Status of the GRACE Follow-On Mission

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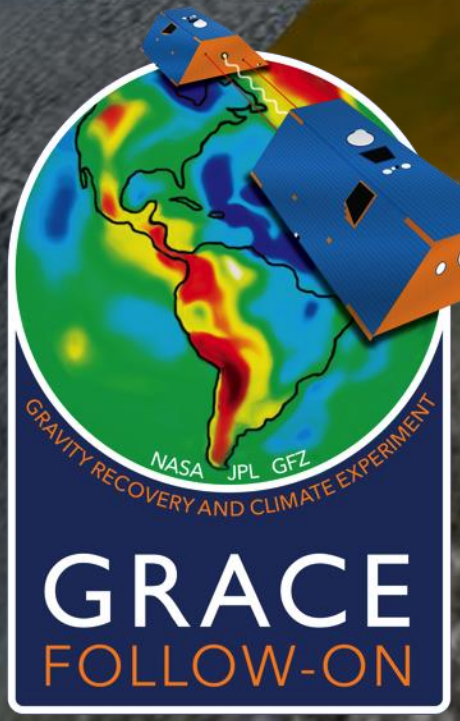

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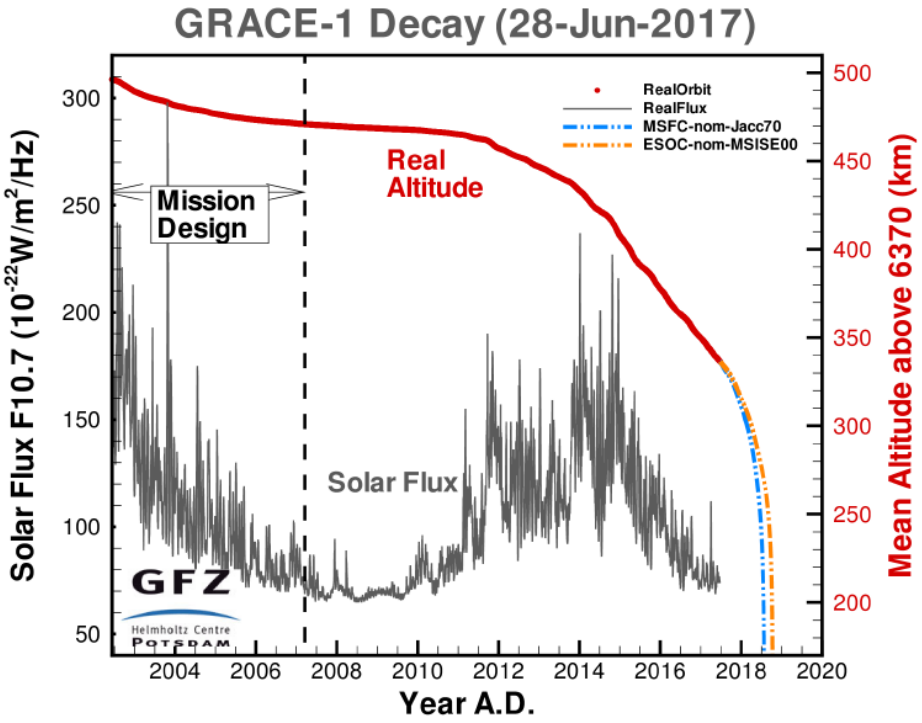
GRACE Mission Lifetime Issues (Status 2.9.2017)

- GRACE nominal life time was 5 years!
- Mission operations team: DLR/GSOC, JPL, UTCSR, Airbus D&S, GFZ
- Mission operations funding: 1.2 MEUR/yr (GFZ, ESA, DLR)



Altitude Decay – Today 320 km. Drag estimates predict lifetime until Aug/Sep 2018

Propellant for Attitude Control: Projections estimate operations until till fall of 2017.

Battery Capacity - Uncertain, but current strategy projects possible operation till fall of 2017.

Single String Instrument Failures: Could end the nominal mission at any point

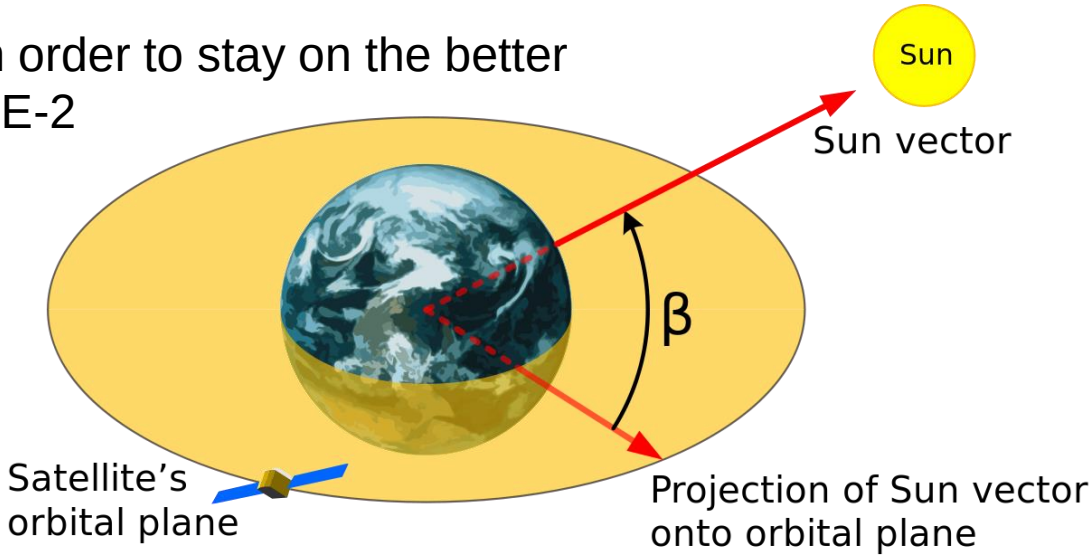
Measures to extend Lifetime to 15+ years (selected)

- Since 2011 regular (every 161 days) switch-offs of the Microwave Assemblies and Accelerometer Instrument Control Unit for about 30-40 days during β´=0° events.

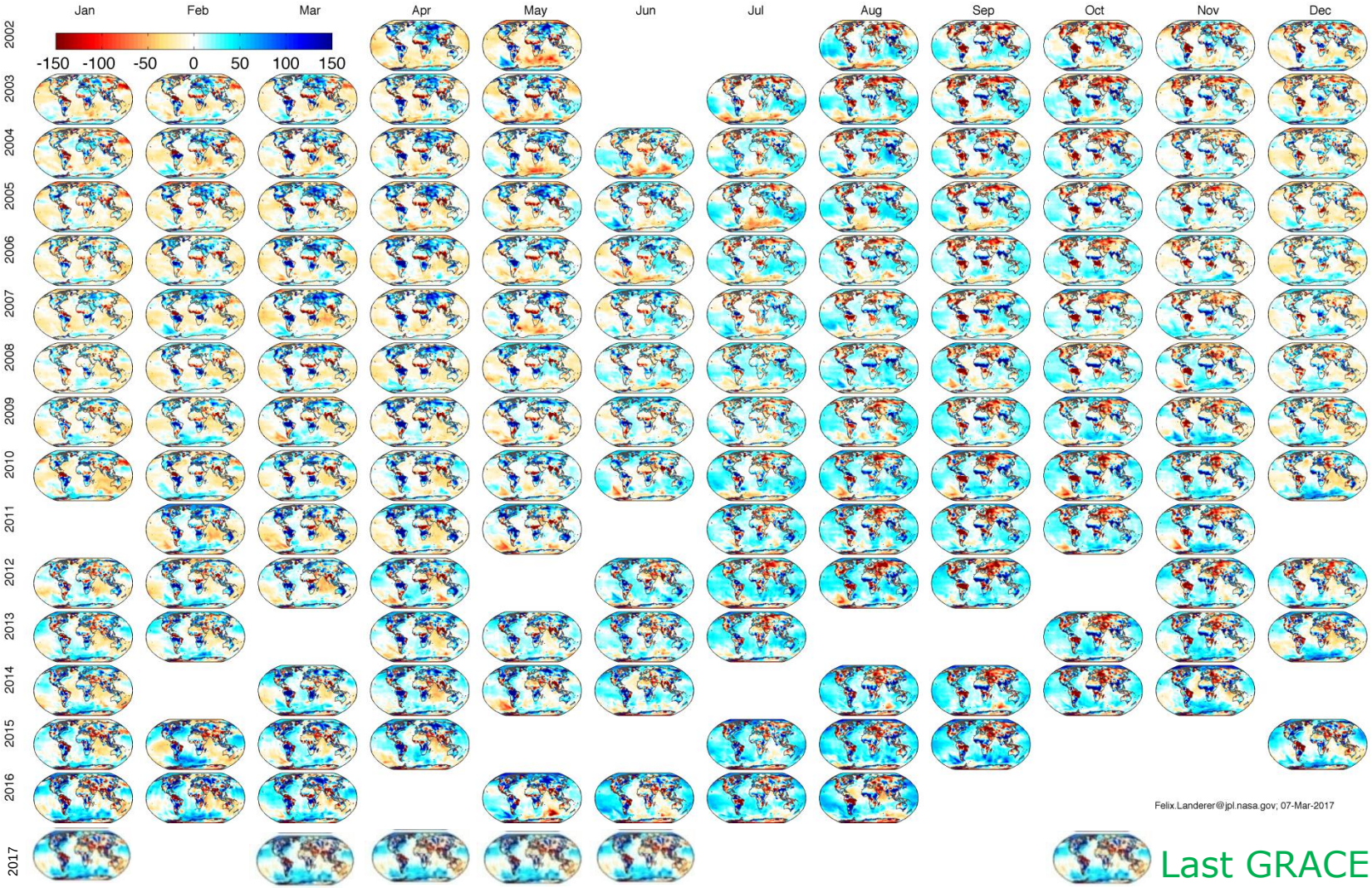
  Background: The GRACE orbit plane precesses at -1.117° /day relative to the Sun, such that the Sun is in the orbit plane every 161 days (β´=0°). Due to the power system status and desire for longevity, this event will henceforth define a 161-day work cycle for science operations.

- The GRACE-B ICU is permanently off (with some weeks of interruption in May 2017) since September 3, 2016 (transplant data from GRACE-A are generated).

- Satellite swaps during β´ events in order to stay on the better per-forming SCA head 2 on GRACE-2



GRACE Monthly Level-2 Products since April 2002



Last GRACE L2?

GRACE in New York Times

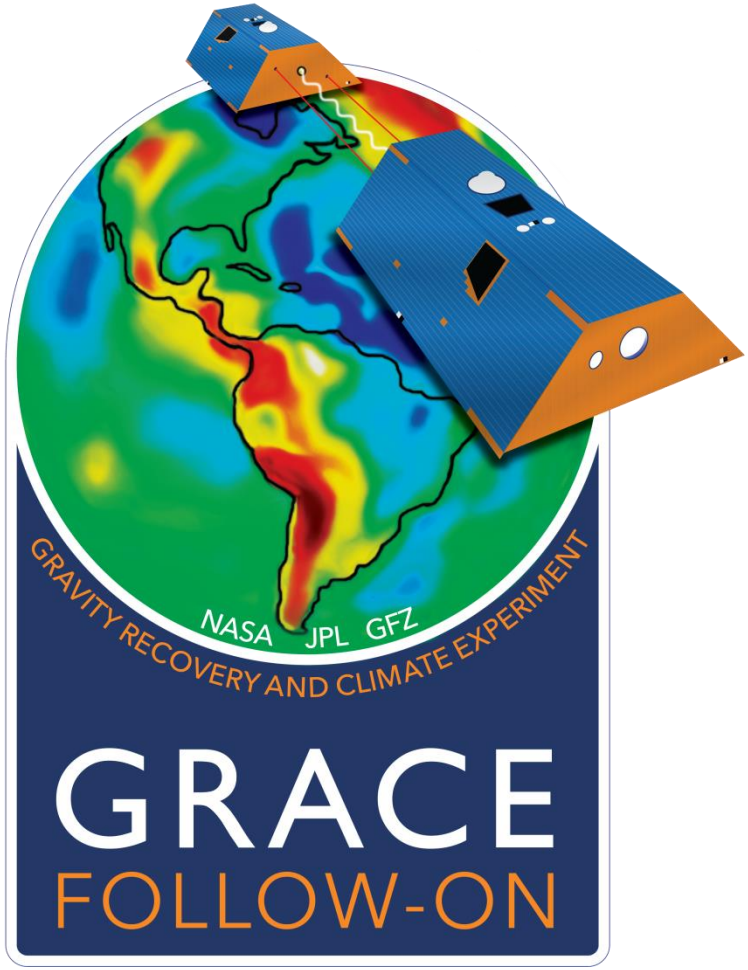
https://www.nytimes.com/2017/09/12/magazine/what-could-we-lose-if-a-nasa-mission-goes-dark.html?smid=tw-share

GRACE-FO

In 2011 **NASA and GFZ** responded to science community call for a continuation mission (GRACE Follow-On).

