Status of the GRACE Follow-On Mission

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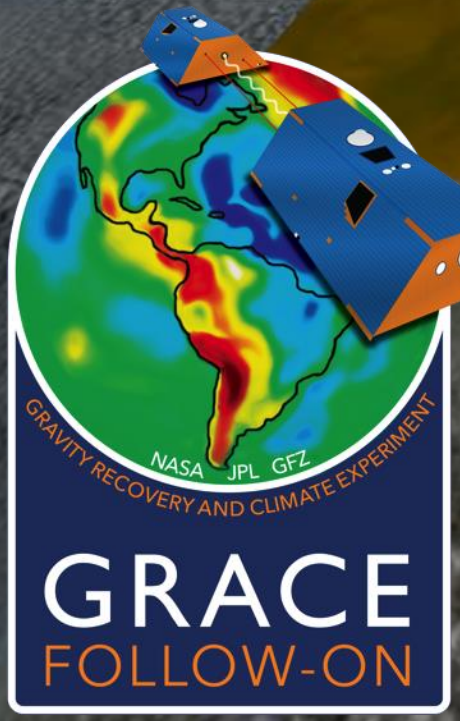
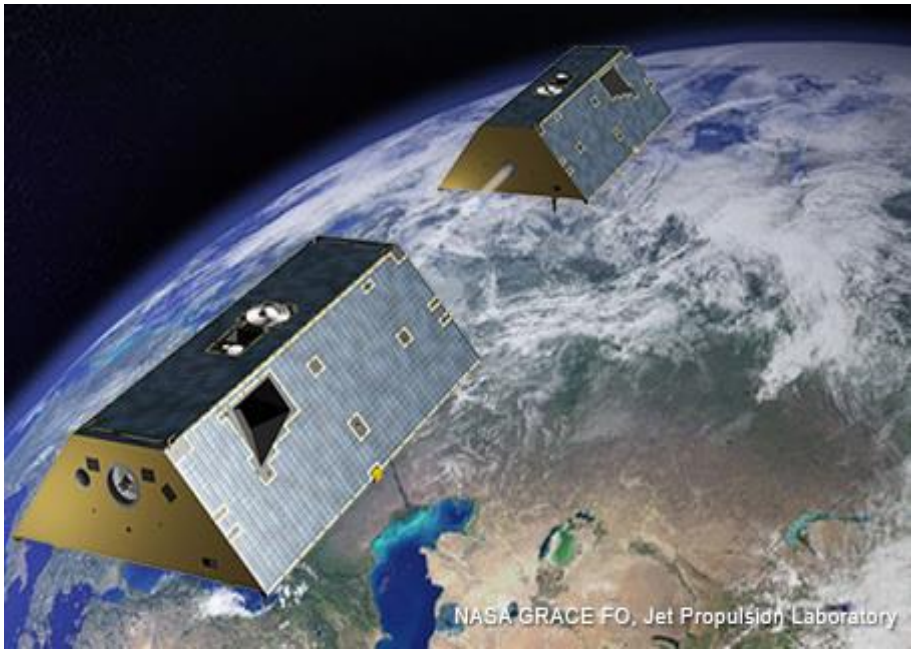


Outline

- **Background**
- **Project Status**
  - Implementation Status of Satellites and Instruments
  - Launch Vehicle
  - Mission Operations
  - Science Data System “Grand Simulation”
- **Activities after Launch**
  - LEOP, IOC, Initial Science Phase
- **Summary/Outlook**

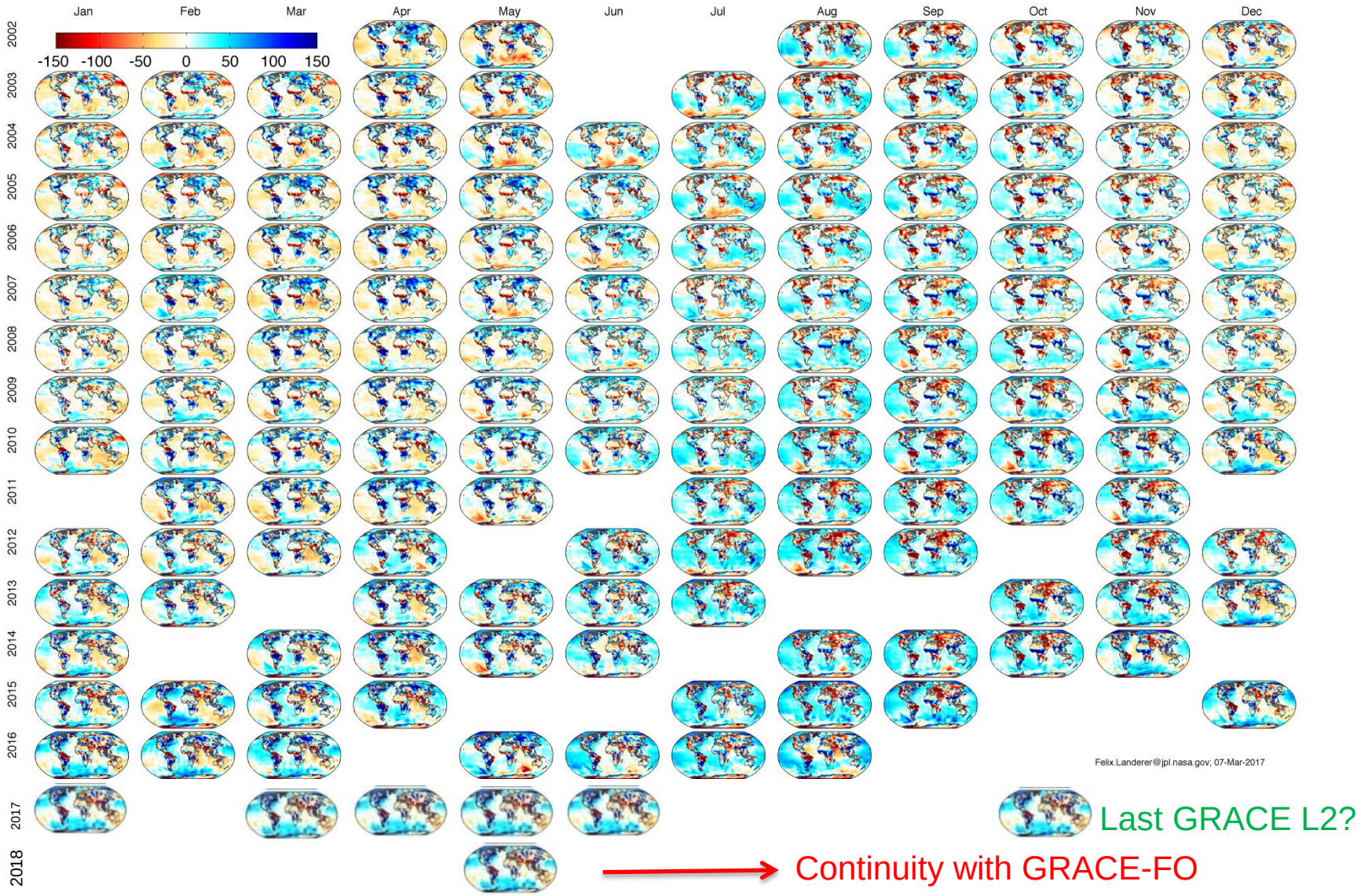


Background

- **Primary Mission Objective** is to continue to obtain the same extremely high-resolution global models of Earth's gravity field, including how it varies over time, as in the original GRACE mission, launched in 2002 and still operating.

