International Challenges of GRACE Follow-On

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Abstract— **The Gravity Recovery and Climate Experiment-Follow-On (GRACE-FO) Mission is a NASA directed mission to continue the goals of the original GRACE mission and provide continuity for the GRACE data set. The GRACE-FO mission is the result of an international cooperation to develop a concept and approach that minimizes cost and risk and maximizes the probability of success through limited changes to the original GRACE system design. The result is a system architecture in which maintenance of heritage is paramount, including heritage derived through the partnership with the German Research Centre for Geosciences (GFZ) in Germany. As a secondary goal, GRACE-FO will carry a Laser Ranging Interferometer (LRI) as a technology demonstration, which will provide laser interferometry measurements of inter-satellite range, complementary to the K/Ka-Band microwave link to demonstrate laser-ranging technology in support of future GRACE-like missions. Another secondary objective is the continuation of GRACE radio occultation measurements.**

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1. MISSION DESCRIPTION

GRACE-FO Mission continues the goals of the original GRACE mission, launched in 2002. It directly contributes to NASA Strategic Goal 2: Expand scientific understanding of the Earth and the universe in which we live and Outcome 2.1: Advance Earth System Science to meet the challenges of climate and environmental change. (Reference 1) The GRACE-FO mission will extend and improve upon the precision measurements of the gravity field and its changes in time arising from mass distribution and mass transport within the Earth System. The primary science objectives of the GRACE-FO mission are to continue to provide estimates of the global high-resolution models of the Earth's gravity field for a period of up to five years at a precision and temporal sampling equivalent to that achieved with GRACE. As with the pathfinder GRACE mission, the temporal sequence of gravity field estimates will yield the mean Earth gravity field, as well as a time history of its variability. A secondary objective is to provide several hundred globally distributed profiles each day of the excess delay, or bending angle due the refraction of Global Navigation Satellite System (GNSS) signals by the ionosphere and the atmosphere, using GPS limb-sounding. These signals are now used to improve weather, climate and ionospheric predictions by the operational weather services, and by the scientific community.

Scheduled for launch in 2017, the GRACE-FO mission is primarily a re-build of the GRACE satellite with the addition of a Laser Experiment. The GRACE-FO mission is the result of a JPL-led study to develop a concept and approach that minimizes cost and risk and maximizes the probability of success through limited changes to the original GRACE system design. A similar study, led by GFZ, was performed in parallel in Germany. The result of the combined studies is a system architecture in which maintenance of heritage is paramount. Changes were limited to resolving performance issues experienced in the operation of the original GRACE spacecraft(s) or issues of hardware obsolescence. GRACE-FO will also carry a Laser Ranging Interferometer (LRI) as a technology demonstration. It will provide laser interferometry measurements of inter-satellite range changes, complementary to the K/Ka-Band microwave link, to demonstrate laser-ranging technology in support of future GRACE-like missions. Another secondary objective is the continuation of GRACE radio occultation measurements.

The GRACE-FO project is being executed under the direction of the NASA Earth Science Division (ESD) within the NASA Science Mission Directorate (SMD) and the Earth Systematic Missions Program Office at Goddard Space Flight Center (GSFC). The mission responsibility for the GRACE-FO mission is delegated to the Jet Propulsion Laboratory (JPL). In accordance with the NASA Procedural Requirement NPR 7120.5e, GRACE-FO is designated a Category 2 project and risk category C with the exception of the Laser Ranging Interferometer (LRI) being a joint US/German technology demonstration with a risk category of D.

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2. SYSTEM DESCRIPTION

The GRACE Follow-On system consists of two identical satellites in circular polar orbits effectively comprising a single measurement system[1]. The satellite orbits are normally freely decaying and do not have a constant repeating ground track pattern. However, the satellite separation is maintained at 220km by occasional orbit maintenance maneuvers. The inter-satellite range variations induced by differential accelerations on the two satellites in orbit are measured using a 2-way microwave link. Two frequencies 24 GHz (K-band) and 32 GHz (Ka-band) are used to enable the removal of variable ionosphere delays. It is important to note that the two satellites effectively comprise a single measurement system.