German Funding jointly secured by BMBF, GFZ, DLR (in kind contributions) and HGF.

GRACE-FO has been build and tested and is due for launch in March/April 2018.



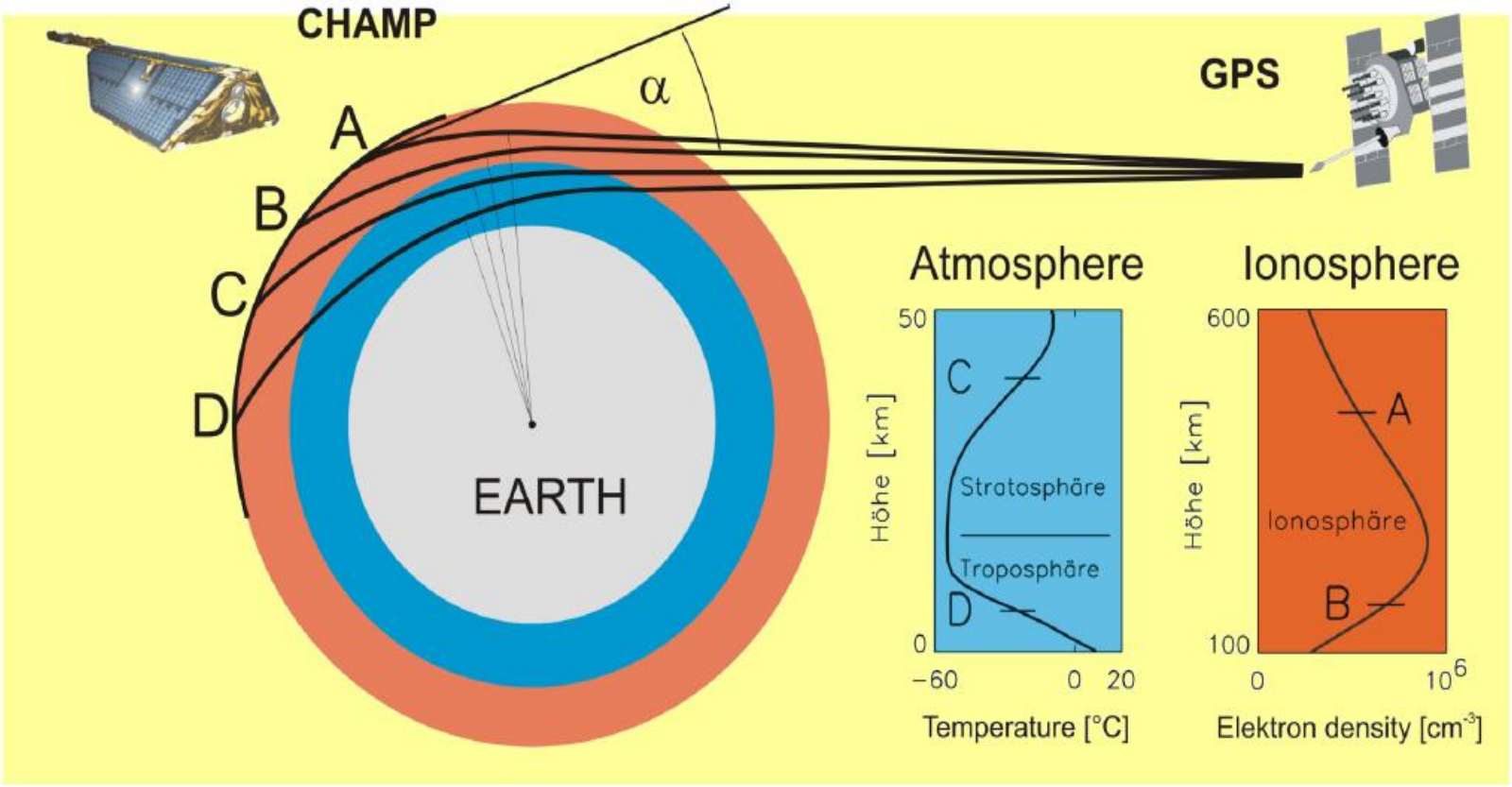
Mission Objectives

- The GRACE-FO mission's **primary objective** is to **continue the high-resolution monthly global models of Earth's gravity field** of the original GRACE mission, for an expected length of 5 years, with launch by 2017 (current target launch date 5 August 2017)
  - For this, evolved versions of the GRACE K/Ka-band microwave interferometer, GPS, star camera and accelerometer will be used

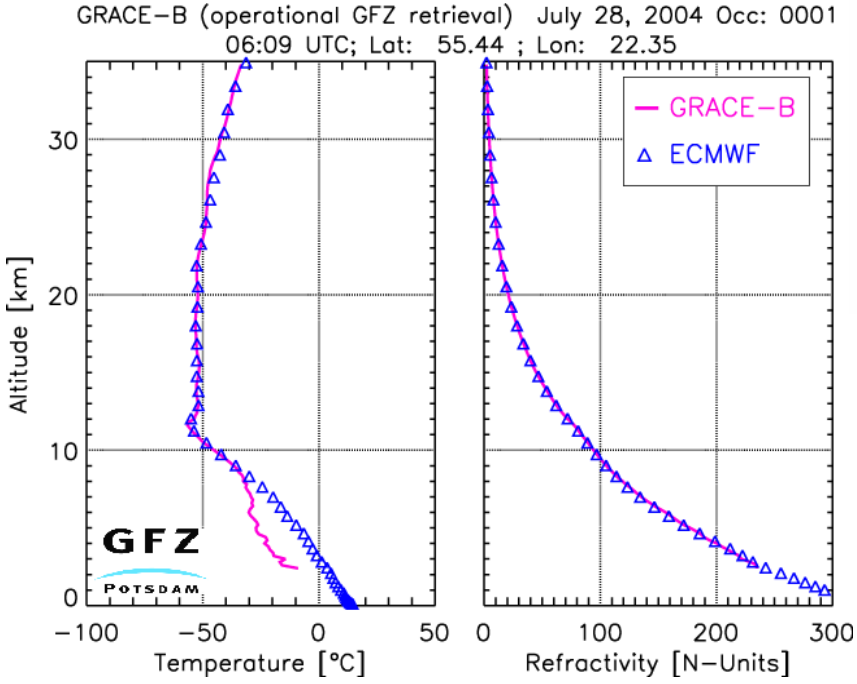
- **Secondary objectives** are
  - to demonstrate the effectiveness of a **laser ranging interferometer (LRI)** in improving low-low SST measurement performance
    - This will be the first ever inter-spacecraft laser interferometer
    - This instrument should lead to improved spatial resolution for future gravity missions, such as GRACE-II (although the final spatial resolution will depend on aliasing, number of satellite pairs, etc.)
  - and to continue measurements of GRACE **radio occultations** for operational provision of e.g. vertical temperature / humidity profiles to weather services.

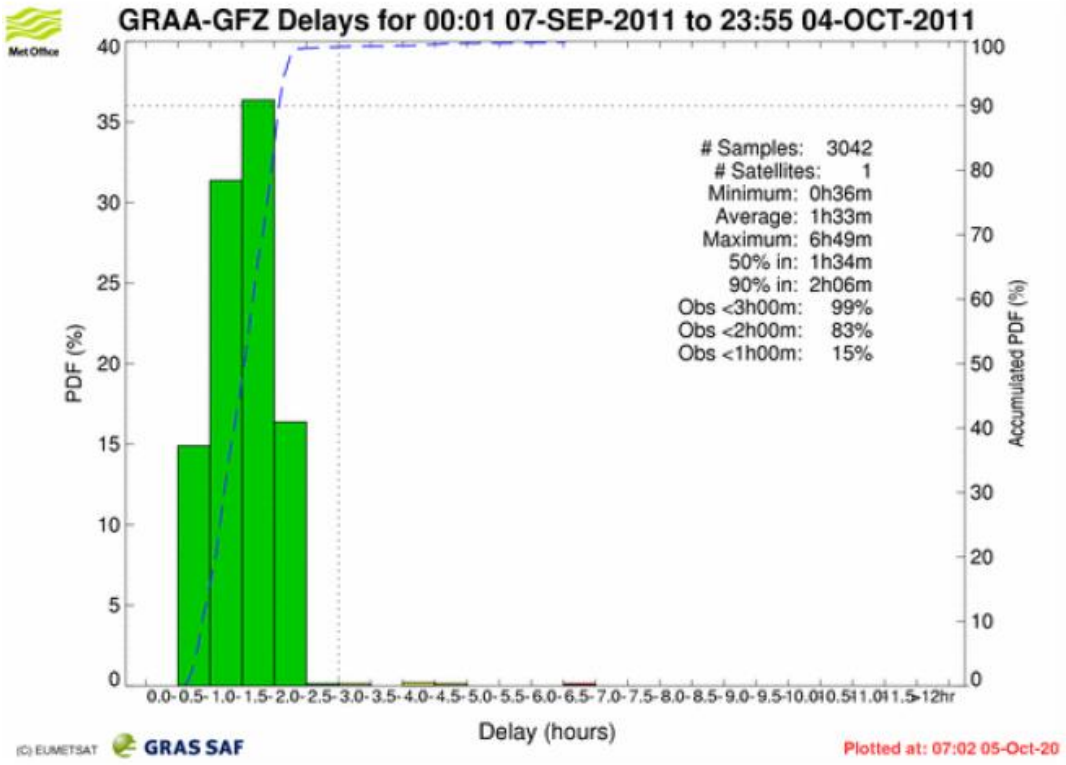
Radio Occultation Principle

or GRACE, COSMIC, TSX, TDX, GRACE-FO…



RO Applications: Operational Provision to NWS

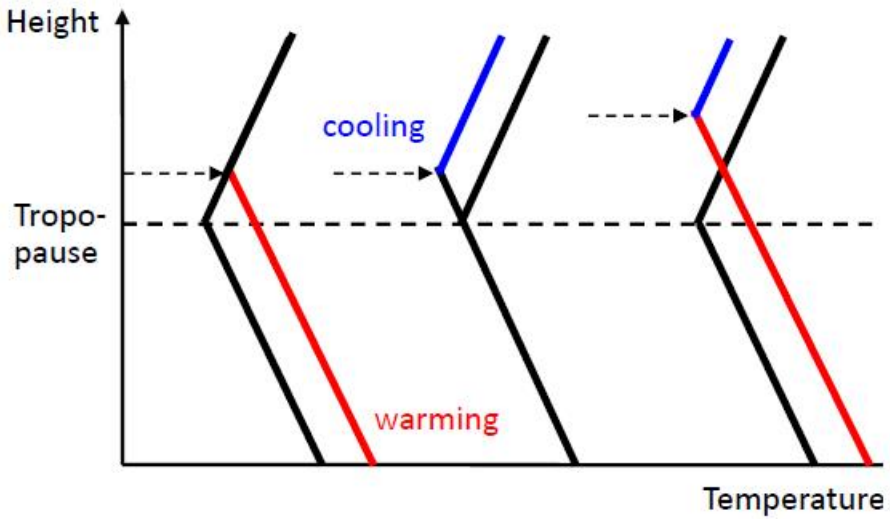




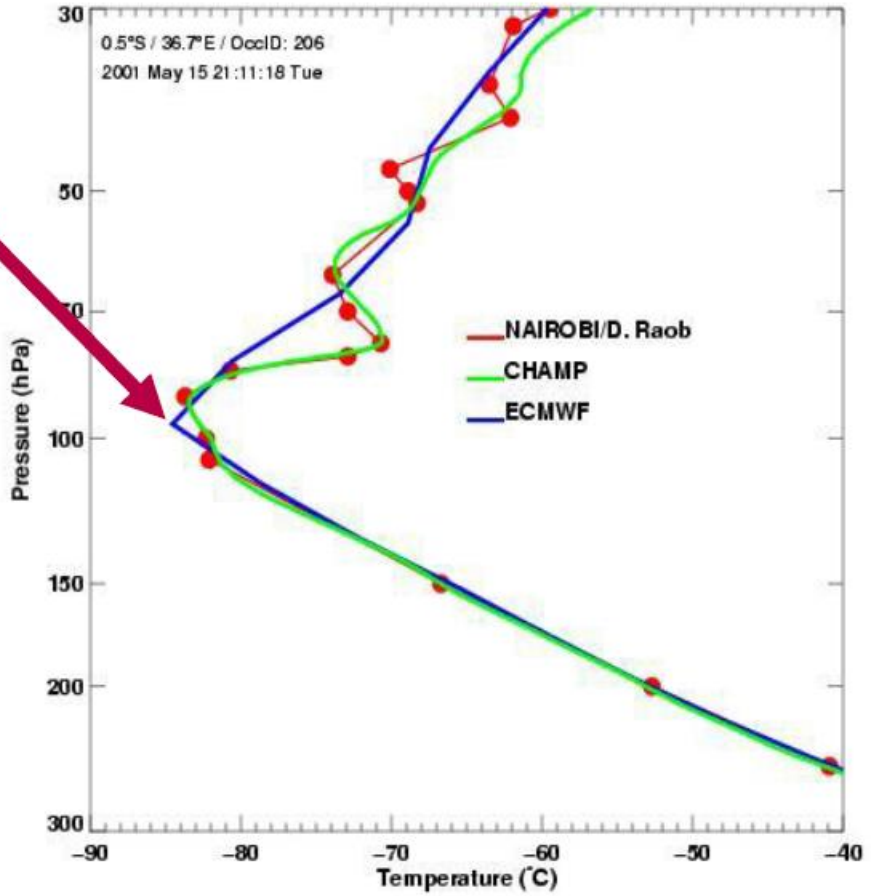
- (Near) Operational provision to NWS since 2006 (>95%)
- Average delay <2h (using GFZ NYA-SRS on Spitsbergen)