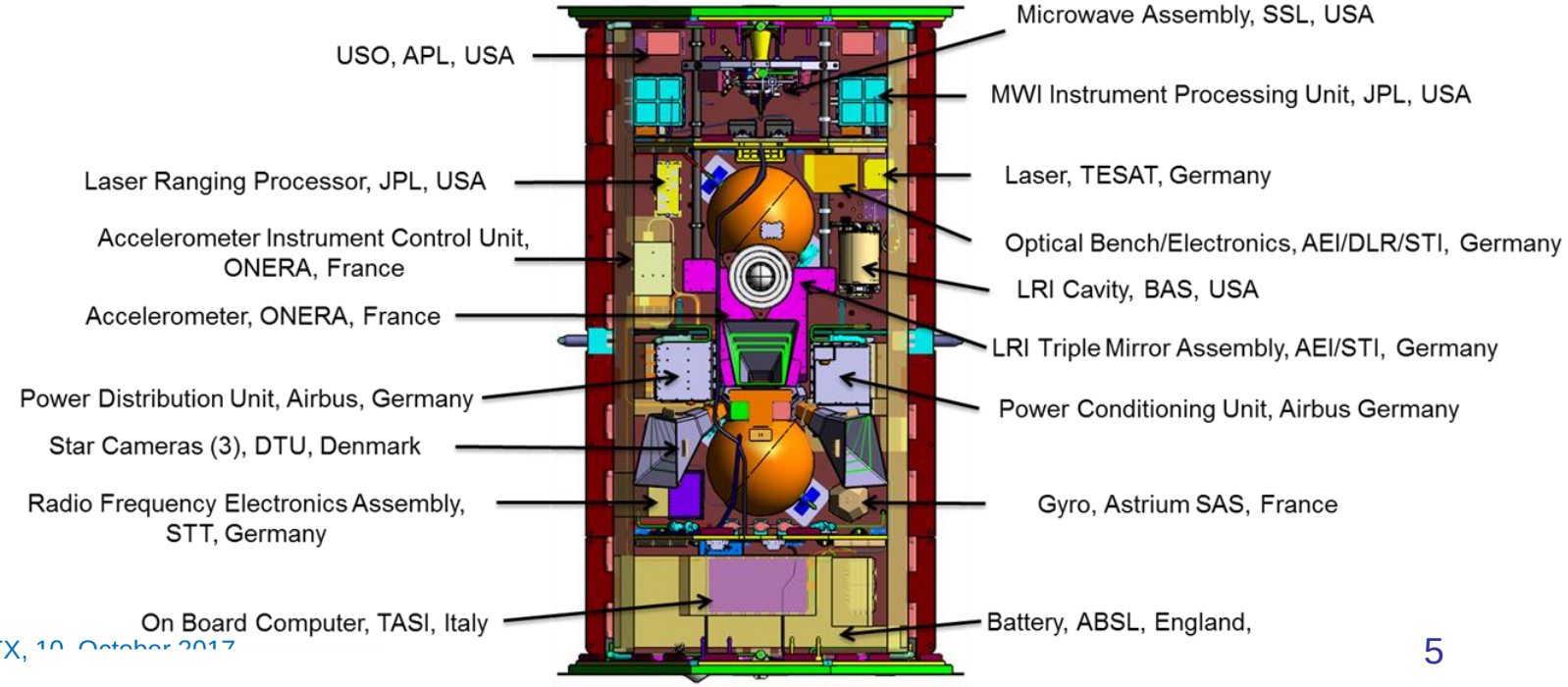
- **GRACE-FO follows the original GRACE mission**
  - Continues the record as a gap filler between GRACE and a NGGM (e.g., GRACE-2)
  - Continues time series of RO measurements (secondary objective)
  - GRACE-FO will also demonstrate Laser Ranging Interferometer technology in support of future GRACE-like missions. This is an important component of interest to both NASA and ESA.

Continuity – from GRACE to GRACE-FO



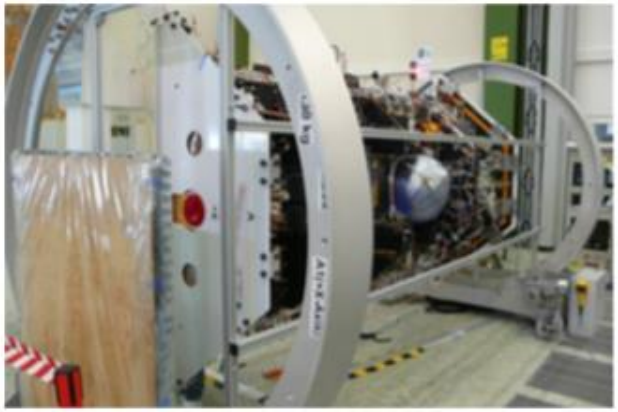
Implementation Status

- Project is currently in ATLO (Assembly, Test, and Launch Operations) phase
  - Both flight systems (FM1 and FM2) are fully integrated (i.e., Accelerometer, Star Cameras, MWI, LRI)
  - All environmental testing has been completed at IABG.
  - Post environmental alignment measurements have been completed on both s/c.
  - Mass Properties was completed on Satellite FM1 and is in process on FM2
  - Both Satellites are completing final system phasing tests prior to shipment to VAFB (planned for mid-Dec)

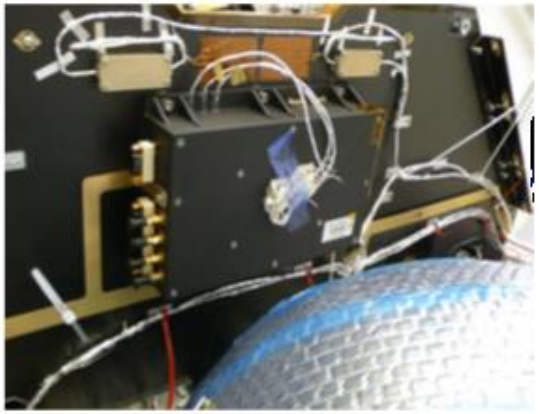


Integration Highlights (@ Airbus D&S GmbH)

ACC/STR/TMA Integration
On FM1 with nominal shims



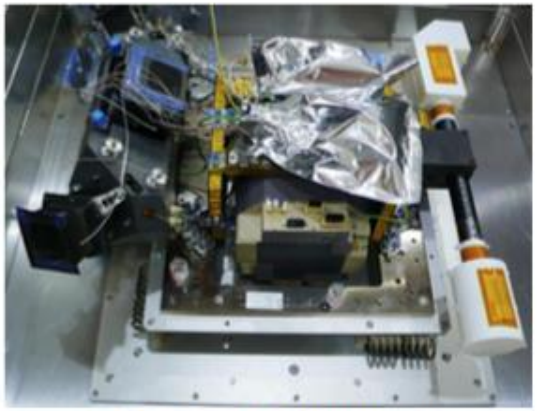
S/C FM1 Status



OBE Integration
Mechanical integration on FM1

MTE integration
On FM2

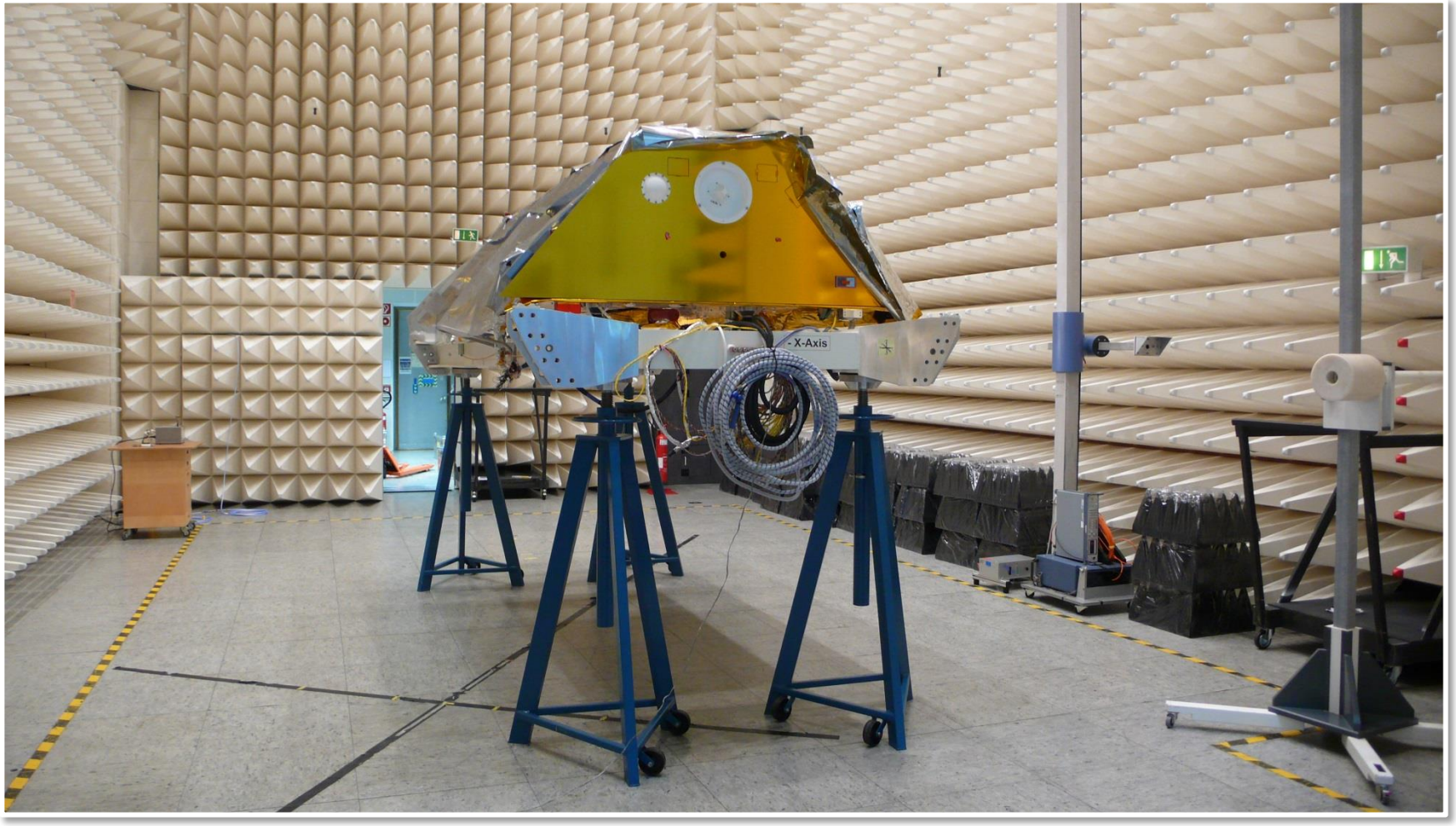
MTQ Electrical Integration
During magnetic field measurement



