 2017 GR-2: CMCPM Every Orbit (low voltage)
- 04-Sep 2017 GR-2: CMCPM / SC Emergency (8th Cell Loss)
 - Also causing OBDH Boots every orbit since 17 Sep 2017

OBDH Cold Reboots

- GR-1: 28-Mar 2017 – Commanded (per plan)
- GR-2: 25-Feb 2017 – Triggered by low voltage
18-Aug 2017 – Triggered by low voltage
17-Sep 2017 – Triggered now every orbit since

NYA Dump Pointer Reset (known OBDH S/W bug)

- GR-1: 26 Dec 2016 14 Sep 2017





Satellite Events since Last GSTM - 4

Revisions to Fault Protection

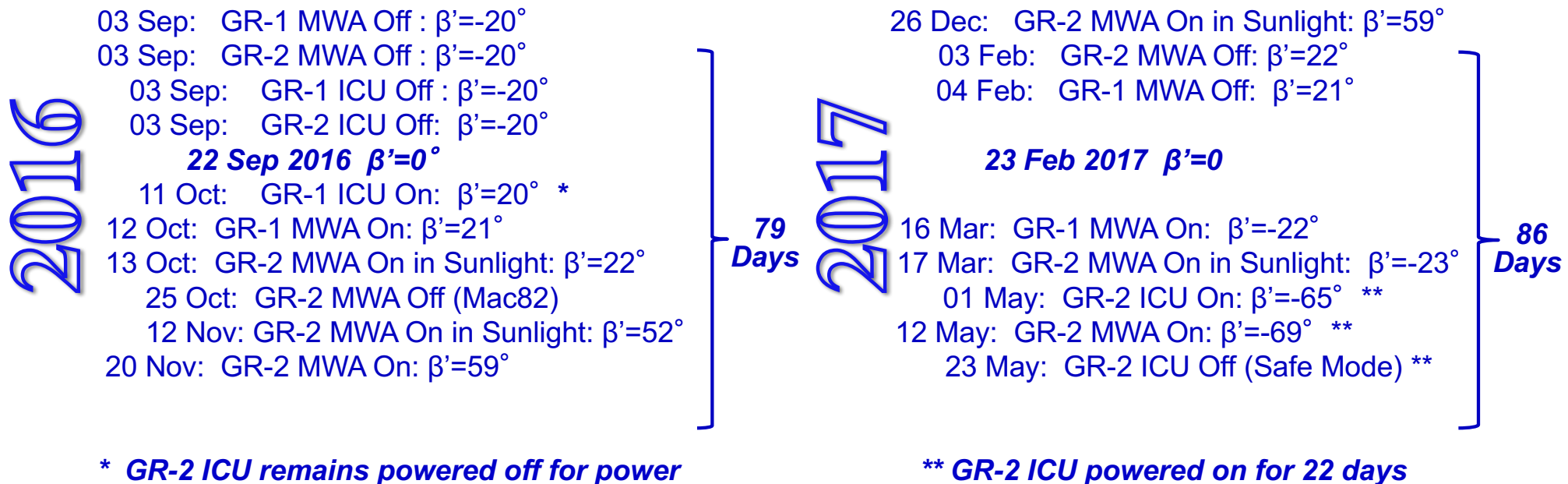
- **Macros 44/45/46**
 - Continue to be used to effectively control charging on GR-2
 - Trigger values modified as necessary
- **Macros 89/90/91**
 - Continue to be used as a back up to MWA On/Off time tags
 - Trigger values modified as necessary
- **New Macros 100/101/102**
 - Macros to block anomalous transient error signals from being used by AOCS
 - Re-enables AOCS control 12 seconds after the IPU begins to return valid data
 - Successfully reduces unnecessary thruster firings and propellant usage
 - 25 Jan 2017: Upload & Test Macros 100-102 on GR-1
 - ✓ Macro 100: Detect IPU reboot based on current ($<0.45A$) & Enable Macro 101
 - ✓ Macro 101: Disable on-board AOCS generated thruster commands
 - ✓ Macro 102: Re-enable on-board AOCS control 12 seconds after IPU data is valid
 - 26 Jan 2017: Macro Chain Uploaded and activated on both satellites
 - 15 Feb 2017: Updated Macro 101 to include disabling the magnetic torquer commands
- **Macros 25 & 65**
 - Macro 25: Auto Recover to Science Mode (modified to turn APWM Off)
 - Macro 65: Go to Coarse Pointing Mode (modified to remove IMU On cmd – for power)



Satellite Events since Last GSTM - 5

Load Reduction actions (around $\beta'=0$ crossing)

- Partial Orbit MWA Ops on GRACE-2 has reduced science data loss
- Satellite Swaps to stay on better SCA heads and reduce fuel consumption





Satellite Events since Last GSTM - 6

Battery capacity on GR-2 disrupted science observations

- General cell weakness on GR-2 necessitated shutting down at the end of June
- GR-1 was shut down at the same time, to conserve battery power
- GR-1: 3rd Battery Cell Failure on 13 July
- GR-2: 7th Battery Cell Failure on 17 August
8th Battery Cell Failure on 04 September (since recovered)