RO Applications: Tropopause Height Changes

Tropopause height as indicator for climate change



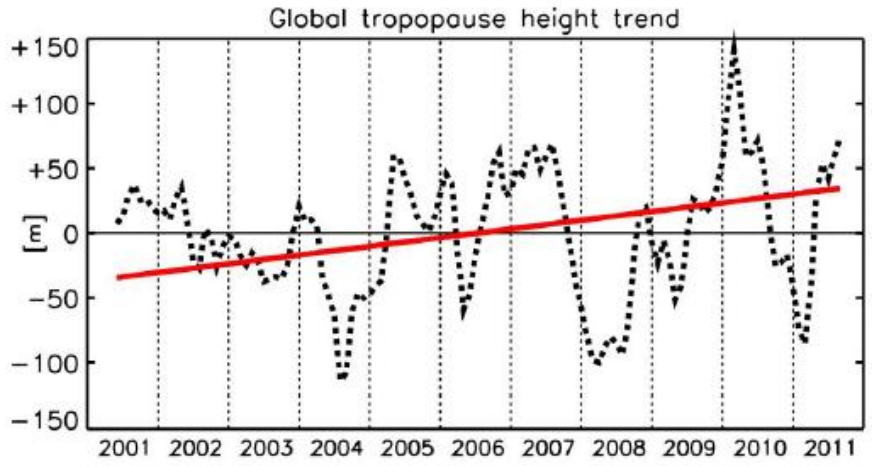
(update from Schmidt et al., ASR, 2010)



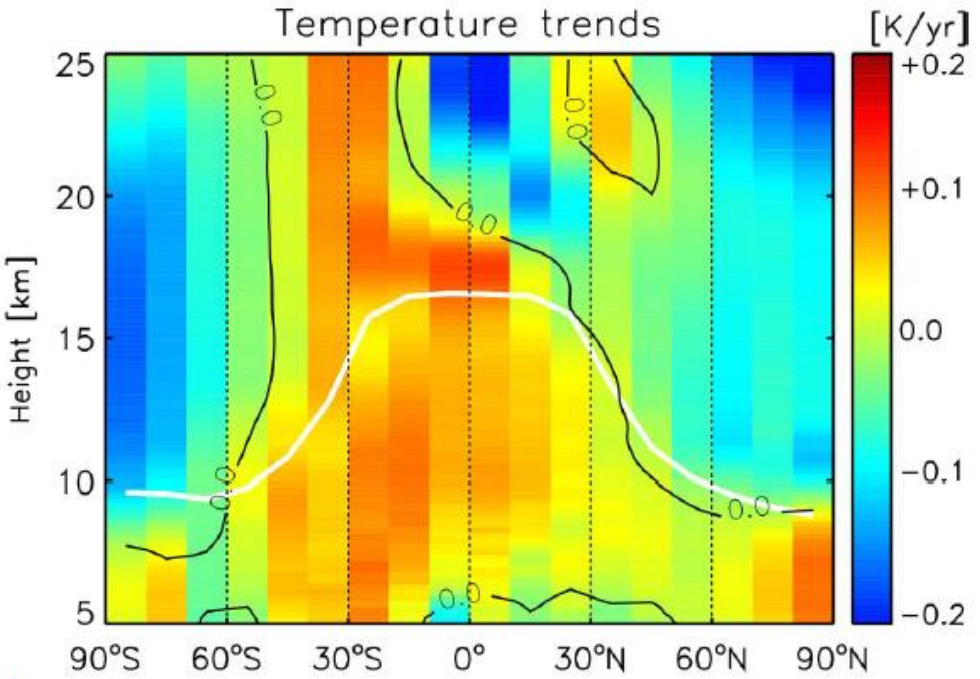
(update from Schmidt et al., GRL, 2008; ASR, 2010)

RO Applications: Tropopause Height & Temperature Changes

Basis: CHAMP/GRACE
May 2001-August 2011



Global tropopause height increase
of about 65 m over time period 2001-2011



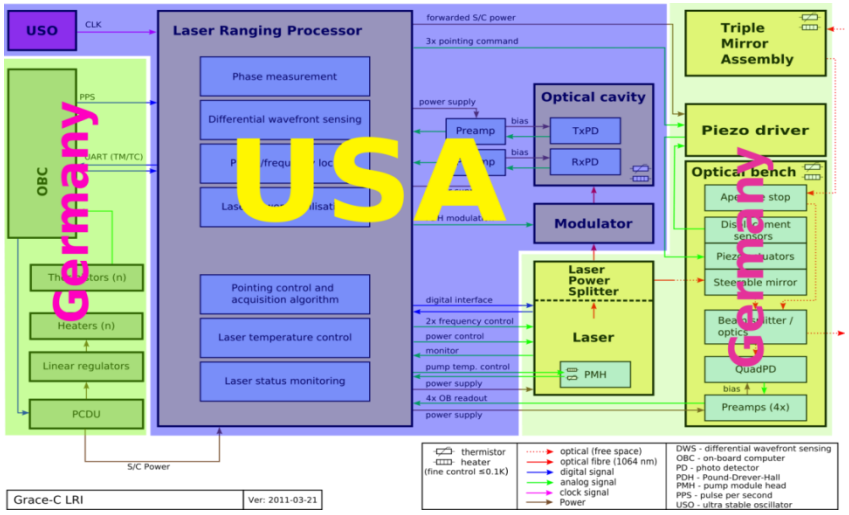
warming in the upper troposphere,
predominant cooling in the lower
stratosphere (except SH subtropics)

(update from Schmidt et al., GRL, 2008; ASR, 2010)

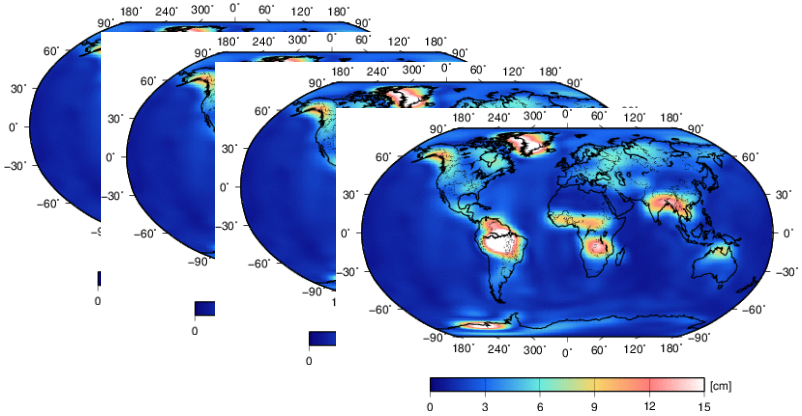
German Contributions (managed by GFZ)

Falcon-9/Space-X
(VAFB, March 2018

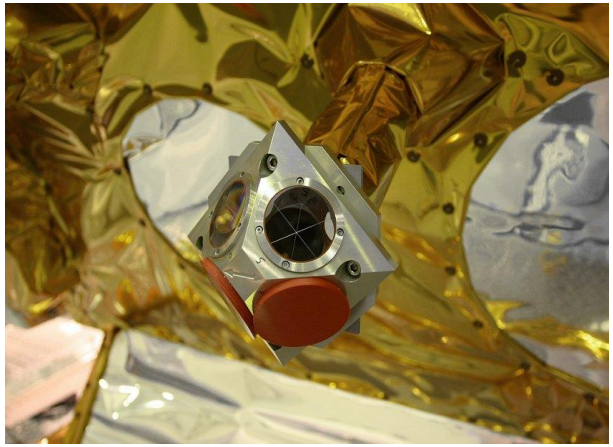
5 Years Mission Operations
(Subcontract to DLR/GSOC)



Contributions to the LRI



Extension of GRACE Mass Transport Time Series
(within joint US/D Science Data System)

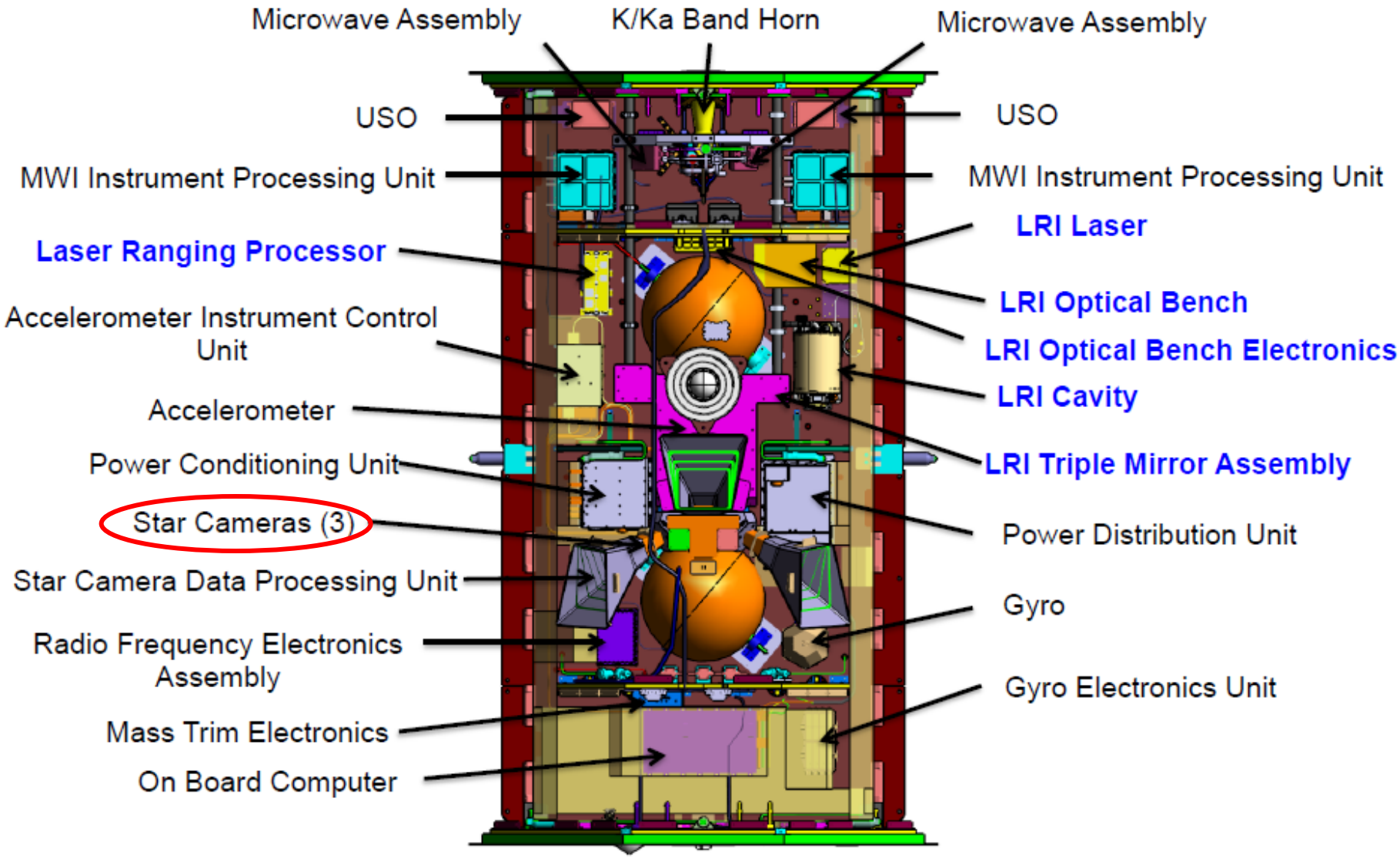


Laser Retroreflectors
(independent orbit control)

GRACE-FO Milestones (Extract)