The GRACE-FO spacecraft is based on heritage from GRACE and Airbus's standard FlexBus architecture adapted from the Swarm Mission. GRACE-FO utilizes the GRACE thermal, mechanical, and propulsion platform slightly rearranged to accommodate the Laser Ranging Interferometer (LRI). The K-Band Ranging assembly (KBR), Accelerometer (ACC), the Laser Retro Reflector (LRR), and Instrument Processing Unit (IPU) including GPS are all unchanged from GRACE. The Launch Vehicle interfaces are also identical to GRACE.

In order to keep the seismic behavior as close as possible to GRACE and the launch vehicle interfaces identical to GRACE, the following areas were intentionally not changed:

- Outer shape and dimensions of the spacecraft
- Structure concept, materials and processes
- Thermal concept, materials and processes
- Attitude control actuators and sensors
- Center of gravity, moments of inertia accuracy / trim capability (mechanism)

Some areas of improvement were identified however:

- On-board data storage and down link capacity
- Power generation, storage, control and distribution
- Heater control concept, radiator foil support to reduce thermal control induced noise
- Attitude sensor arrangement and performance

The GRACE-FO design utilizes the structural concept from GRACE, which is based on a Main Equipment Platform (MEP) stiffened by a framework on the nadir side. Most of the equipment and the payload are mounted to the upper and lower side of this MEP. All of the panels are made out of Carbon Fiber Reinforced Polymer (CFRP)/Aluminum core sandwiches.

Both satellites are designed such that the satellite in-flight center of air drag is located in the +/- x-axis direction with its origin in the S/C center of gravity (CoG). The CoG of the spacecraft is balanced such that it is located at the CoG of the ACC proof mass. The in-orbit GRACE trim mechanism system is used to adjust the CoG in flight.

The solar array panel design features a foam layer underneath. This photo-voltaic-assembly provides a significant damping function during acoustic testing such that the S/C internal random loads are quite low.

The basic thermal concept of GRACE is retained. It is a passive thermal control system comprising thermal insulation by foams and MLI, appropriate thermal control surfaces, and thermal doublers or stand-offs as needed. Resistance heaters are implemented for fine temperature control and keeping equipment above operating temperatures.

The dissipated heat is transferred to the nadir-oriented radiator within the S/C by means of thermal radiation. The radiator itself has changed from the GRACE foil radiator to a honeycomb panel. This change will prevent small movements of the radiator foil during flight. Dedicated radiators are used for the KBR, the ACC, and the Star Camera (STR) heads, where the heat transfer from the dissipating units is managed by conductive straps. This improves radiator efficiency for high dissipating units and allows fine temperature control without being disturbed by parasitic heat flows from other parts of the S/C. Electrical resistance heaters are provided in order to keep the equipment above lower temperature limits in cold or safe mode conditions and for fine thermal control. Heaters are controlled by the S/C avionics. To avoid the disturbances in the measurement signals caused by heater switching as seen in the GRACE Mission, linear heater control is utilized for GRACE-FO.

The GRACE-FO Electrical Power Subsystem (EPS) architecture comprises a 3-panel solar array, a 78 amp hour Beginning of Life (BOL) Li-Ion battery, a Power Control Unit (PCU) and a Power Distribution Unit (PDU). All functions required to control and condition the power from the solar array, the charge /discharge management of the battery and the distribution of power to the spacecraft and the instruments are allocated to the PCU and the PDU. A state-of-the-art triple junction GaAs solar array is implemented for GRACE-FO to handle the increased on-board power consumption caused by the accommodation of the LRI and the changes in the electrical architecture. This change generates a power increase of about 60% compared to the original Si cell Photo-Voltaic Array (PVA) design of GRACE. The GRACE-FO solar array consists of three panels, two side panels providing >500 W each and one top panel providing > 365 W under worst case conditions End of Life (EOL) in summer solstice.

The 78 Ah (BoL) Li-ion battery being used for GRACE-FO has a significant weight and volume to energy ratio advantage compared to a NiH battery used for GRACE. The PCU manages the power system for the solar array, the battery and all power consumers. It provides a sun-

regulated power bus, limiting bus voltage to 33.6V. During eclipse and battery recharge phases, the bus voltage varies with the state of charge of the battery. During this time, the Solar Array Regulators provide the maximum power to the main bus and the battery.