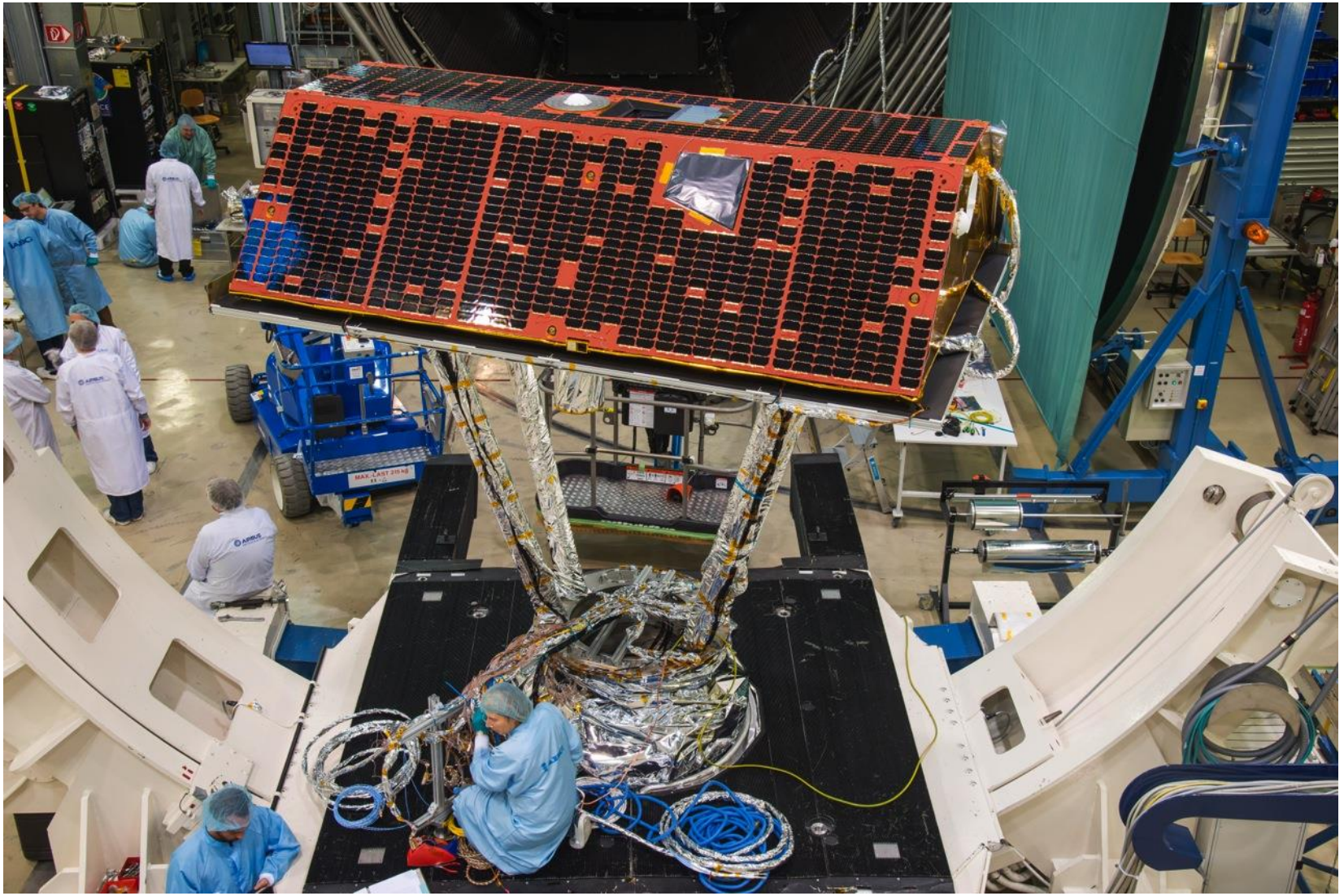
ACC/STR/TMA Integration
Final mounting of LRI TMA on FM1

FM1 during Integration (@ Airbus D&S GmbH)

FM1 during EMC Test (@ IABG)



FM1 in Thermal Vacuum Chamber



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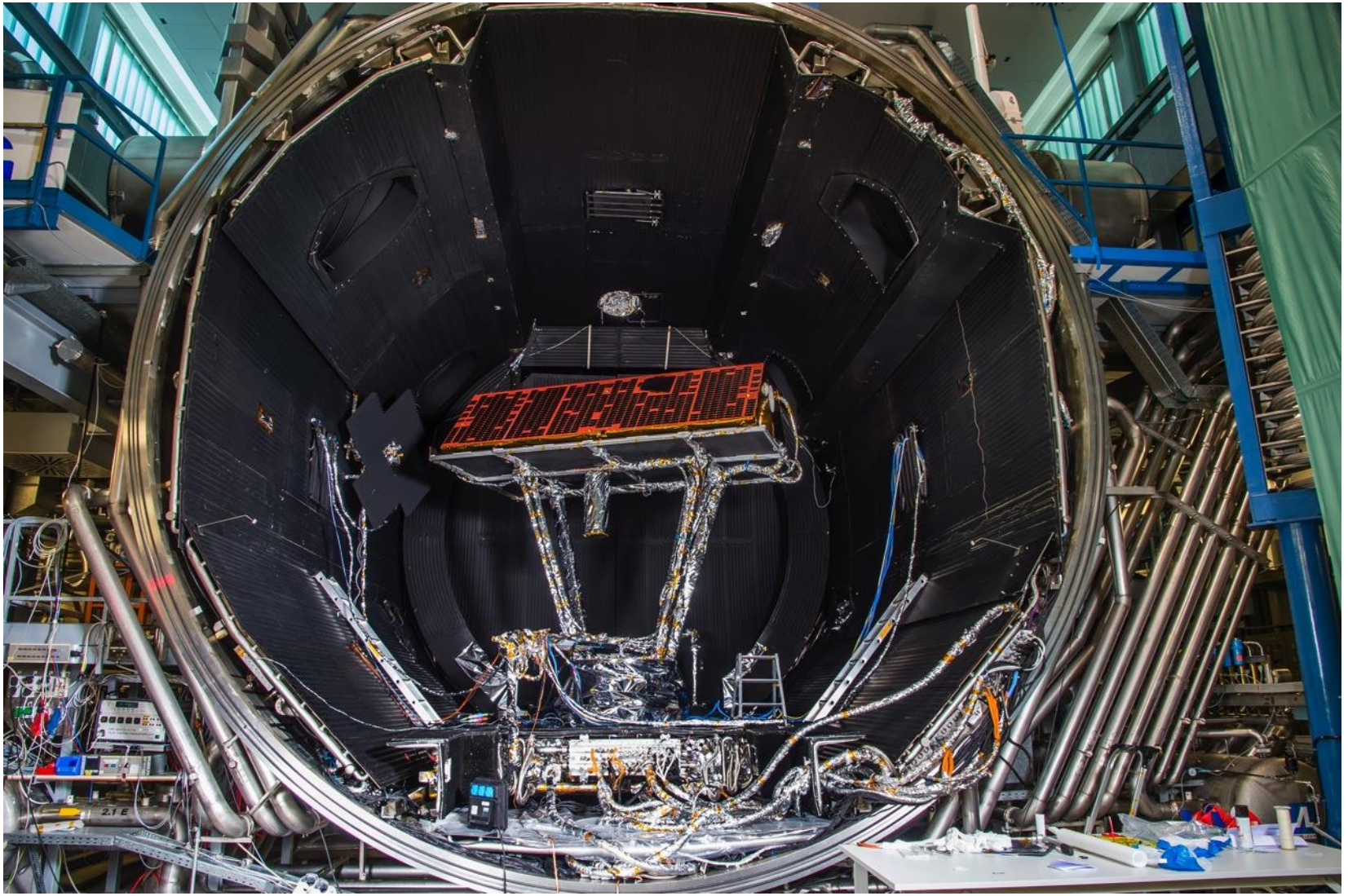