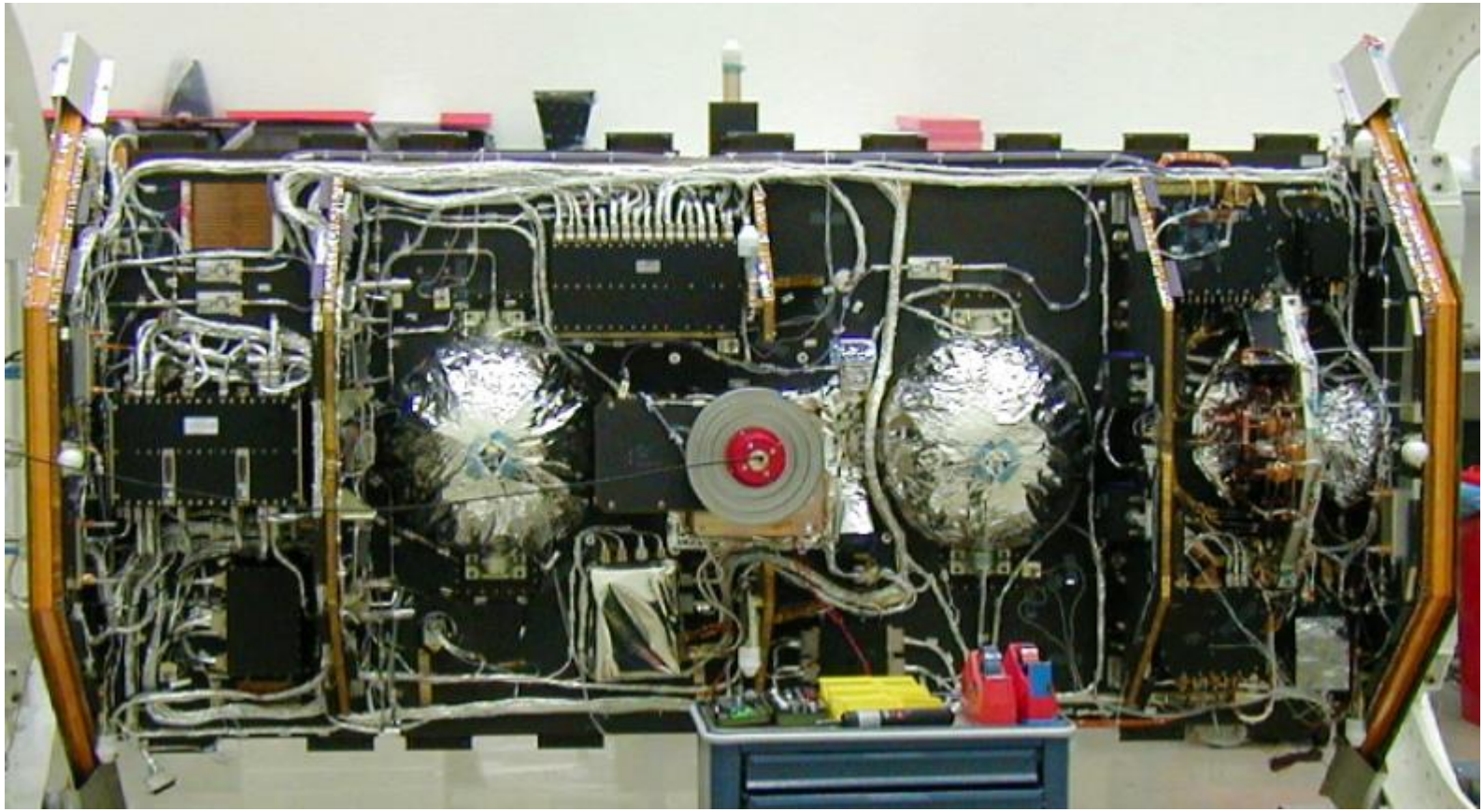
- 10/2012: (Official) Project Start in Germany ✓
- 02/2014: Project Preliminary Design Review ✓
- 02/2014: GFZ-NASA MOU signed ✓
- 02/2015: Project Critical Design ✓
- 07/2015: System Integration Review ✓
- 08/2015: Start Satellite and Instrument Integration ✓
- 09/2016: Start Environmental Testing @ IABG/Ottobrunn ✓
- 11/2016: Exchange of launcher from Russian Dnepr to Falcon-9/SpaceX ✓
- 11/2017: Pre-ship Review
- 12/2017: Shipment of S/C and MSD to Vandenberg Air Force Base (VAFB)
- 01/2018: Operations Readiness Review
- 03/2018: Launch at VAFB

GRACE-FO Satellites and Instruments



Satellite and Instrument Implementation Status

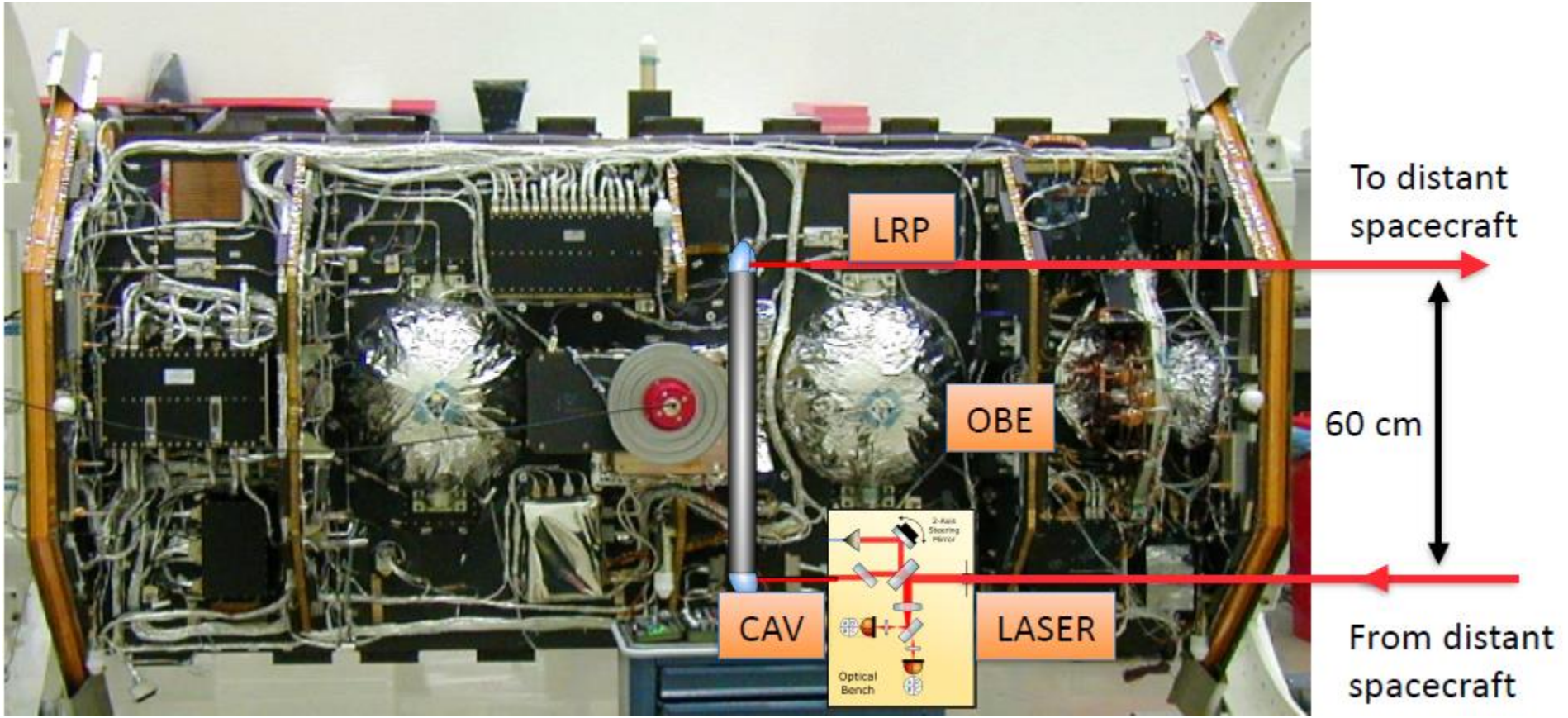
FM1 @ Airbus D&S



courtesy: Airbus D&S

Satellite and Instrument Implementation Status

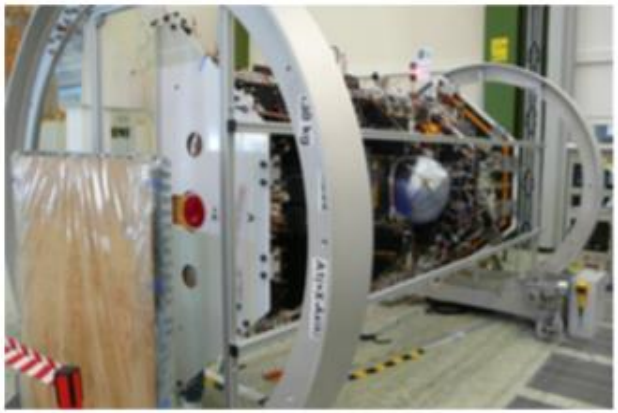
LRI components in FM1



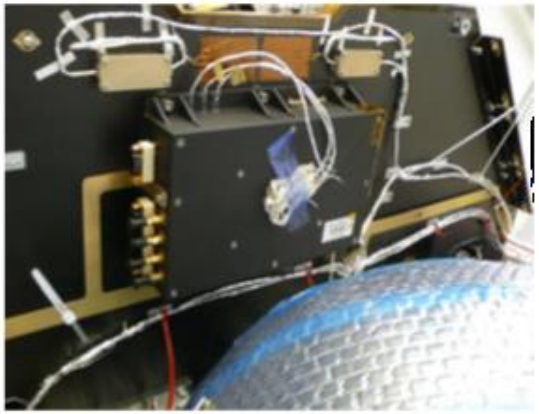
FM1 during Integration (at Airbus)