Spacecraft command, control, and data management are provided by the Onboard Computer (OBC). Utilizing significant heritage from SWARM, the OBC provides all of the on-board command and data handling functions as well as the spacecraft attitude control within a single internally redundant unit.

The OBC collects payload and satellite data and stores it in mass memory until requested for downlink to ground. Commands are decoded and validated by the OBC and then further processed or distributed on-board. The OBC also generates and distributes timing data and synchronization signals.

The OBC mass memory provides data storage capabilities based on a modular solid-state mass memory unit (MMU). Stored data is protected by an Error Detection and Correction (EDAC) function. The EDAC function works in real-time during data retrieval from memory and is also used to periodically check the integrity of the stored data using background memory scrubbing

The Flight Software Design approach identified for GRACE-FO is the same construct that was utilized by GRACE and enhanced for SWARM. This allows reusing a significant amount of essential data-handling software components to ensure a proven technology, which decreases implementation risks.

The GRACE-FO Attitude and Orbit Control System (AOCS) together with the Cold Gas Propulsion System (CGPS) provide all functions necessary to manage spacecraft attitude during all operational phases of the mission, and to provide necessary orbital control and maintenance capabilities to satisfy the GRACE-FO mission requirements.

The AOCS design provides a 3-axis stabilized earth pointing attitude during all operational modes. The compact satellite design with fixed solar arrays keeps the external disturbance torques low, allowing a favorable actuator concept utilizing magnetic torque rods and small cold gas thrusters. A GPS receiver and Star Tracker assembly are used together with a high performance Inertial Measurement Unit (IMU), a Coarse Earth and Sun Sensor (CESS) and Fluxgate Magnetometers (FGM) to measure the attitude, spacecraft rate and orbit position similar to GRACE.

Two cold redundant dual-band GPS Receivers are included as part of the Microwave Instrument (MWI) Instrument Processing Unit (IPU) providing real time measurements of satellite position, velocity and time.

A Coarse Earth and Sun Sensor (CESS) is used as the main attitude sensor for the Initial Acquisition and Safe Mode. The CESS provides a measurement of the earth and sun vector in S/C coordinates. The GRACE-FO sensor is the same sensor that was used on GRACE and many other missions. It consists of 6 omni-directional accommodated sensor heads with each head providing a 2-out-of-3 redundancy.

FGM is comprised of two “cold” redundant three-axis fluxgate magnetometers that will be used for magnetic torquer control during Acquisition and Safe Mode. This change provides for enhanced system reliability from the GRACE mission which utilized a magnetometer with one non-redundant sensor head and two cold redundant electronic modules.

The GRACE-FO IMU is different from the GRACE IMU. It is a four-axis high performance IMU instead of a three-axis coarse performance IMU. This enhances the rate measurement performance and introduces one-failure tolerance of the rate sensor. The GRACE-FO IMU features 4 independent angular rate detection axes in a skewed configuration, which offers a one-failure tolerant sensor. The inertial sensors are separated from the processing electronics, which ensures control of the detection axes mechanical stability.

The GRACE-FO Star Tracker Assembly (STR) provides high accuracy autonomous inertial attitude determination from a “lost in space” situation. It consists of 3 redundant star tracker heads with 90 deg separation angles cross-coupled to 2 redundant data processors. The GRACE mission utilized two Star Tracker camera heads. The GRACE-FO design increases the attitude data availability and attitude accuracy about all spacecraft axes.

A set of 3 internally “cold” redundant magnetic torquers of 27.5 Am^2 each are used as the main actuators for compensation of environmental disturbance torques in all operational modes. The GRACE-FO torquers consist of 2 cold redundant and simultaneous wound coils around a high permeability core material. The design is optimized to reach a linear dipole moment of ±30 Am^2 at an input current of ±120 mA and has a remarkable low residual dipole moment of less than 0.1 Am^2. For GRACE-FO the input current is limited to ±110 mA, providing a magnetic dipole moment of ±27.5 Am^2, which is sufficient for attitude control. The three Magnetic Torquers are orthogonally accommodated such that each torquer is aligned to one of the spacecraft axes.