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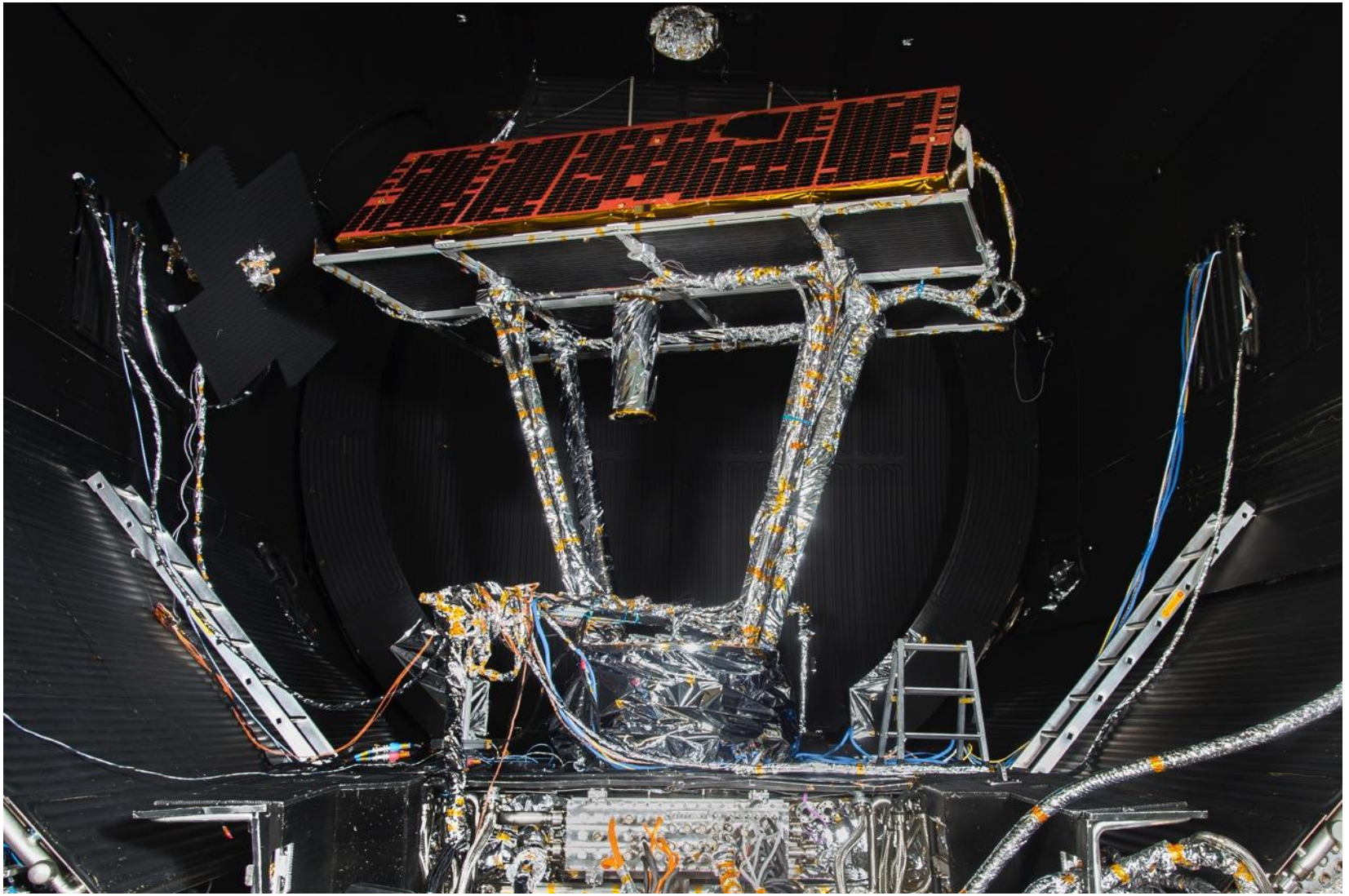
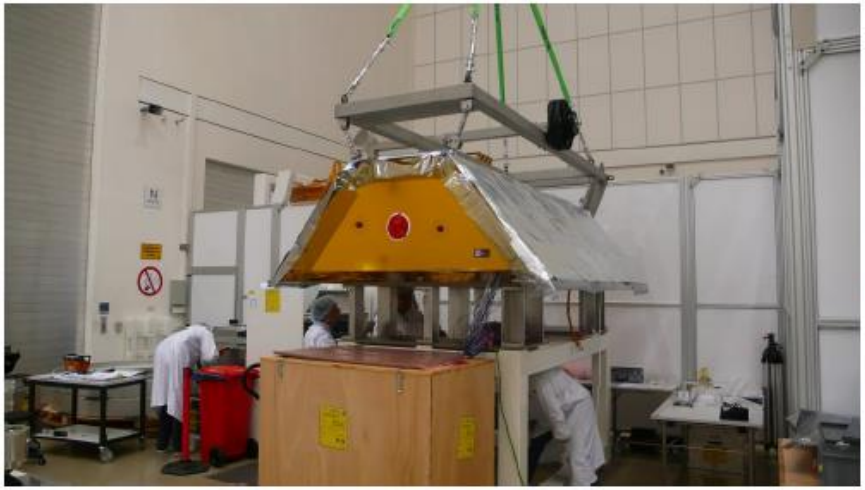


Recently: Vibe Tests & Boom Deployment Test

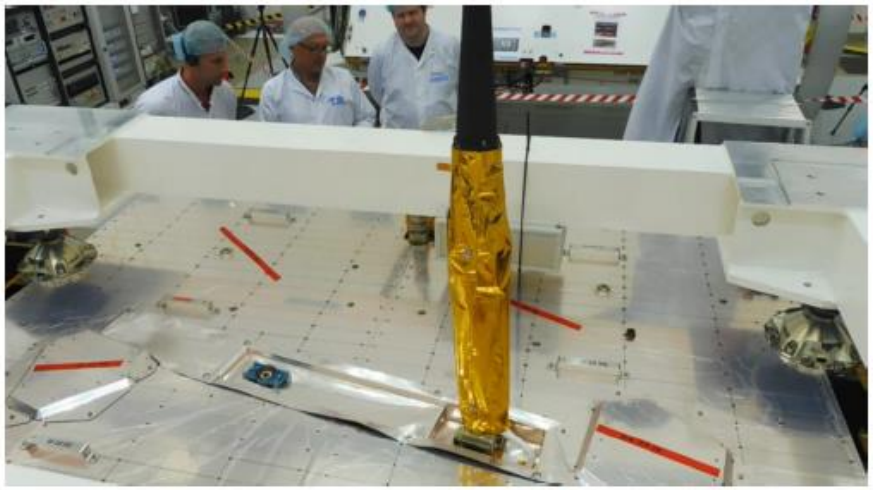
Highlights 6/2017

FM2 during sine testing (x-axis)