Integration Highlights

ACC/STR/TMA Integration
On FM1 with nominal shims



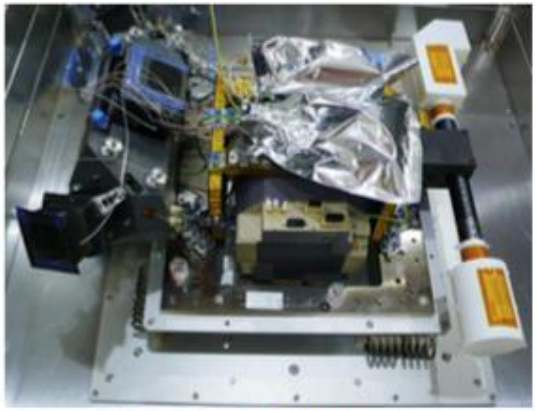
S/C FM1 Status



OBE Integration
Mechanical integration on FM1

MTE integration
On FM2

MTQ Electrical Integration
During magnetic field measurement

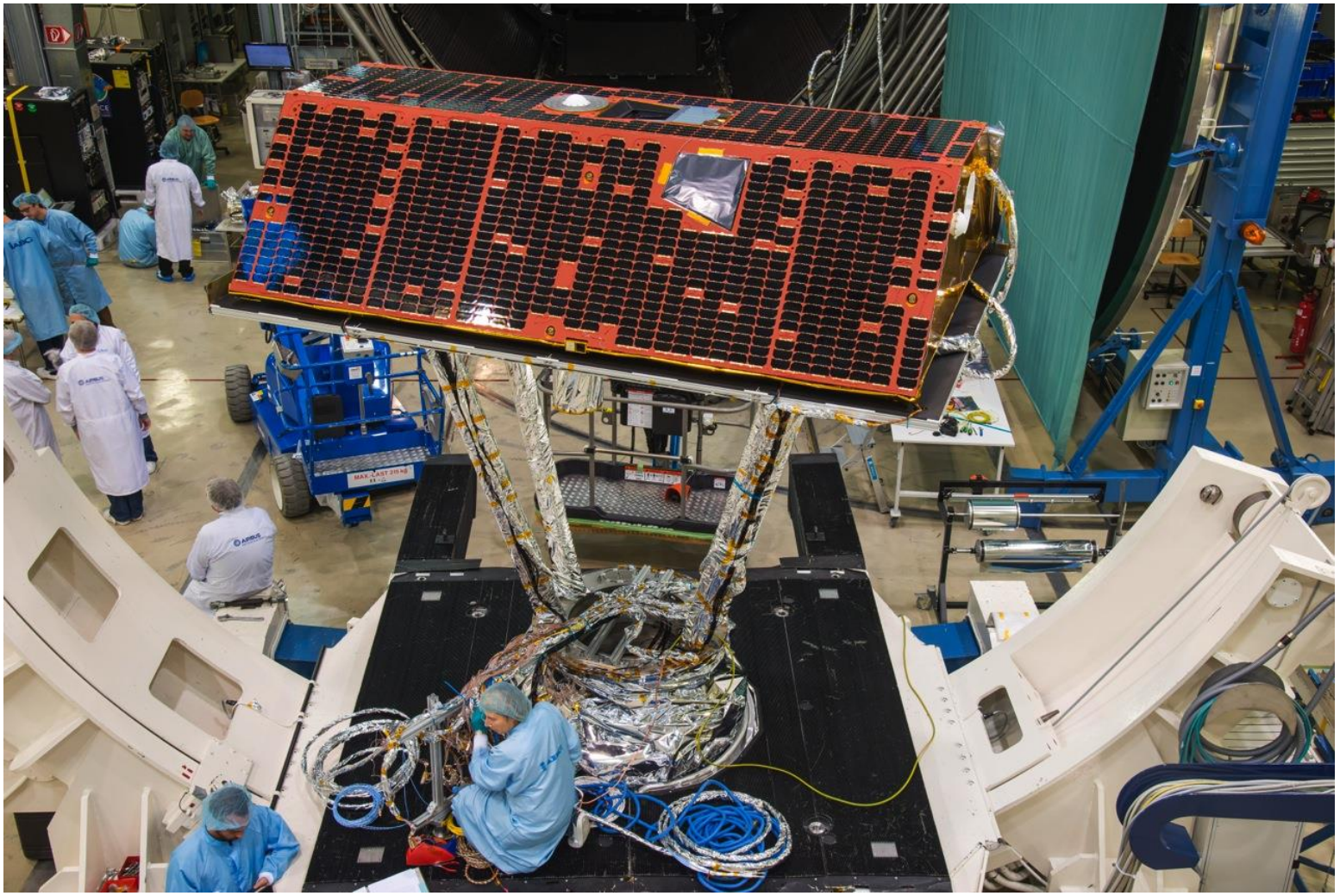


ACC/STR/TMA Integration
Final mounting of LRI TMA on FM1

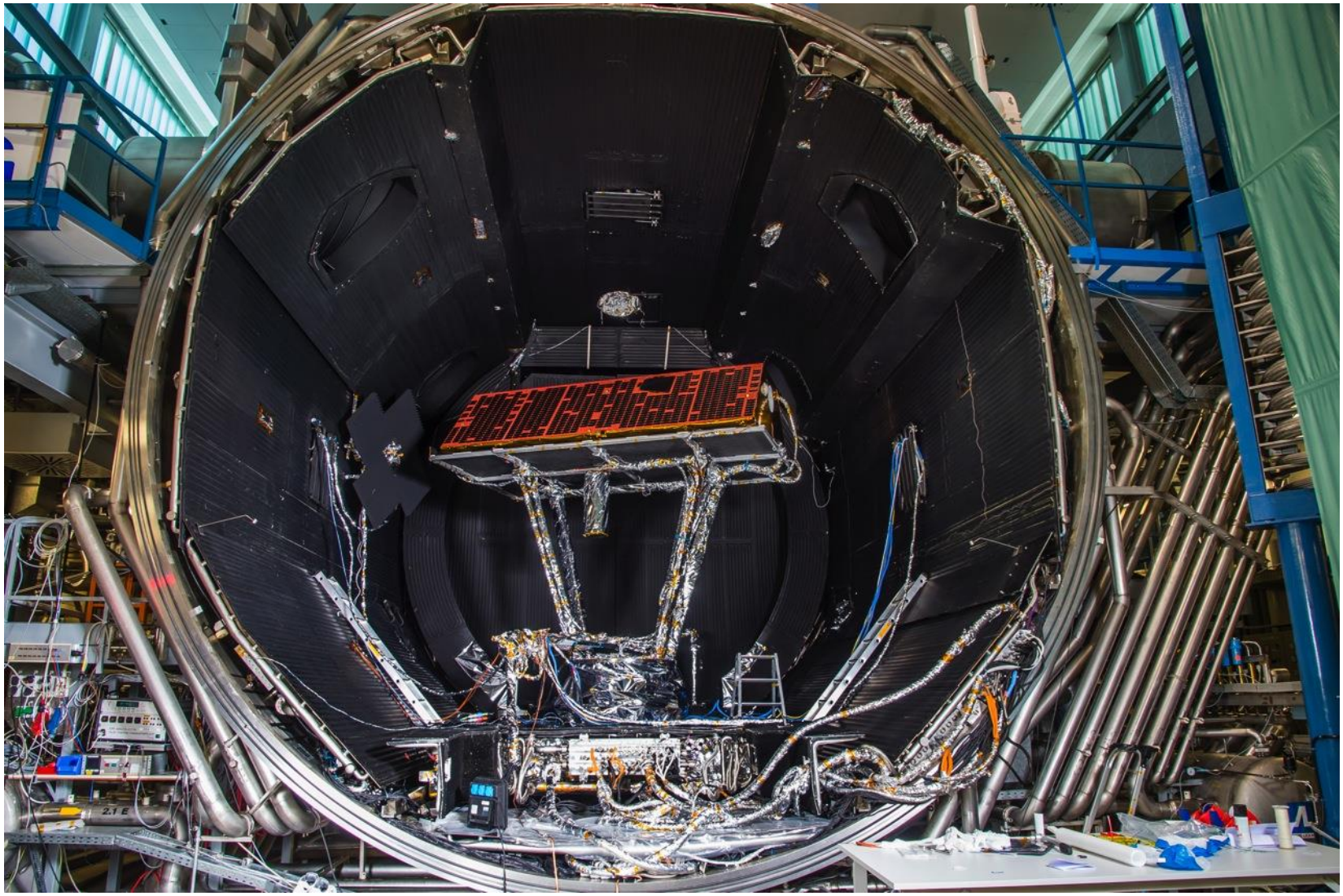
Implementation Status

- 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 tests are completed (started in 9/2016).

FM1 in Thermal Vacuum Chamber (Nov 2016)



FM1 in Thermal Vacuum Chamber (Nov. 2016)



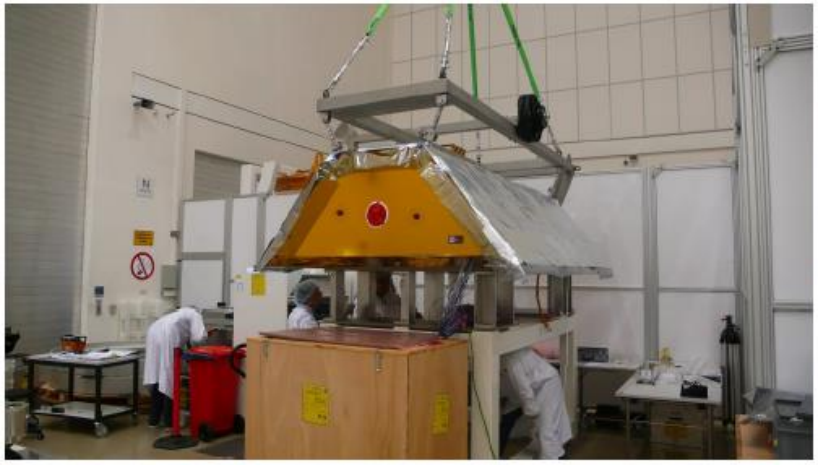
FM1 in EMC Test (Dec 2016)

Vibe Tests & Boom Deployment Test

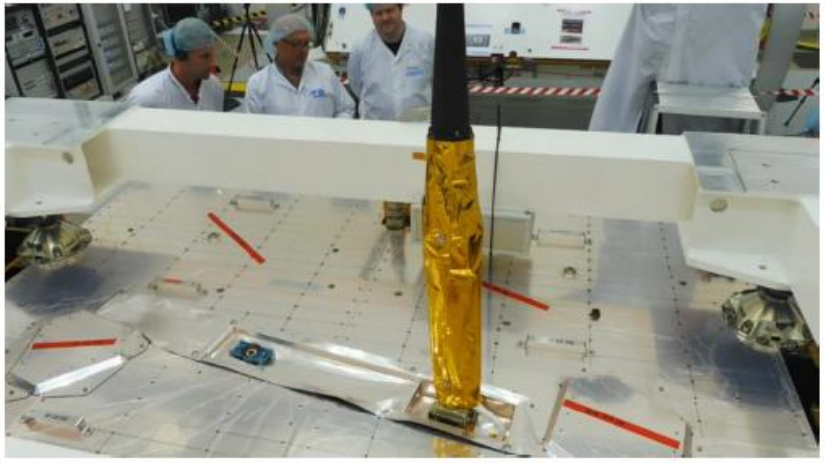
Highlights 6/2017

FM2 during sine testing (x-axis)

FM1 prepared for post-environmental alignment measurements

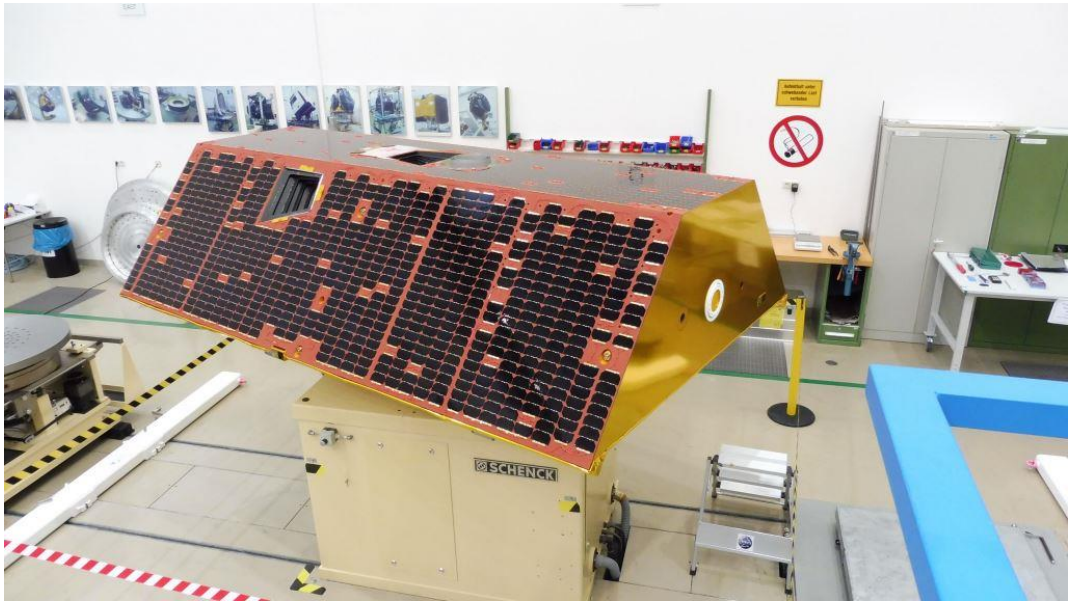


HRS removal on FM2 after sine testing



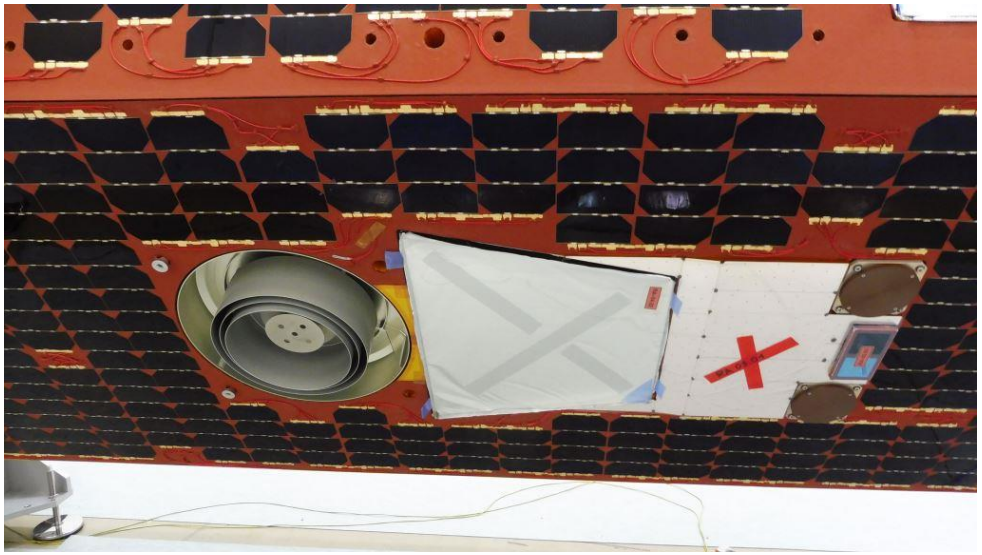
FM1 after successful boom deployment test

Mass Property Test (FM1)