For GRACE-FO the CGPS design of the GRACE mission will be re-used with some small design enhancements and the use of current cold gas component evolutions, inherited from the other Cold Gas Propulsion Systems built by Airbus since GRACE. GRACE-FO will use 28.6 kg of gaseous nitrogen (GN2) as propellant stored in two 52 liter tanks at 275.8 bar (4000 psi), which satisfies the total delta-v demand with sufficient margin as already proven on GRACE.

The main purpose of the Cold Gas Propulsion System

(CGPS) is to perform attitude control by generating all the reaction moments in excess of the capability of the magnetorquers, to perform attitude maneuvers (e.g. slew maneuver), and to perform orbit and constellation maintenance maneuvers.

3. SCIENCE INSTRUMENTS

The GRACE Follow-On mission supplements the original GRACE microwave measurements with a new Laser Ranging Interferometer as a technology demonstration. The shorter wavelength and excellent wavelength stability of the laser can provide an improvement in measurement accuracy by a factor of 25 while maintaining the continuity with the original GRACE measurements. The Microwave system will remain as the primary instrument.

Microwave Instrument

The Microwave Instrument (MWI) is the prime instrument on GRACE Follow-On and provides ultra-precise satellite-to-satellite tracking in low earth orbit. The MWI is designed and built at JPL utilizing a similar architecture to the original KBR in GRACE. Utilizing Dual-One-Way-Ranging (DOWR), each of the two satellites transmits a carrier signal and measures the phase of the carrier generated by the other satellite relative to the signal it is transmitting. The sum of the phases generated is proportional to the range change between the satellites. The GRACE Follow-On K-band and Ka-band frequencies provide for range measurements in the micrometer level. Variations in the Earth's gravity field cause the range between satellites to change. The relative range is measured by the MWI and the variations are corrected for non-gravitational effects by an accelerometer.

Each satellite has a redundant pair of Ultra Stable Oscillators (USO). They output ~38.656MHz and ~57.984MHz, which provide the coherent frequency references for the MWI MicroWave Assembly (MWA) and Instrument Processing Unit (IPU). The USO frequencies used for Spacecraft-1 vs. Spacecraft-2 are actually slightly offset, to set up the RF mixing products which result in a desired baseband frequency of measurement for the IPUs. The USOs additionally provide a reference for the LRI subsystem.

The K/Ka-Band Ranging Assembly (KBR) provides the RF front end to the measurement system. It is comprised of a dual-band, dual-linearly polarized horn antenna, waveguide feeds, and redundant MWA K/Ka-Band transmitter/receivers. The antennas are near build to print from the GRACE design, with a few modifications to the aperture cover and the feed components. The MWAs up-convert the USO signal to K & Ka-Band for transmission, as well as down-convert the received K & Ka-Band signals to baseband frequencies of 670Khz and 500Khz in orthogonal In-phase and Quadrature (I/Q) signals. The MWAs are near build to print, based on the original GRACE and Gravity Recovery and Interior Laboratory (GRAIL) designs.

The Instrument Processing Unit (IPU) receives and digitally samples the MWA baseband I/Q signals down-converted from the K & Ka-Band links. These measurements are the basis for the radiometric observables. The GPS component of the IPU provides navigation information, time tagging / correlation of data products, and also provides ancillary earth limb occultation measurements. Additionally, the IPU subsystem includes the primary, redundant, and occultation GPS antennas.

Accelerometer

The electrostatic space accelerometer developed by Office National d'Etudes et Recherches Aérospatiales (ONERA) in France under contract to JPL is designed to measure the weak level of acceleration sustained in orbit by the GRACE Follow-On satellites. In addition to thermal stability improvements and better operating reliability demonstrated on the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission, the GRACE Follow-On accelerometer exhibits lower noise levels at low frequency bandwidth and better stability to satisfy the LRI performance requirements.