FM1 prepared for post-environmental alignment measurements

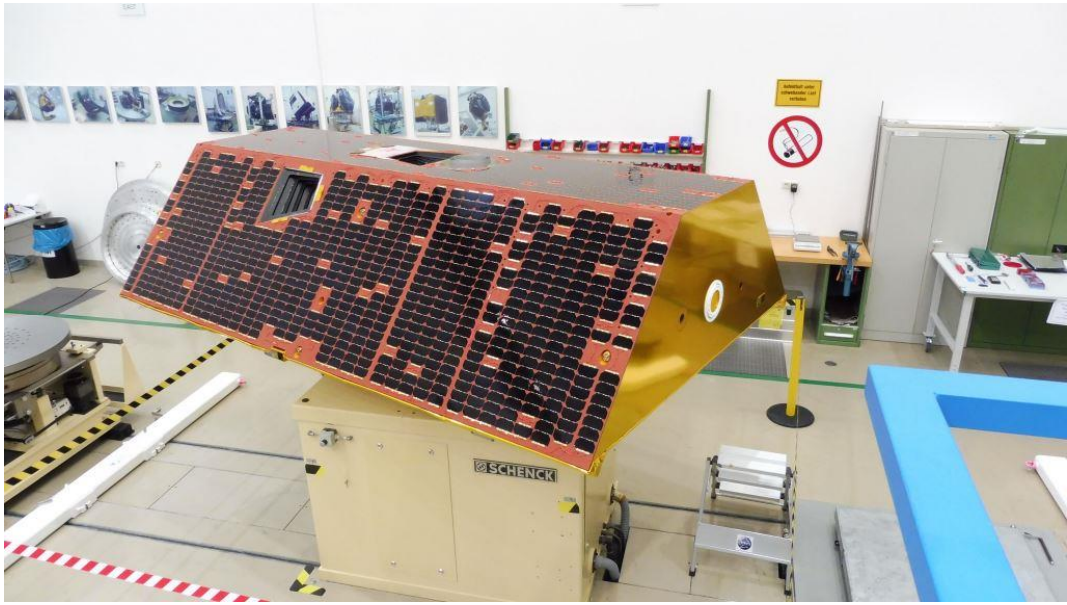


HRS removal on FM2 after sine testing



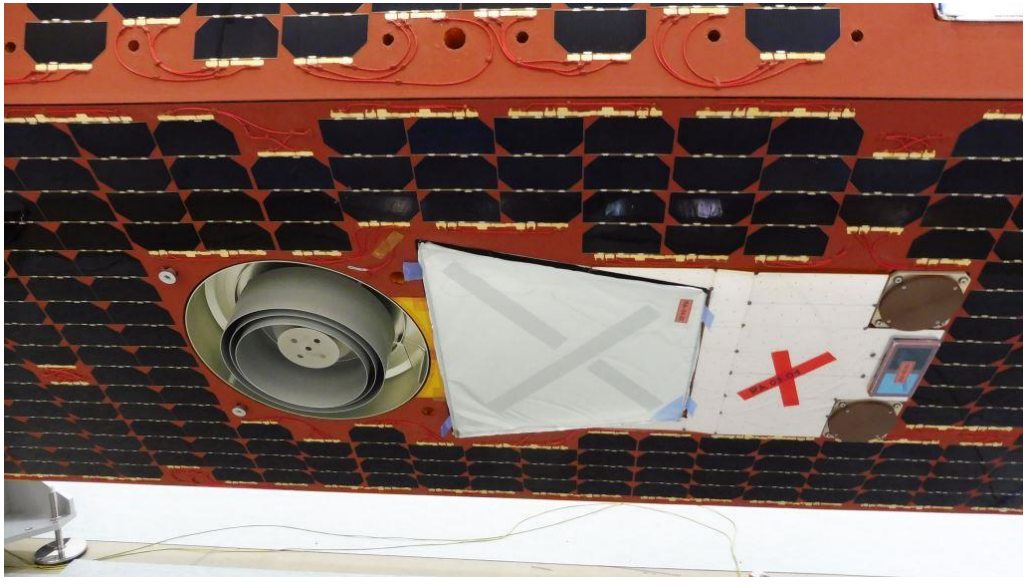
FM1 after successful boom deployment test

Recently: Mass Property Tests (FM1)

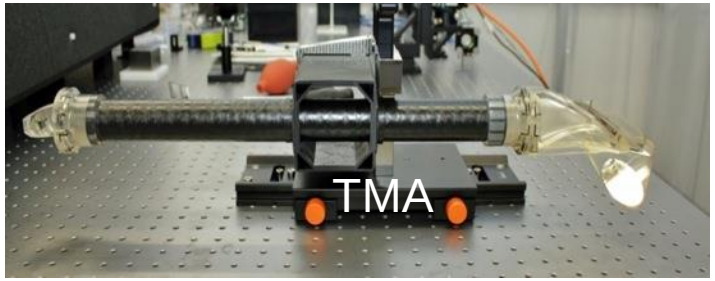


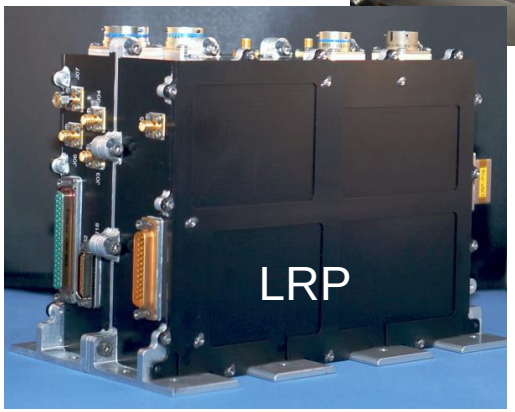
GPS POD Antenna

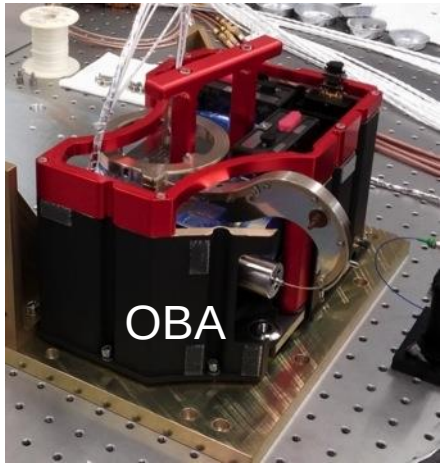
- During lifetime testing (PQV testing), after approx. 700 thermal cycles, the GRACE-FO GPS Antenna exhibited unexpected performance change.
- Alternate flight qualified GPS antenna has been identified from RUAG; EM unit was characterized at JPL.
- RUAG antennas with choke rings were procured to replace the current POD antennas.
- No impact on Assembly, Test, and Launch Operations (ATLO) schedule.

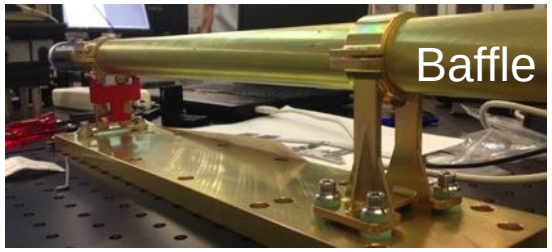


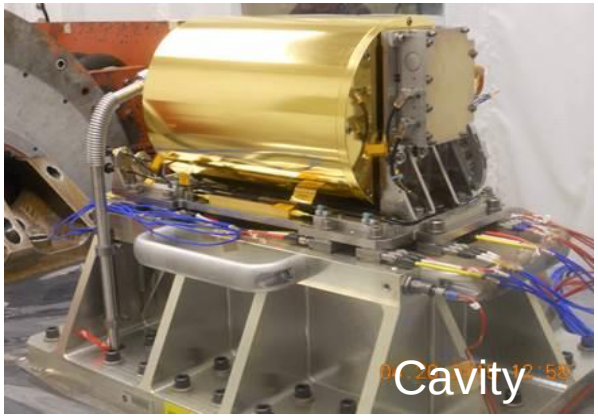
LRI components











Cables not shown (complete):
LRP-CAV: power, coax (x2)
LRP-LAS: power, cmd/tel
LRP-USO: coax (x2)
OBE-LRP: coax (x4), cmd/tel
OBE-OBA: Tel, power