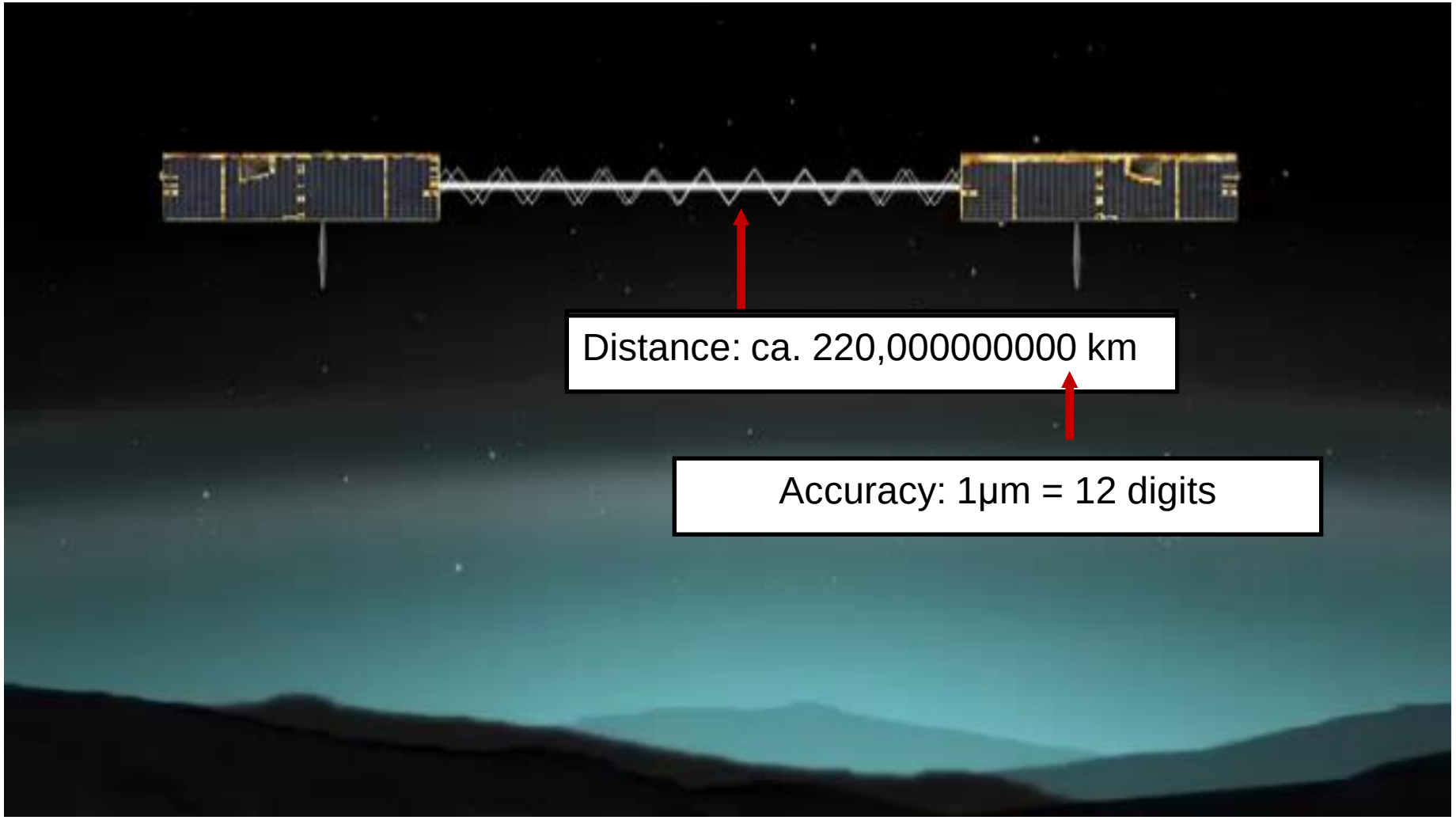


GPS POD Antenna

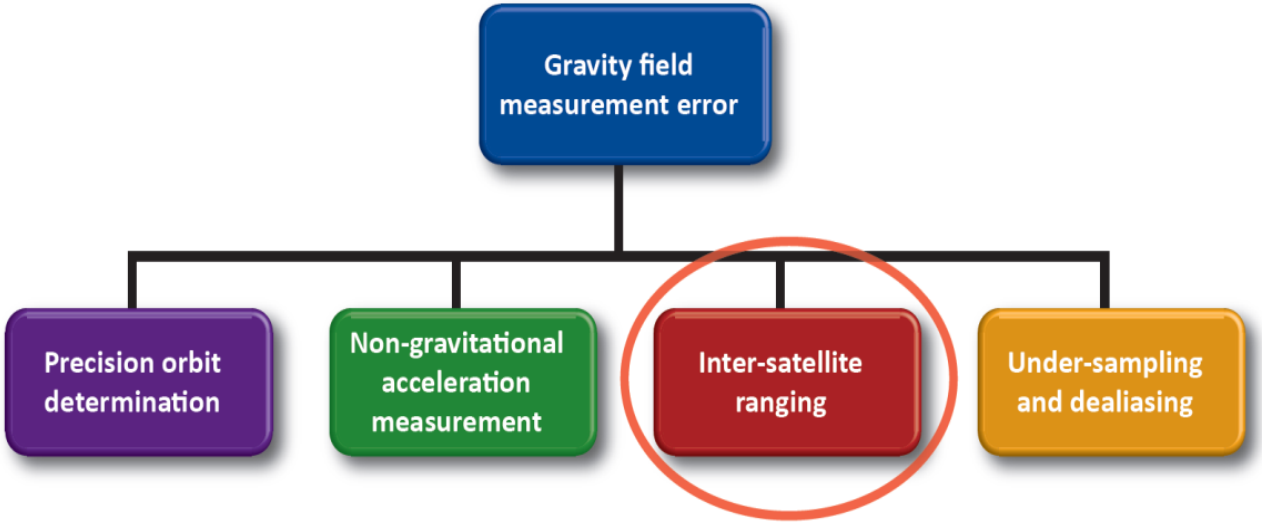
- During lifetime testing (PQV testing), after approx. 700 thermal cycles, the GRACE-FO GPS Antenna exhibited unexpected performance change.
- Alternate flight qualified GPS antenna has been identified from RUAG; EM unit was characterized at JPL.
- RUAG antennas with choke rings were procured to replace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

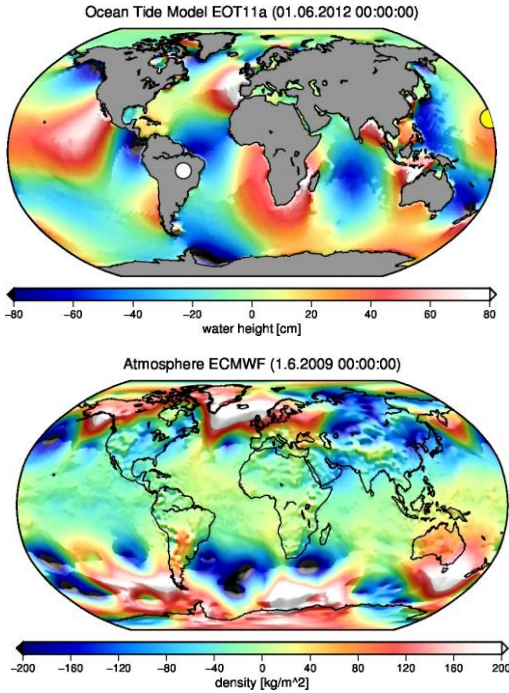


KBR Measurement Accuracy



GRACE-FO Laser Ranging Interferometer Accuracy

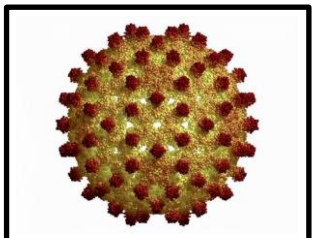




K-Band Instrument (GRACE) 1 µm

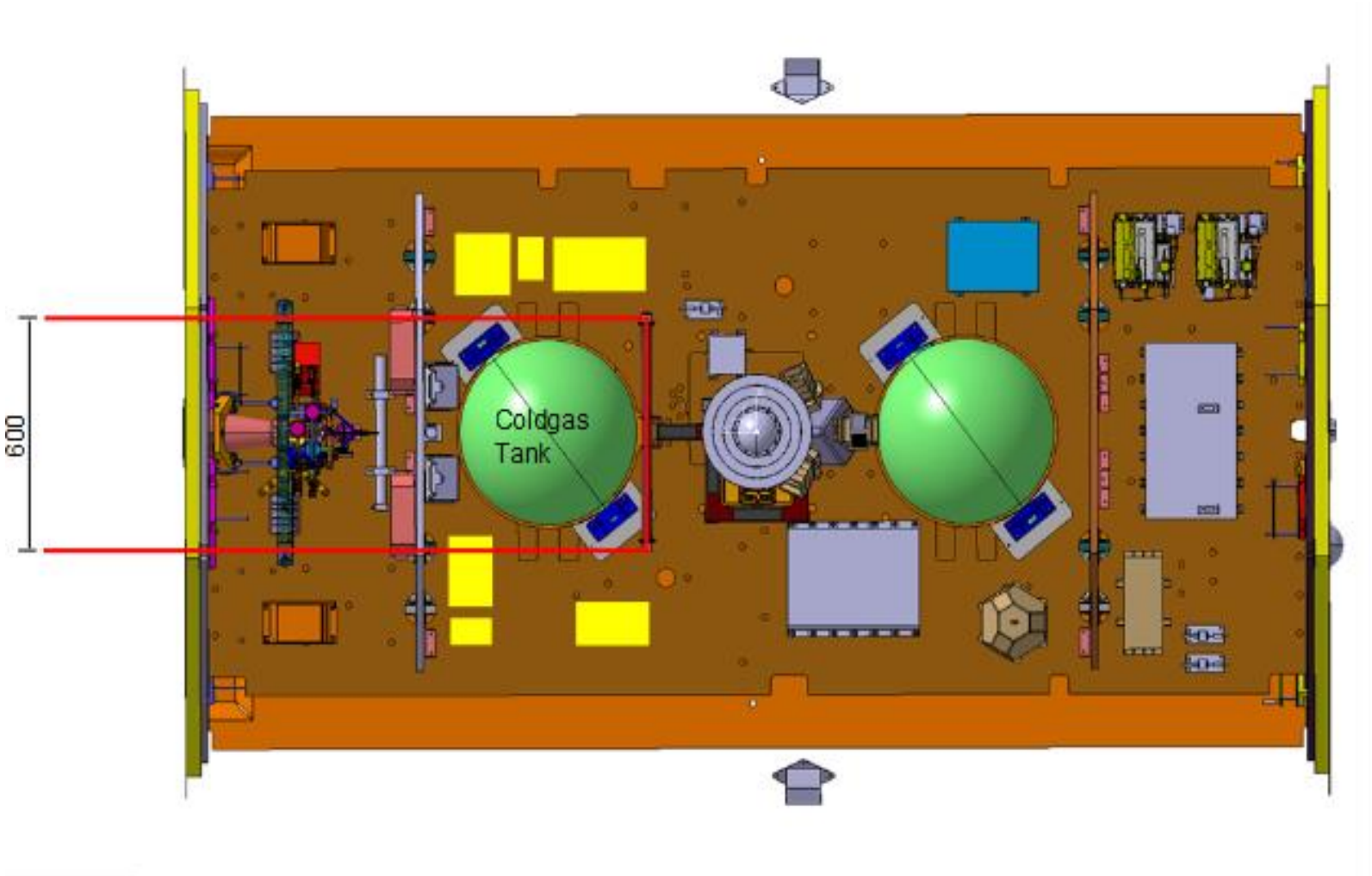
Laser Ranging Interferometer (GRACE-FO, NGGM) 80 nm