The operation of the GRACE Follow-On accelerometer is based on a highly accurate position and attitude measurement of an inertial Titanium alloy proof mass, which provides a resolution better than 10^{-10} ms^{-2} $Hz^{-1/2}$. The accelerometer measures the satellites' linear acceleration along three axes and angular acceleration about these same axes. The accelerometer outputs are obtained from the measurements of the analog voltages, which provide the electrostatic forces needed for keeping the proof mass at the center of the electrode cage.

Laser Ranging Interferometer

The LRI instrument is a joint US-German development. NASA provides the laser, cavity assembly, and ranging processor; Germany provides the measurement optics and steering mirror assembly along with instrument integration and testing. The instrument hardware on both spacecraft is identical. It consists of a single frequency laser, a Fabry Perot reference cavity, a Triple Mirror Assembly (TMA) an Optical Bench Subsystem (OBS), and a Laser Ranging Processor (LRP).

The objective of the LRI is to measure the same range fluctuations as the MWI, but with less noise and more precise measurements of the relative satellite-to-satellite pointing. As a technology demonstration, the LRI has less stringent lifetime and reliability requirements. However, the LRI is designed to be operated in parallel to the MWI for a large part of the mission.

The LRI will be the first space laser interferometer to

measure distance variations between remote spacecraft and will have significant implications for other missions using similar measurements.

The LRI uses laser interferometry to measure fluctuations in the separation between the two GRACE-FO spacecraft. This is the same measurement made by the MWI, but the use of laser interferometry promises substantially improved sensitivity, largely due to the laser wavelength being ten thousand times shorter than the microwave wavelength. Just as for the MWI, the desired optical axis would be positioned on the line between the centers of mass between the two spacecraft to avoid coupling of spacecraft attitude. For GRACE-FO a "virtual" optical axis runs through the center of mass, with the physical transmitted and received beams routed around the MWI components using an extended corner cube.

The optical bench assembly includes three key assemblies: a quadrant photoreceiver, a steering mirror, and an optical bench. The optical bench accepts laser light via a fiber-optic cable, routes it to the outgoing spacecraft via a steering mirror, and combines the light from the local and distant spacecraft to form the heterodyne beat note on the quadrant photoreceiver. The steering mirror is required because variations in the spacecraft pointing from the local to distant spacecraft are larger than the laser beam divergence. The photoreceiver converts the laser signals into an electrical signal for tracking by the LRP. The use of a four-element detector provides a readout of the angle between the outgoing and incoming laser beams.

The optical bench electronics provides power to the steering mirror and the photoreceiver and provides signal conditioning between the photoreceiver and the optical bench. For the steering mirror it includes a current driver and electronics for an angle sensing readout along with analog electronics to steer the mirror position to a commanded position.

The TMA consists of three mirrors arranged as part of a "virtual" corner-cube retroreflector, including only mirrored elements where the laser light would hit the cube. The purpose of the TMA is to route the incoming and outgoing laser beams around the MWI while maintaining a virtual optical axis running through the center of mass of the spacecraft. Optical baffles are used to prevent obstruction of the laser beams and to control scattered light effects in the interferometer.

The primary function of the LRP is to measure the phase of the laser interferometer signal from the photoreceiver as representative of fluctuations in the separation between the two orbiters. This functionality is similar to the function of the IPU in tracking the microwave IF frequency from the MWI. It also is used to control the laser frequency, either phase locking the local laser to the incoming light or stabilizing the laser frequency to the Cavity frequency reference. The LRP also commands the angle of the steering mirror and implements the search required to establish the optical link.

The laser provides the light used for laser interferometry. It follows the "Non-Planar Ring Oscillator" topology used in many ground-based precision metrology systems. It puts out approximately 40 mW of light at 1064 nanometers. Most of the light is delivered to the optical bench; a small fraction is sent to the Cavity for laser frequency stabilization.

The Cavity is used to stabilize the laser frequency using the Pound-Drever-Hall technique. Changes in laser frequency look like changes in separation between the spacecraft, and it is expected that the limit to the LRI measurement precision will be how well we can stabilize the laser to the cavity.