Implementation Status – LRI

Cavity

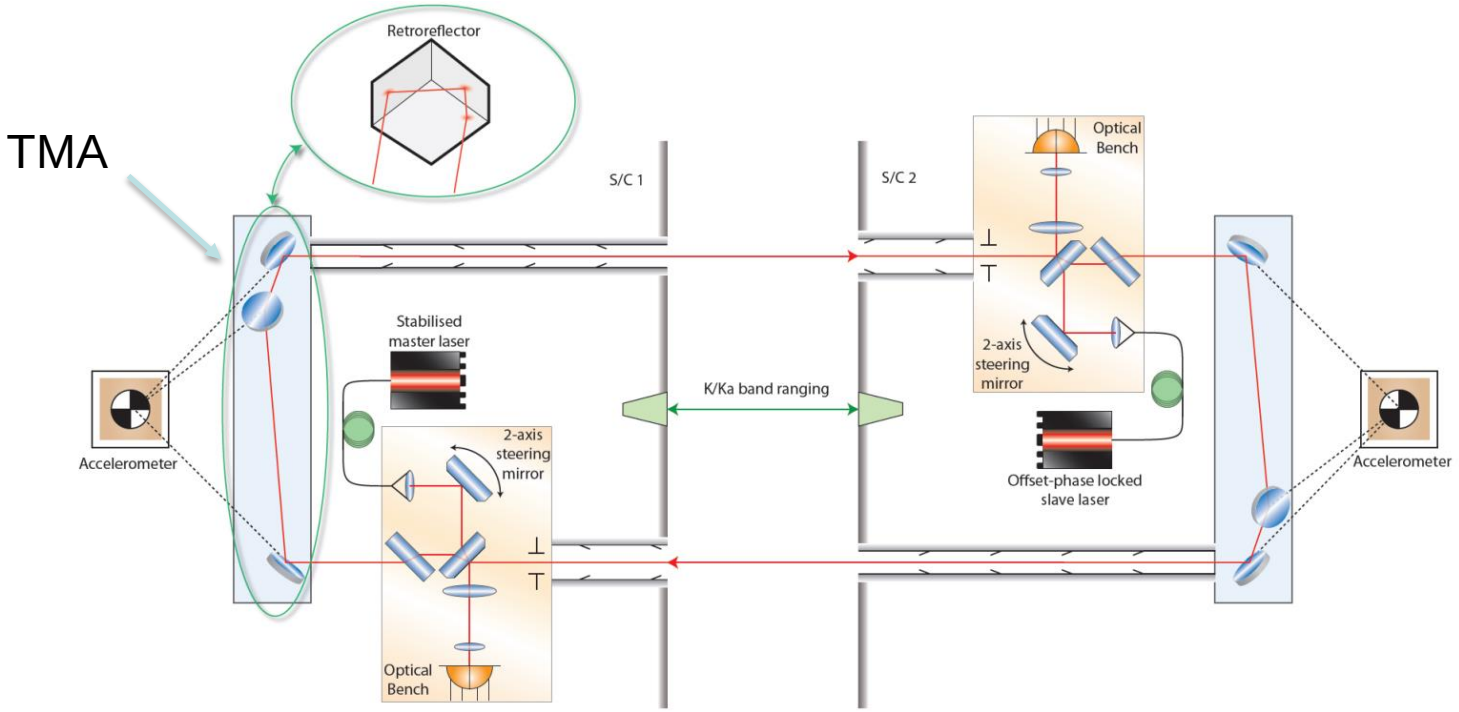
- Anomalies were observed in LRI S/C-2 Cavity after thermal tests
- Repair and spacecraft re-integration of the Cavity on S/C-2 is complete.
- All tests have shown that LRI Cavity #2 is meeting its performance requirements after re-work (Cavity #1 has always met its performance requirements).

Tripple Mirror Assembly (TMA)

- An anomaly was detected on the TMA on SC-1 in August 2017 after sine vibration test

TMA in the Laser Ranging Interferometer

- "Racetrack" originally conceived to evade constraints has triple mirror assembly (TMA) to route beam through spacecraft
  - Outgoing beam counter-propagates to incoming beam to precision of TMA construction: any deviation from this is called *"Co-alignment error"*
  - Vertex of TMA designed be located at the CoM, first order insensitive to spacecraft jitter
  - Measurement is exactly the round-trip distance, insensitive to paths on optical bench



Sheard et al. *"Intersatellite laser ranging instrument for the GRACE follow-on mission"*, Journal of Geodesy,

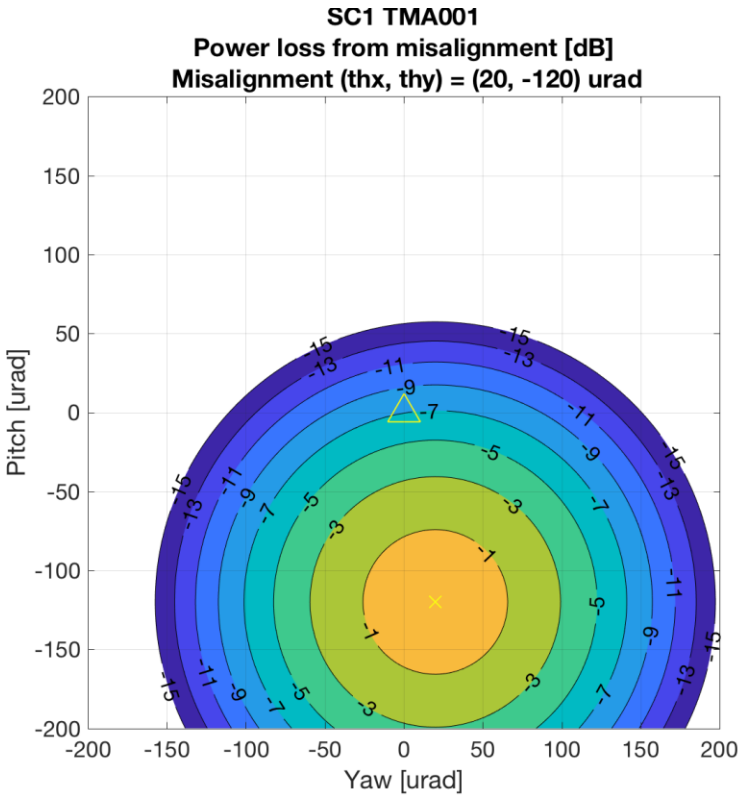
Implementation Status - LRI

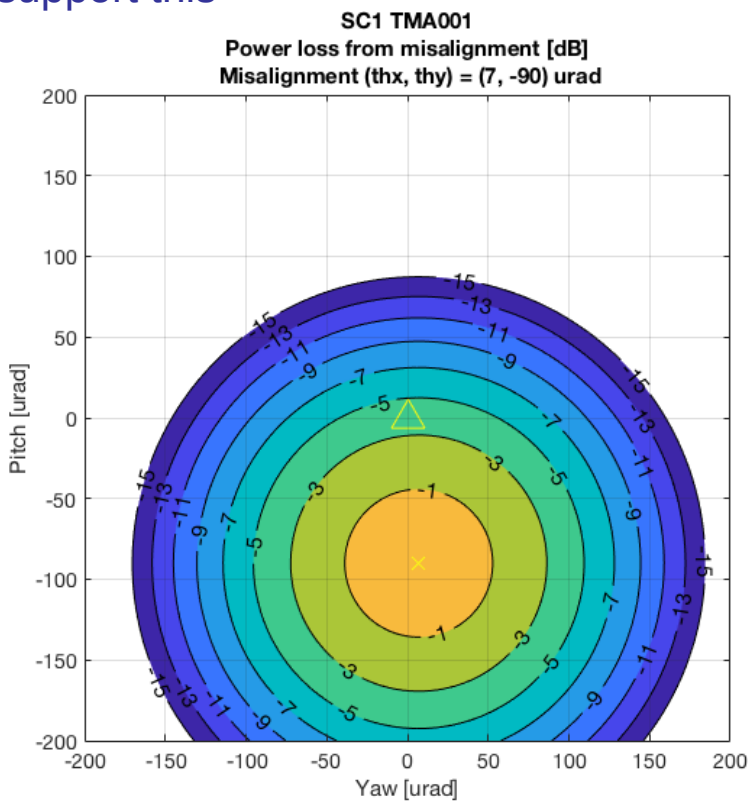
- An anomaly was detected on the TMA on SC-1 in August 2017 after sine vibration test
  - The co-alignment error (deviation from a perfect retroreflector) increased (120 urad) and no longer meets requirements (<40urad).
  - At the current co-alignment error; less optical power will reach the distant spacecraft but the LRI is expected to be able to operate (i.e., form the inter-spacecraft optical link). In this case the LRI performance won‘t be degraded.

TMA co-alignment error with pre-compensation

Power loss at distant Spacecraft due to co-alignment error is -7dB
-> LRI would have negative margin on received power

Power loss at distant Spacecraft can be reduced by **compensation on the local SC.**
Approx -1dB signal power loss on **local** SC
Approx -4dB signal power loss on **distant** SC
-> New LRI FSW is in development to support this



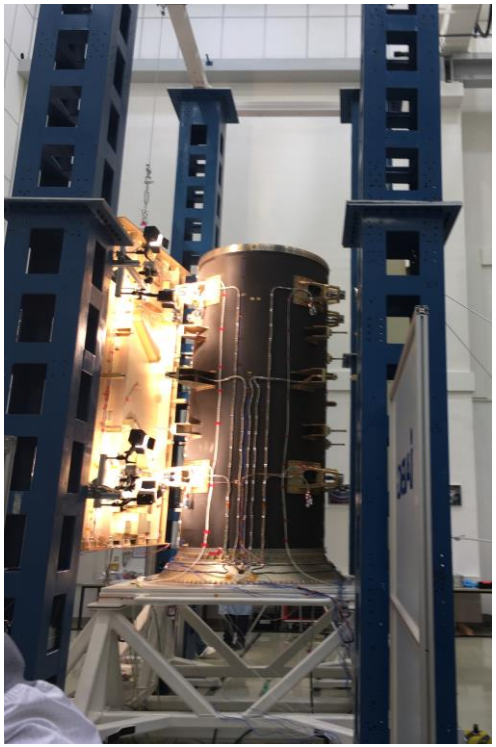


Launch Vehicle

- GRACE-FO is a collaboration between NASA, leading on the US side, and GFZ, leading on the German side.
  - GFZ is responsible for providing the launch services and the multi-satellite dispenser.
- GFZ was notified by Russian Foreign Ministry early 2016 that the Dnepr program is now on hold; subsequently, the GRACE-FO Project decided to pursue other launch opportunities in order to maintain schedule (original launch date was 5. August 2017).
- GFZ has signed in November 2016 a contract for a ride-share launch with five Iridium NEXT Communications satellites on a SpaceX Falcon 9 rocket from Vandenberg Air Force Base in California in the December 2017 – February 2018 timeframe.
- Launch Period shifted by CCN to January 15 – April 15 2018 with a Launch Slot March 17 till April 15; Target launch date: March 21, 2018.