Red blood cell 8 µm



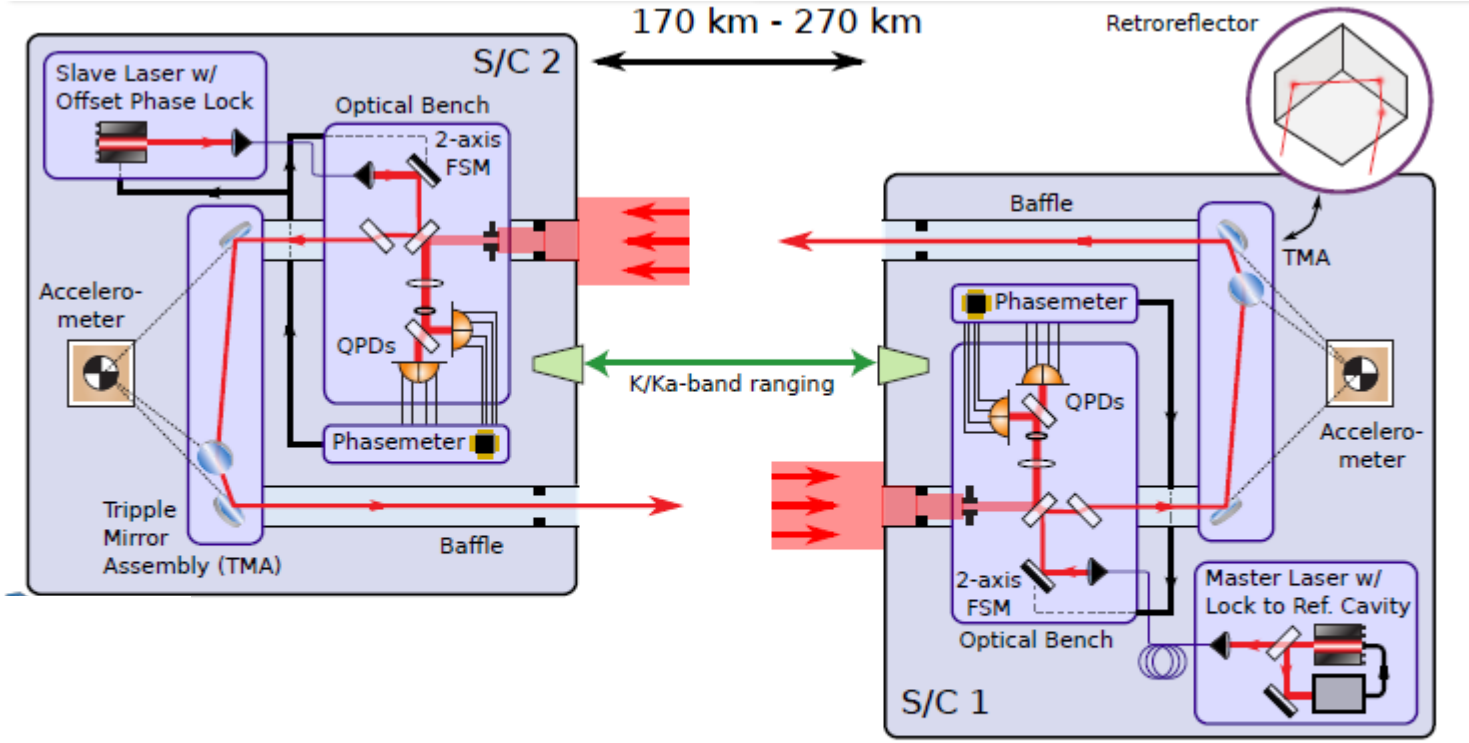
Hepatitis B virus 42 nm

GRACE-FO LRI Configuration



GRACE-FO requires off-axis optical measurement (due to MWI and tanks)…

GRACE-FO LRI Configuration

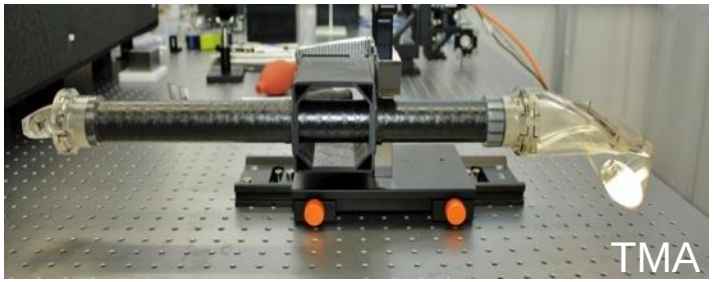


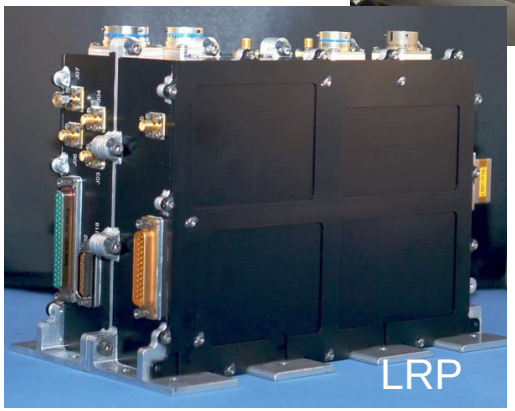
B. S. Sheard et al. Intersatellite laser ranging for GRACE Follow-On mission. Journal of Geodesy. 86(12):1083-1095. DEC 2012

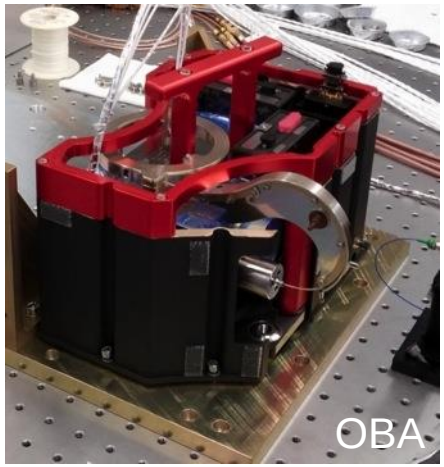
… realized by racetrack configuration using triple mirrors (Folkner/JPL)

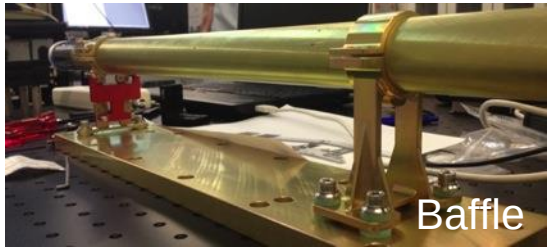
Mirrors are plane and orthogonally mounted that the beam intersects at COM (pivot around which the disturbing angular misalignment and jitter takes place)

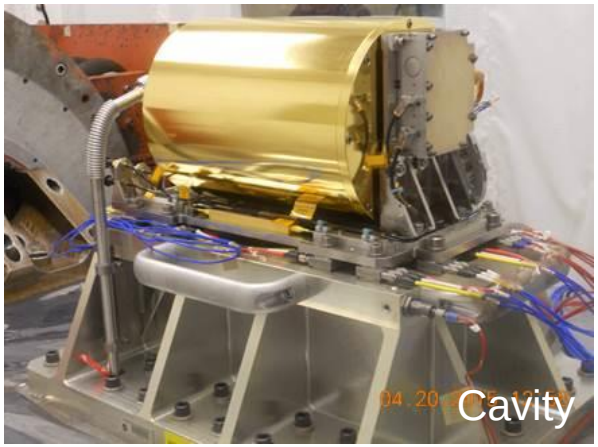
LRI Components











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

Laser Ranging Instrument Cavity

- Anomalies were observed in LRI SC-2 after thermal tests
- Cavity FM2 rework and retest is complete (JPL/Ball). Unit has returned to Satellite 2 for re-integration end of August 2017
- Tests show that LRI Cavity #2 is meeting its performance requirements after re-work (Cavity #1 has always met its performance requirements). Re-integration in Satellite 1 finished.

Launch Vehicle

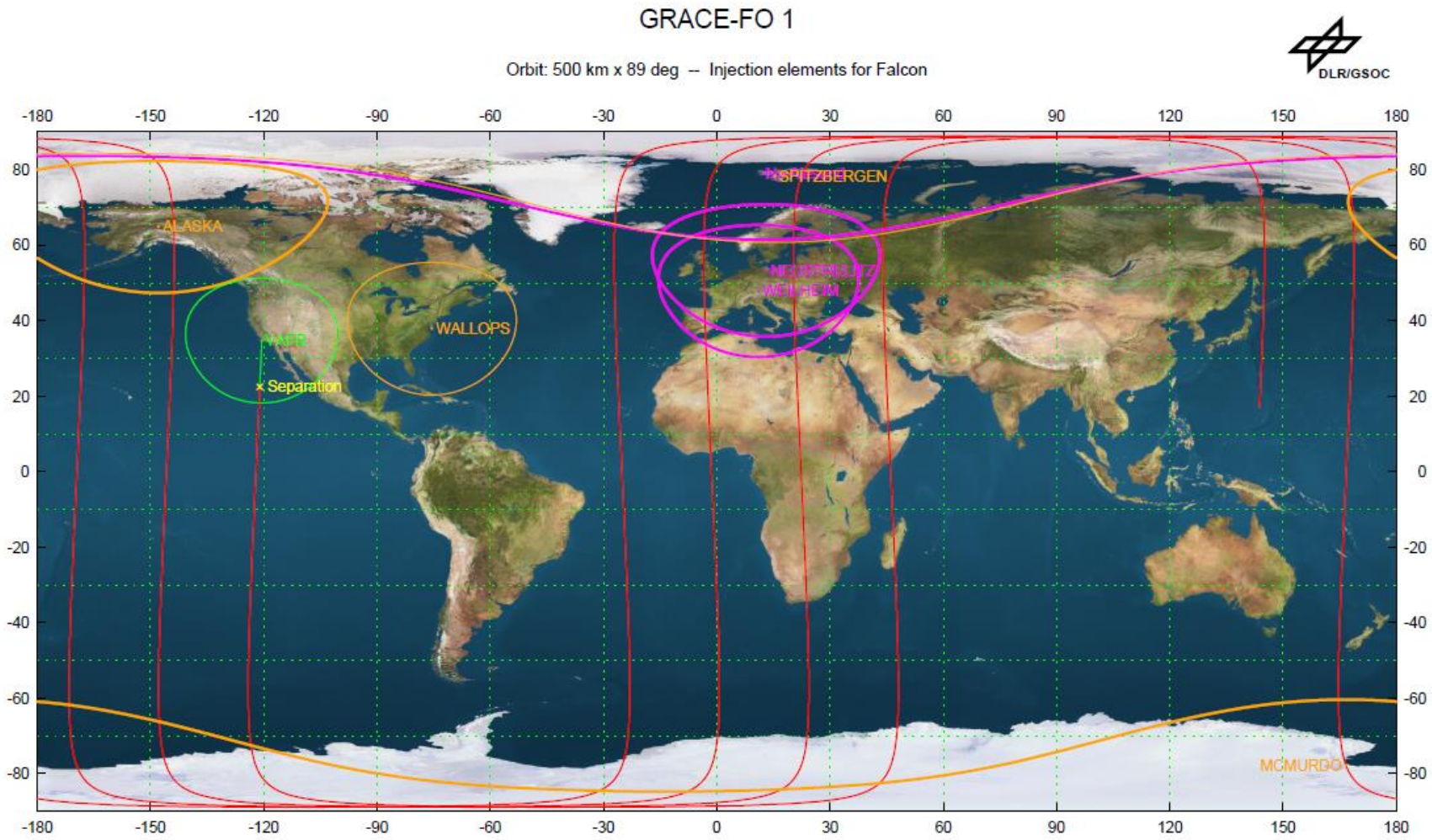
- GRACE-FO is a collaboration between NASA, leading on the US side, and GFZ, leading on the German side.
  - GFZ is responsible for providing the launch services and the multi-satellite dispenser.
- GFZ was notified by Russian Foreign Ministry early 2016 that the Dnepr program is now on hold; subsequently, 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.
- Shall be shifted by CCN to January 15 – April 15 2018, Target launch date: March 21, 2018.

Multi Satellite Dispenser

- Built by CASA Espacio (Spain): long & robust history for this MSD design
- Pyro Harness electrical checkout at SpaceX successfully passed: June 13
- 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

Fairing Logo (5x2.5m)

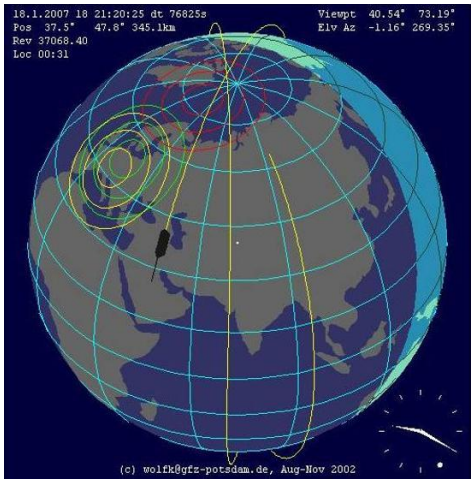
Preliminary Injection Orbit for March 21, 2018



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

Mission Operations System

- 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

- 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 training sessions at Oberpfaffenhofen

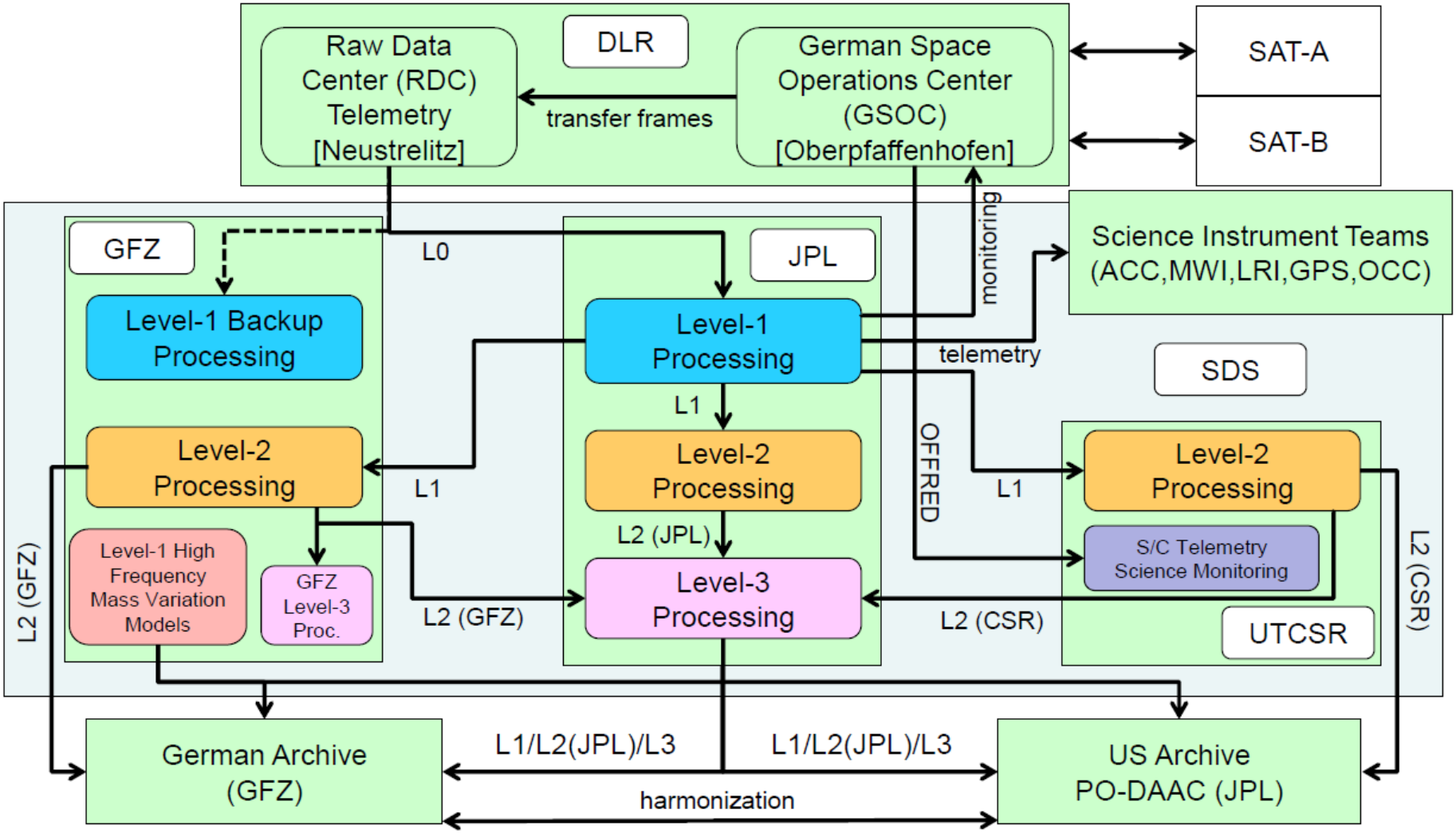
- Successful interface tests
  - RF compatibility tests were performed between the ground stations (WHM, NEN and NYA) and the Radio Frequency Equipment Assembly (RFEA)

- Flight Control Procedures (FCP) development is in progress (~97% ready), FCP validation on schedule (~77% done).