Laser Retro-Reflector

The Laser Retro-Reflector is a contributed item from GFZ. The purpose of the passive, corner cube laser retro-reflector assembly is to provide support for orbit determination verification through satellite laser ranging from ground observatories. The assembly has four corner cubes and is installed in the nadir surface of the satellite. The operating characteristics for the LRR are completely determined by the ground segment of this experiment.

4. CHALLENGES

Development and implementation of a space system is a daunting organizational challenge, which can be fraught with many technical, programmatic and cultural pitfalls. Implementing a space system with international partners has added complexities, which must be recognized and considered at an early stage of the development. Addressing these challenges early in the planning stages plays a key role in reducing the impact of problems, which naturally occur during the formulation, implementation, and operational phases of the mission lifecycle.

International Partnerships

As a cooperative development between NASA and GFZ, the GRACE-FO mission includes significant work contributions from the United States and Germany, and also contributions from France, Denmark, Spain, and the United Kingdom.

The NASA-GFZ government-to-government agreement for the GRACE-FO mission is codified in a memorandum of understanding[2] (MOU), which describes the general responsibilities at a higher level. In support of the MOU, JPL and GFZ also developed a Cooperative Project Plan[3] (CPP), which described the process and details of the interactions and responsibilities for development, delivery, and operation of the various products. Both the MOU and the CPP derived heavily from the organization and responsibilities defined for GRACE, taking full advantage of pre-existing relationships, system heritage, and existing

or similar roles and responsibilities.

In the GRACE-FO MOU, NASA is responsible for the development and delivery of the two GRACE-FO spacecraft and the instruments needed to collect the primary science data, including the Microwave Instrument and the Accelerometers. NASA is also responsible for providing the electronics and laser components for the Laser Ranging Interferometer. In addition, NASA will provide ground networks of GPS stations and laser ranging stations for spacecraft navigation and participate in science and science data processing as on GRACE.

To implement this cooperative project, NASA assigned to JPL the responsibility to lead the overall project management for the GRACE-FO mission and to lead the overall design, development, integration and qualification of the flight segments; and support GFZ as necessary to assure compatibility of the flight segment with the launch vehicle and the mission operations systems. This assignment includes the design, development, integration and qualification for space flight of the two GRACE-FO spacecraft, the Microwave Instrument, the Accelerometers, and the electronic and laser components of the LRI.

In turn, GFZ agreed to develop the optical components for the LRI and provide the launch vehicle and all launch services. GFZ also agreed to provide the GRACE-FO Mission Operations and Telecommand Systems, ground networks of GPS stations and a Potsdam Laser Tracking Station, a Laser Retro-Reflector for each of the two GRACE-FO spacecraft and to participate in the science and science data processing as on GRACE.

Establishing a trusting working relationship among partners is critical to assuring the success of an international mission. This is especially true when the dependencies are based on contributions rather than contractual agreements. A key component of developing these trusting relationships is a clear and common understanding of the goals, roles, and responsibilities of all participants. The NASA-GFZ MOU established the required framework for the mission, and the Cooperative Project Plan documented the management methods, relationships and responsibilities of the various participants (partners, subcontracts, and contributors) responsible for the successful development and operation of the GRACE-FO mission.

Communication and Reporting

A second aspect of building trusting working relationships is open and honest communication. It was important for all the parties involved in GRACE-FO to gain visibility and insight into the various development and implementation activities in order to properly influence decision-making. Early on, the Project adopted a broad inclusion principle and established frequent interactions at the working and management levels to communicate the status of the common developments and tasks. In addition, the project encouraged frequent face-to-face interactions to work through technical problems or programmatic issues.

However, in an international setting, special attention had to be applied to remain in compliance with the International Traffic in Arms Regulations (ITAR). Therefore, for each of the international partners, a Technical Assistance Agreement (TAA) had to be developed and approved by the Department of State and all involved parties, which defined the nature and extent of permissible information exchange. In addition, all project personnel were provided ITAR compliance training to facilitate the exchange and communicate the applicable rules. In 2015 the project transitioned from ITAR compliance to Export Administration Regulations (EAR) compliance with the Department of Commerce. This transition required the establishment of new Support Agreements with all parties but significantly reduced the level of regulation. At this point in time, all spacecraft subsystems are no longer ITAR controlled and the only remaining ITAR-controlled agreements in place are for the launch service.