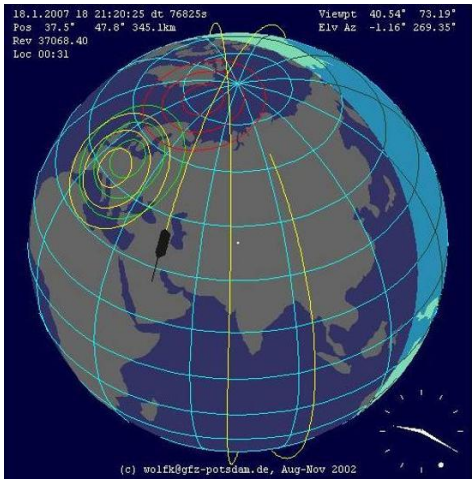
Multi Satellite Dispenser

- Built by CASA Espacio (Spain): long & robust history for this MSD design
- MSD delivered to IABG: July 7
- Fit check between SpaceX Payload Adapter Ring and MSD: July 18
- Fit Check MSD to S/C: July 27
- Separation Test MSD – S/C Dummies: September 19
- DRB Airbus – GFZ: September 25



Mission Operations System (MOS)

- MOS and Phase E operations (5 years) are contributed (funded!) by GFZ
  - DLR/GSOC provides the GDS (based on existing multi-mission GDS) and Phase E operations (similar to GRACE mission) under contract to GFZ
  - GFZ provides and operates the primary downlink station at Spitzbergen and performs Flight Control Procedure (FCP) development and validation
  - DLR/GSOC & DLR/DFD provide the stations for uplink (& additional downlink)
  - NASA provides 4 NEN stations for LEOP and contingencies (up- & downlink)



- GDS has already been successfully validated in 4 System Validation Tests (SVT) – 2 on the Flight Model.

Mission Operations System (MOS)

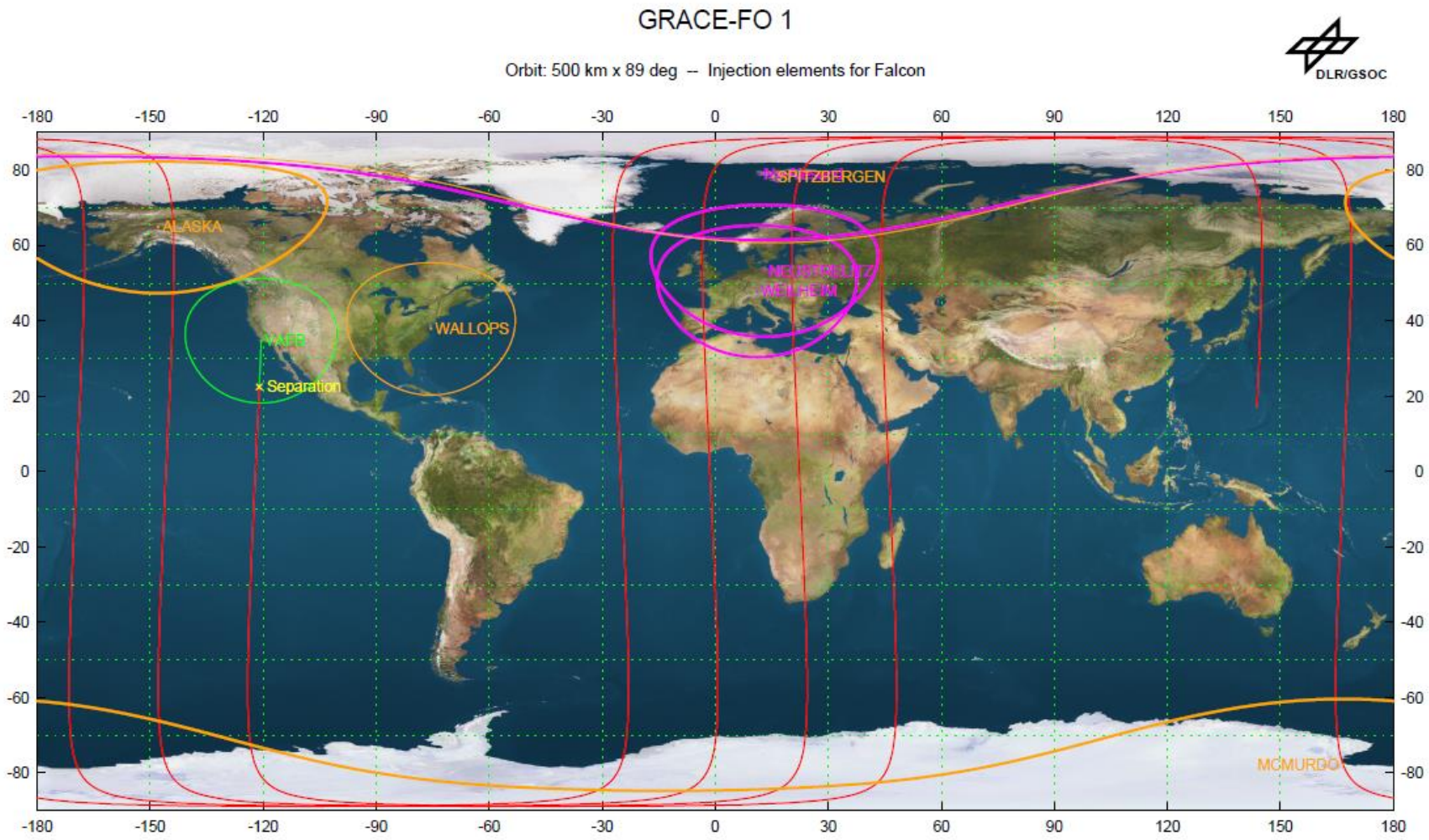
- Airbus D&S
  - is supplying key MOS documentation and satellite FCPs according to plan
  - has supplied 4 spacecraft simulators to GSOC used for GDS integration and testing as well as FCP validation
  - has performed 7 training sessions at Oberpfaffenhofen
- Successful interface tests
  - RF compatibility tests were performed between the ground stations (WHM, NEN and NYA) and the Radio Frequency Equipment Assembly (RFEA)
- Flight Control Procedures (FCP) development is in progress (~91% ready), FCP validation on schedule (~74% done).
- Ongoing / Upcoming
  - Simulation & Training Sessions: CTS-1 (July 26/27), CTS-2 (November 13/14), CTS-3 (mid February)
  - Operations Readiness Review (ORR) (18./19. January)
- MOS is on schedule for launch in March 2018!