- Ongoing / Upcoming
  - Simulation & Training Sessions (CTS/ORTs) (Jul, Oct, Nov/Dec tbd)
  - Operations Readiness Review (ORR) (10. Jan., tbc)

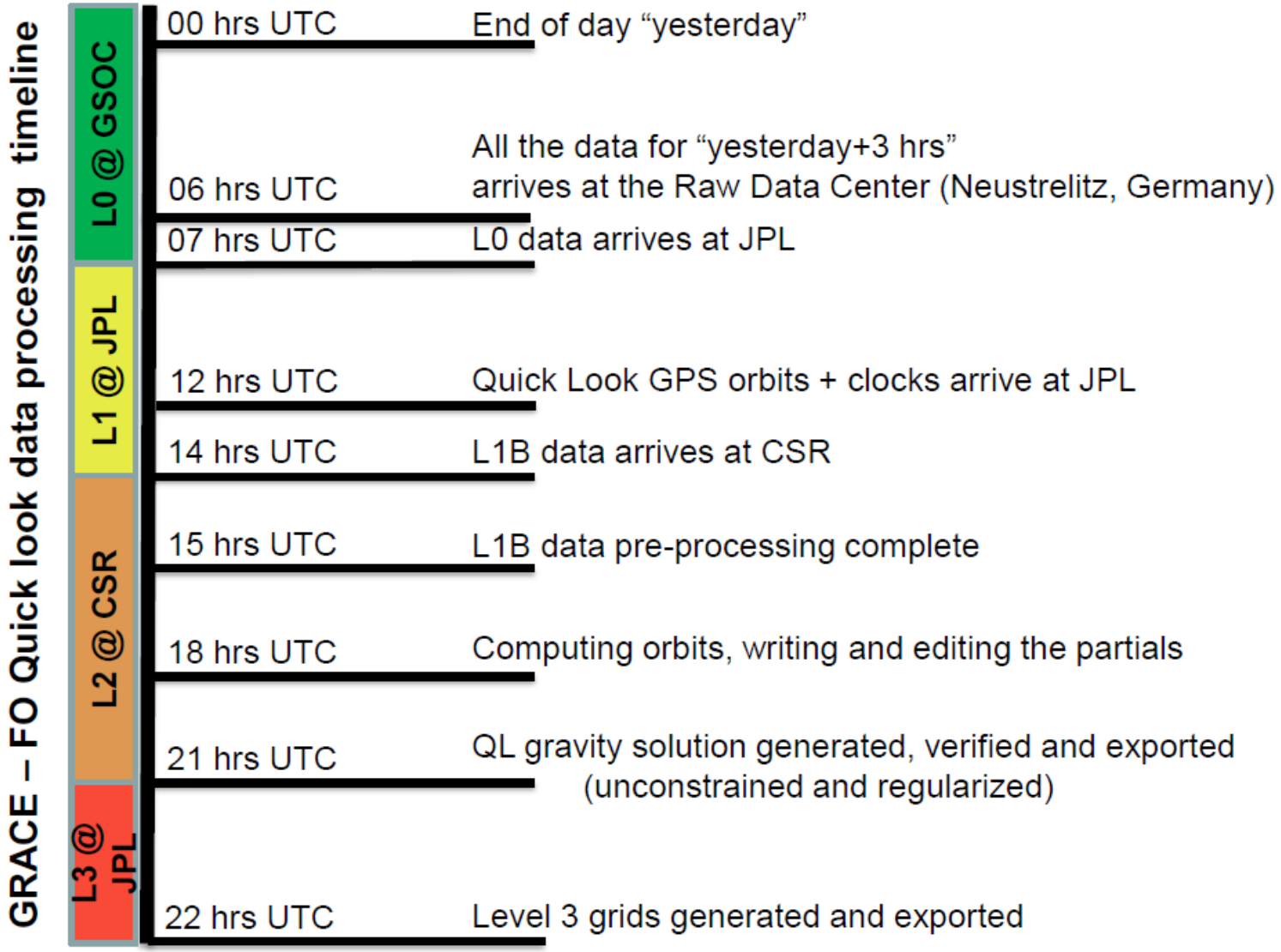
- MOS is on schedule for launch!

Science Data System Overview



SDS Readiness Review: October 11/12 @ UTCSR

SDS Low-Latency Products

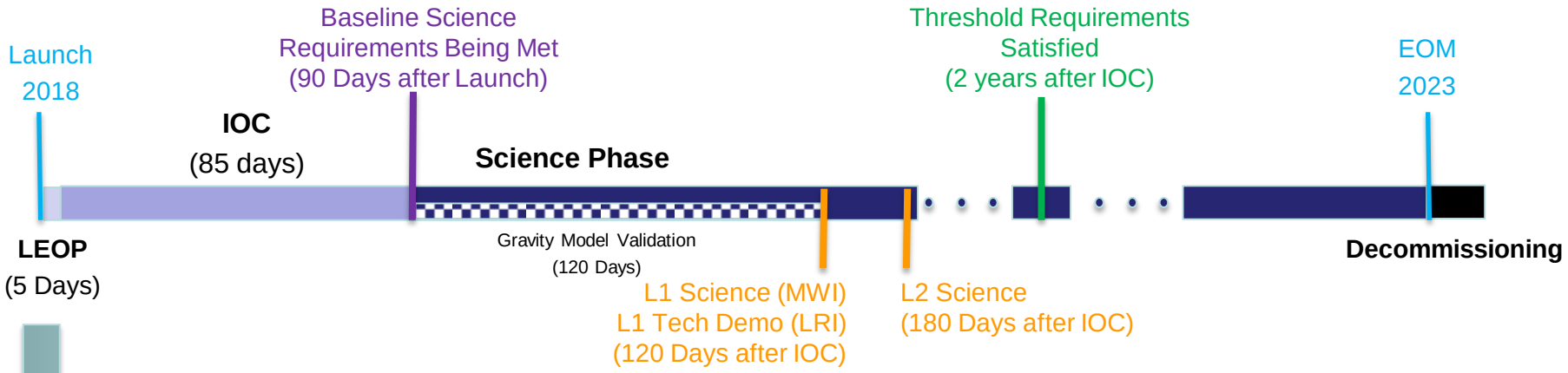


SDS Grand Simulation

- "Grand simulation" is intended to Verify and Validate the SDS centers' software and interfaces using a realistic data set, which includes:
  - Current best estimate of instrument noise for KBR, LRI, ACC, SCA and GPS
  - Timing errors, alignment errors
  - AOD product included but no AOD errors or any other geophysical related errors
  - JPL Conducted "Grand Sim" Test Readiness Review (2016-07-15)

- "Grand simulation" data release to science community:
  - Initial Level-1B release (Late 2017) via PO.DAAC and GFZ archives. This is 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)
  - Full disclosure of models used for simulation at time of release

After Launch: LEOP & IOC Activities / Time Line

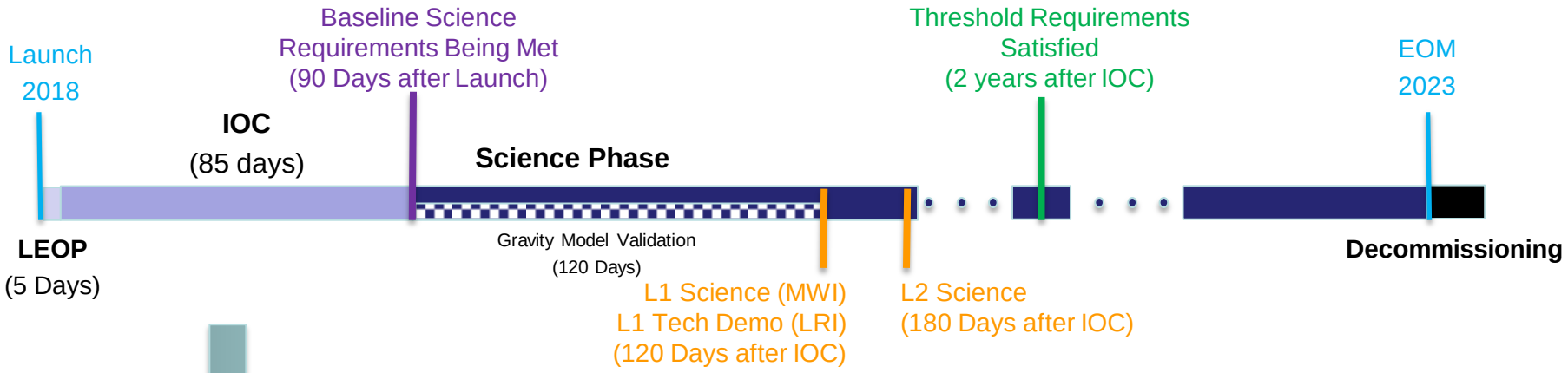


LEOP (~ 5 days)

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

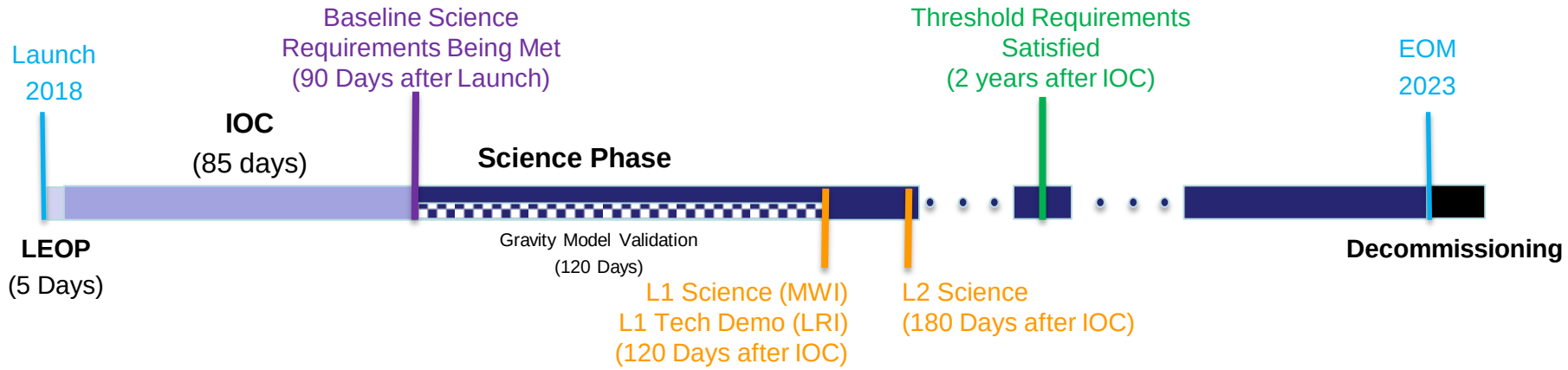


IOC (lasts 5-90 days after launch)

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!

Schedule Summary

- 7./8. November: Pre-ship Review
- 10. December: Ship GRACE-FO to Vandenberg, CA
- 10. January: Operations Readiness Review
- 17.3.2018 – 30.4.2018: Launch Slot (target Launch Date 21.3.2018)
- 3 months after launch
  - End of Commissioning (IOC) / Start of science operations
- 4-6 months after launch
  - 1st Level 1/2 data delivery to users