The English language is used in many parts of the world as a universal communication language and the GRACE-FO Project benefited from that and utilized it to facilitate effective communications across the suite of international partners. Although most international partners were very fluent in English and there was no need for the use of translators, the GRACE-FO project personnel had to be vigilant in making sure that the intent of the conversation was clearly understood. Often, similar terminology may mean different things depending on the context or experience of the communicators or a difference in development standards being applied. Regardless of the language proficiency of the international partner, the project personnel applied added rigor in their communications to manage expectations and assure that the intention of the message, in addition to the words, were clearly communicated.

An exception to the fluency in the English language occurred at an early stage while the team was investigating launch services offered by Russian and Ukrainian launch service providers where language translators were required throughout to assure proper translation of technical or programmatic terms. The use of translators consumed substantial additional time during our meetings, telecons, and official communications. This required an additional level of diligence and review to insure accurate communication of information. However, due to world political events, the relationship was not carried forward.

Regular reporting on the status of development, build, and test activities was established at an early stage of the mission and documented in the Cooperative Project Plan (CPP) for contributed items and the contractual agreements for procured or contracted items. An architecture for communication was established which allowed frequent (weekly) interactions between lead project personnel and

subsystem and instrument developers. Regular open discussions provided a deep level of insight into development and implementation activities and a path for quick resolution of problems. In addition, the project required monthly reporting with summary presentations in Monthly Management Reviews (MMRs), which included the current status of the sub-system developments and reports by all the lead personnel. MMRs provided a complete project status, both technical and programmatic, and formed the basis for reporting information to JPL and NASA program offices through the monthly Project Status Reports (PSR) and Quarterly Reports. In addition, frequent weekly interactions with the NASA Earth Science Division Project Executive and the Mission Manager at the Earth Systematic Mission Program office provided progress data and risk assessments of the activities across the mission.

The lead project personnel were also involved in the assessment of any non-conformances or test anomalies at the subsystem level. The anomalies were addressed at the home institution and tracked by the JPL lead project personnel and the Mission Assurance Manager (MAM) and reported at project monthly reviews.

Differences in Standards and Practices

As engineers in the aerospace industry, we are trained to follow established processes in doing our work. Differences in processes and practices across organizations can be the source of many technical or contractual difficulties or differences of opinion. To minimize such differences, the project adopted a policy regarding the use of the native processes of the doing institution. This allowed each organization to do the work following their internal processes and not be forced into adopting an unfamiliar process, which may result in unintended errors or design and fabrication issues. This approach made it critical for the JPL team to understand the native processes, compare them to internal JPL practices and perform a gap analysis, and assess any associated risks. Any significant gaps or concerns were addressed with the doing organizations and a process for dealing with the differences was negotiated.

In addition to internal processes, European aerospace organizations use the European Space Agency (ESA) standards and specifications in performing their tasks. These standards are similar to the standards used by JPL and NASA, but do have differences, which had to be evaluated and assessed against JPL project practices.

One key example of differences in practices related to the conduct of subsystem and project level reviews, as specified in the GRACE-FO Project Review Plan. Where ESA standard reviews are based on the Review Item Disposition System (RIDS), which are detailed reviews of documents associated with a design; the review process used by JPL provides for a technical review of the product by a review board and associated Requests For Action (RFA) in addition to the standard document review. While most international partners and participants had limited exposure to this type of review approach, teams quickly adapted to the approach and found it constructive. However, it required a learning curve for the international partners to be able to structure the content of the reviews to satisfy the expectations of the review boards. This required added attention by lead project personnel in the preparation and construct of the subsystem and project review material.

All subsystems and instruments were required to hold a standard set of reviews, typically Preliminary Design and Critical Design Reviews. Review boards typically consisted of lead subcontract personnel, lead project personnel, Mission Assurance, Project System Engineering, Project Management, and members of the Project Standing Review Board (SRB). This approach was beneficial in reporting review results at higher-level project and NASA reviews. Inclusion of SRB members in the lower level review process provided an exceptional added benefit in communication and understanding of issues and actions at the higher level reviews.