Science Data System (SDS):

- Verify and Validate the SDS centers' software and interfaces using a realistic, simulated data set, including:
  - Current best estimate of instrument noise/errors: KBR, LRI, ACC, SCA and GPS
  - Timing errors, alignment errors
  - AOD product included, but no AOD errors or any other geophysical related errors
  - JPL has been conducting "Grand Simulation" tests (more on this later)

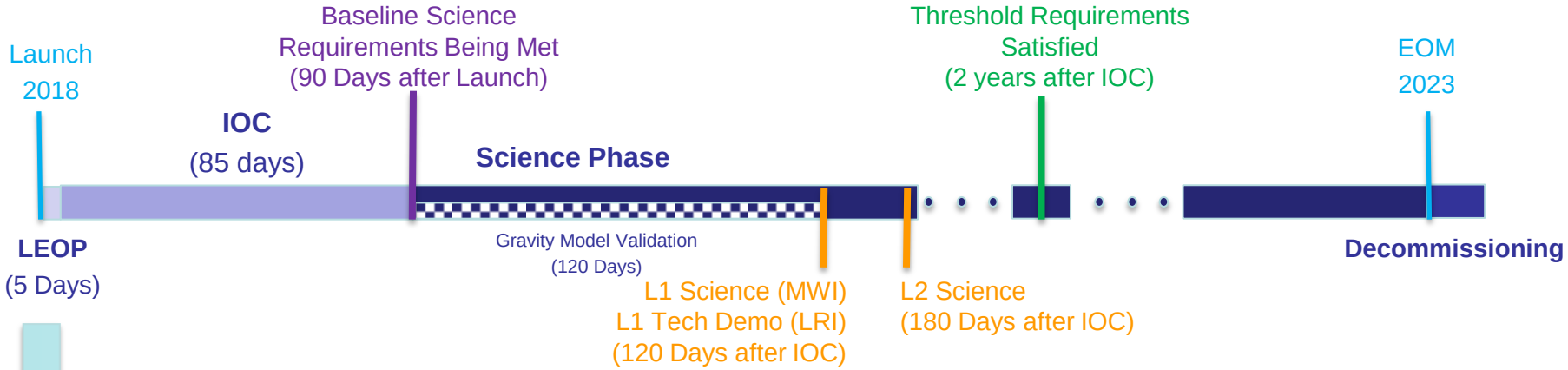
- "Grand simulation" data release to science community:
  - Level-1B release (Late 2017): for science community software V&V only, and *not* gravity recovery science analysis.
  - All Level-1B data will use standard GRACE formats (in ascii) (LRI1B uses KBR1B format), but with some updates;
  - Models used for simulation at time of release to be fully disclosed

Preliminary Injection Orbit for March 21, 2018



~L+25m: MGS ~L+69m: SGS ~L+77m:ASG ~L+140m: WHM

After Launch: LEOP & IOC Activities / Time Line

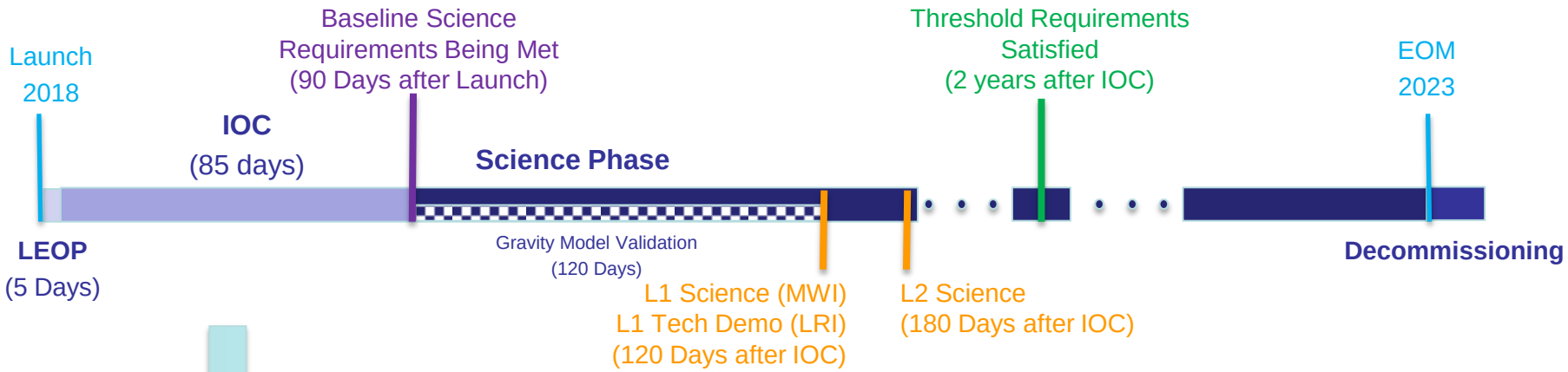


LEOP (~ 5 days)

Main Tasks:

1. Assess flight dynamics
2. Nominal uplink/downlink communications with ground stations
3. The nominal separation distance between the satellites has been achieved and stabilized
   - First GPS and SCA data
   - GPS data, clock, SCA quality analysis
   - Achieve orbit / separation specs
   - KBR baseband predicts
   - GPS-only precision orbit determination (POD)
   - AOCS performance analysis

After Launch: LEOP & IOC Activities / Time Line

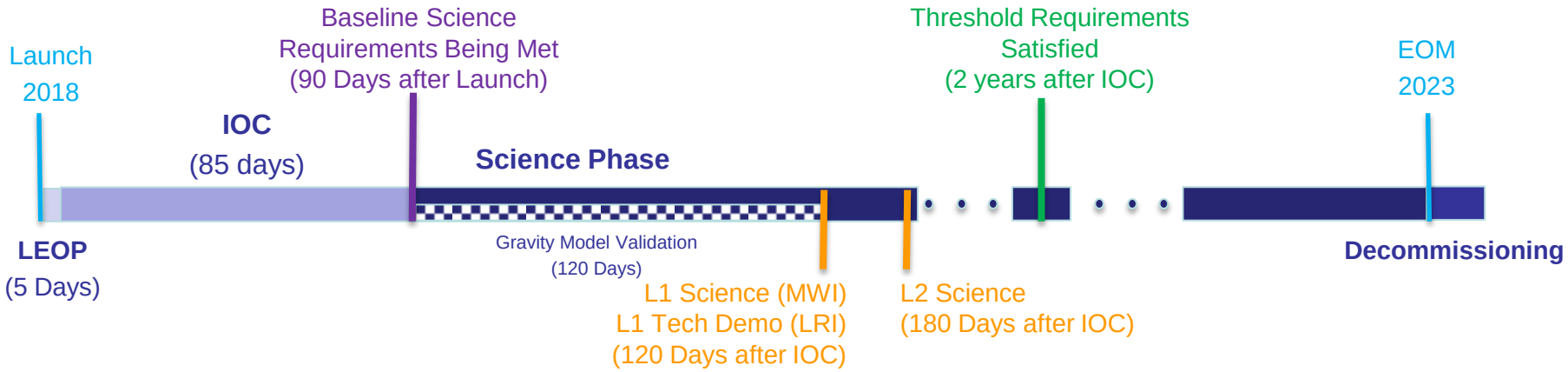


IOC (lasts 5-90 days after launch)

Main Tasks:

1. Full power-on and check-out of all systems
2. Instrument Calibrations / Characterizations
3. Achieve thermal stabilization of the 2 satellites in ops. mode
   - ACC On, 1st data analysis (temperature stable)
   - Calibration and trim of CoM offsets in three axes
   - KBR and LRI Boresights calibration
   - Turn-On LRI-1 & LRI-2: LRI initial acquisition / locking
   - Software patches and parameter updates (as required)
   - Flight system characterization
   - 1st Daily QL fields / fine tune
   - SDS inter-comparisons/validations/updates

After Launch: LEOP & IOC Activities / Time Line



Science Phase (begins 90 days after launch)

Main Tasks:

1. Validation over 120 days ***after*** IOC completion; focus on providing an end-to-end characterization of the Science Instrument and Data Systems prior to first science delivery.
   - Continuous records of science data down-linked, any data flow problems are resolved.
   - The KBR bore-sight calibration is verified.
   - Precise orbit solutions are obtained and verified using terrestrial laser tracking data.
   - Initial solutions for the gravity field, along with ACC, LRI and MWI calibration
   - gravity field solutions are verified through a combination of internal consistency checks and comparisons with in-situ data.
   - Complete 3 monthly gravity models and perform Inter-comparison
   - 120 days after IOC: first official **GRACE-FO Level-1** delivery to User Community!
   - 180 days after IOC: first official **GRACE-FO Level-2** delivery to User Community!

Summary

- GRACE-FO satellite/instrument implementation & testing is proceeding well
  - Science instruments on both satellites are fully integrated
  - Test campaign at IABG wrapping up, S/C transport to VAFB early Dec.
- LRI TMA current co-alignment error on SC-1 may result in less optical power at the distant spacecraft, but the LRI is expected to be able to operate (i.e., form the inter-spacecraft optical link). New LRI FSW is in development to support this
- MOS implementation and testing is on schedule (ORR on January 18/19)
- Launch Vehicle
  - Switched to Falcon-9 (shared ride with Iridium-Next)
  - Target launch date is 21 March 2018
- “Grand Simulation” – Science Data System
  - Testing the complete SDS system from science telemetry to science Level-2/3 products and serves as the V&V.
  - though somewhat delayed, SDS still plans to distribute data to community