2017

01 Jun: GR-2 MWA On in Sunlight: $\beta' = -59^\circ$

29 Jun: GR-1 MWA Off: $\beta' = -36^\circ$

29 Jun: GR-1 ICU Off - $\beta' = -36^\circ$

30 Jun: GR-2 MWA Off: $\beta' = -35^\circ$

03 Aug 2017 $\beta' = 0^\circ$

06 Sep: GR-1 ICU On

xx Oct: GR-2 ICU On

xx Oct: GR-1 MWA On

xx Oct: GR-2 MWA On

xx Days



Satellite Events since Last GSTM - 7

Battery Issues

- **GR-1 Battery Cell Issues**

- 09 Jul 2017: Cell Dropout / Voltage Drop / Weak Cell Indication
- **13 Jul 2017: 3rd Cell Failure**

- **GR-2 Battery Cell Issues**

- **27 Oct 2016: 7th Cell Failure**
 - ✓ DNEL Trigger / Numerous OBDH reboots (no H/W swap) / IPU & USO Off
- **11 Nov 2016: Low Voltage Anomaly / Extended IPU Outage / Loss of Attitude Control**
 - ✓ Numerous FDIRs / OBDH boot (caused by long earth pointing error)
 - ✓ Large attitude deviations resulted in deep battery discharges
 - ✓ Deep discharge resulted in recovery of 1 failed battery cell!
- **25 Feb 2017: Low Voltage Anomaly / Extended IPU Outage / Attitude Anomaly**
 - ✓ Numerous FDIRs / OBDH boot
 - ✓ HPLV-1 closed by Macro 5 (likely due to artificially low pressure readings due to low voltage)
 - ✓ 2 Mar 2017: HPLV-1 re-opened
- **06 Jul 2017: Low Voltage / Data Dropout / IPU Reboot / Weak Cell Indication**
- **17 Jul 2017: 7th Cell Failure**
 - ✓ Data Gaps / IPU Reboots / CMCPM every orbit
- **04 Sep 2017: Low Voltage OBDH Boot / SC Emergency Declared**
- **04 Sep 2017: 8th Cell Failure**
 - ✓ Numerous FDIRs / OBDH boots / Loss of S/C Signal
 - ✓ 08 Sep 2017: S/C Signal Re-acquired! (S/C was in “hibernation”)
 - ✓ 09 Sep 2017: Close High Pressure Latch Valves (to conserve fuel)
- **11 Sep 2017: 8th Cell appears to have recovered (due to deep discharge)**



Satellite Events since Last GSTM - 8

GRACE-2 Fuel Conservation Measures & Way Forward

- 17 Aug 2017: Revise Monitors (34, 37 & 67) to relax entry into CPM
- 26-29 Aug 2017: Rate Damping in CPM (characterization)
- 30 Aug 2017: Rate Damping in CPM (continuous)
- 30 Aug 2017: Move Trim Masses Forward
- 01-02 Sep 2017: Fly at Roll Bias = $+15^\circ$ (characterization)
- 01-02 Sep 2017: Open Solenoid Valve (balance mass in tanks)
- 02 Sep 2017: Disable Auto transition to Science Mode (characterization)
- 09 Sep 2017: Close High Pressure Latch Valves
- 21 Sep 2017" AOCS Commanded to not use Thrusters

Event	Date
Conserve Fuel on GR-2	September – Early October 2017
Monitor GR-2 via Real-time Telemetry	September – Early October 2017
Maneuver GR-1 back into position with GR-2	September – Early October 2017
GR-1: ICU & MWA On in preparation for SM	September – Early October 2017
GR-2: MWA On in preparation for SM	Early October 2017
Resume Science Mode Operations (full sun)	9 October – 5 November
Passivate Satellites	November / December 2017
Decommission Satellites	November / December 2017



Summary

GRACE celebrated 15 years in orbit on 17 March 2017!!

Additional battery cell failures on both satellites have disrupted data collection

- GR-2 experienced the loss of a 7th cell in October 2016
 - *This cell subsequently recovered after a significant attitude control anomaly and very deep discharge period in November 2016*
- GR-1 lost a 3rd cell in July 2017
- GR-2 lost a 7th & 8th cells in August & September 2017
 - *The 8th cell recovered a week later, after another significant attitude control anomaly and very deep discharge occurred*
- The satellites are operating at a lower system voltage than was ever imagined

High priority on surviving and collecting science data during the full sun period

- Consistent with approval from Joint Steering Group to “Fly Until Dry”
- Aging batteries and propellant are now critical life limiting factors
- Anticipate the satellites will be passivated and decommissioned by the end of the year

GRACE Mission Operations has been very labor intensive over the past year

- The team at GSOC, JPL and UTCSR have worked tirelessly to continue the operations
- They are to be commended for an excellent effort to bridge the gap to GRACE-FO

15 Years! 3 Times Mission Life ... It's been a heck of a ride!!