Cultural Considerations

In addition to internal-work-processes and standards differences among international partners; one has to be very mindful of the cultural practices, expectations, and work-related legal regulations. Embracing and taking such cultural expectations into account in the project planning are essential to maintaining a productive and respectful working relationship among partners.

Accommodations for the different national or local holidays and vacation periods in the various countries or regions of a country are important in managing expectations and establishing a meaningful development and implementation schedule. The project planning put in place accommodations for standard European and United States holidays in addition to known regional holidays and also planned the work to minimize the impact of standard vacation periods.

In addition to holiday and vacation considerations, the project also accounted for legal work hour limitations and associated facility access issues. The work limitations and associated rules are more rigid in Germany where the system integration and test activities take place.

5. SUMMARY

The GRACE Follow-On mission is on plan for launch in 2017 to continue the primary science objectives of the GRACE mission and provide estimates of the global high-resolution models of the Earth's gravity field for a period of up to five years at a precision and temporal sampling

equivalent to that achieved with GRACE. Addressing the organizational challenges of an international collaborative space mission has been critical to assuring the success of the development and implementation of the GRACE Follow-On Mission. In addition to planning the system with robust technical designs, the mission was also planned with a robust implementation and test schedule and with consideration for the cultural and organizational differences.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

Sammy Kayali *is the Deputy Director for the Office of Safety and Mission success at the NASA Jet Propulsion Laboratory. Prior to this position, Mr. Kayali held several positions at the Jet Propulsion Laboratory including: Deputy Project manager for the GRACE Follow-On Mission, Mission Assurance Manager for the Juno Mission, Mission Assurance Manager for the Prometheus Project and the Jupiter Icy Moons Orbiter Mission, Manager of the Electronic Parts Engineering Organization, and Manager of the NASA Electronic Parts and Packaging Program. Mr. Kayali's specialty is in the area of compound semiconductor device reliability where he has over 30 publications, and a published book on the subject of GaAs MMIC Reliability. He has served as the chair of the Government Microcircuit Applications & Critical Technology Conference (GOMACTech), the International Reliability Physics Symposium's (IRPS) Compound Semiconductor Session, was a member of the Reliability of Compound Semiconductors Committee, and has participated and chaired a number of various other industry working groups and workshops. He is the recipient of a number of honors and awards including the NASA Exceptional Service and Exceptional Achievement Medals. He holds degrees from Texas A&M University and Sam Houston State University in Solid State Physics and Electrical Engineering.*

Phillip (Phil) Morton *is the Project Manager for the GRACE Follow-On Mission, responsible for the management and implementation of the mission for the Jet Propulsion Laboratory and NASA. Mr. Morton has over 37 years experience in space flight systems, avionics, and instrument development, including six years as the Spacecraft Manager for the original Gravity Recovery and Climate Experiment (GRACE) Mission, and seven years as the Science Payload Manager for the Juno Mission to Jupiter. He has been involved in numerous JPL and NASA missions, including the Galileo mission to Jupiter, Magellan mission to Venus, Cassini mission to Saturn, and Mars Observer and Mars Pathfinder missions.*

Mr. Morton has a B.S. in Electrical Engineering from California Polytechnic University in Pomona, CA and has received the NASA Exceptional Service Medal for GRACE and two NASA Exceptional Achievement Medals for the Cassini and Juno Missions.

Michael Gross *started his career at the Jet Propulsion Laboratory in August of 1996. Mike has served as the Gravity Recovery and Climate Experiment (GRACE) Project Mission Assurance Manager, the Deputy Mission Assurance Manager of the Mars Exploration Rovers Project, the Phoenix Mars Lander Project Payload Manager, Assistant Division Manager for Flight Projects of JPL's Autonomous Systems Division, and Manager of the Power and Sensor Systems Section. He was awarded the NASA Exceptional Service Medal for his work on the GRACE Project and the NASA Exceptional Achievement Medal for his work on the Phoenix Mars Lander Project. Mike is currently the Gravity Recovery and Climate Experiment Follow On Flight System Manager. He holds a B.S. (Summa Cum Laude) and an M.S. (with Distinction) in Electrical Engineering from California State University, Northridge.*