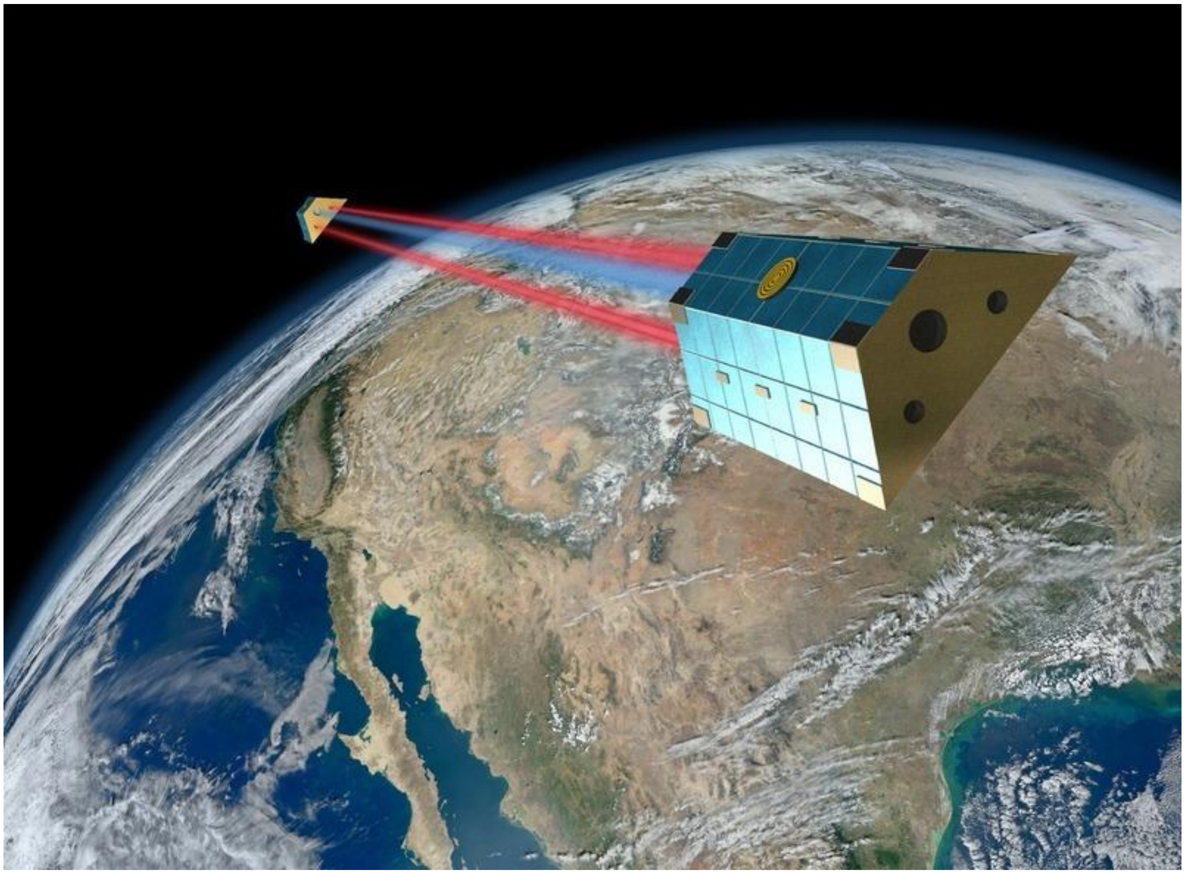
NASA Earth Science Division
Applied Science Program
GRACE Missions

Applications Plan for the Gravity Recovery And Climate Experiment (GRACE) Missions: GRACE, GRACE-FO, and Future Missions

October 2, 2016



The work was carried out, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Contributors to the GRACE Missions Applications Plan

Editors

Brad Doorn, Applied Sciences Program, NASA Headquarters
Michael Jasinski, Hydrological Sciences Laboratory, NASA GSFC
JT Reager, Jet Propulsion Laboratory/Caltech
Margaret Srinivasan, Jet Propulsion Laboratory/Caltech

Contributors

Srinivas Bettadpur, Center for Space Research, University of Texas
John Bolten, Hydrological Sciences Laboratory, NASA GSFC
Carmen Boening, Jet Propulsion Laboratory/Caltech
Molly Brown, Department of Geography, University of Maryland
Frank Flechtner, GFZ German Research Centre for Geosciences
Erik Ivins, Jet Propulsion Laboratory/Caltech
Sujay Kumar, Hydrological Sciences Laboratory, NASA GSFC
Felix Landerer, Jet Propulsion Laboratory/Caltech
Phil Morton, Jet Propulsion Laboratory/Caltech
Fritz Policelli, Hydrological Sciences Laboratory, NASA GSFC
Matt Rodell, Hydrological Sciences Laboratory, NASA GSFC
Lucia Tsaoussi, Earth Science Deputy R&A Lead, NASA Headquarters
Frank Webb, Jet Propulsion Laboratory/Caltech

Table of Contents

Executive Summary

The NASA Applied Sciences Program (ASP) supports applied research and targeted projects focused on innovative and practical uses of Earth remote sensing observations and modeling resources for societal benefit. The approach is to offer NASA environmental data products and necessary expertise to relevant public and private stakeholders to improve decision-making tools and techniques. An important element is identifying and enlisting those interested stakeholders, an applied science community of practice, to participate in relevant activities of the mission life cycle from its inception through launch and operations. Participation at an early stage allows stakeholders to be ready to use the data at launch. Typical Applied Science focus areas include water resources, natural disasters, ecological forecasting, health and air quality and wildfires.

The GRACE Missions Applications Plan (AP) presented herein provides a framework for implementing the above NASA ASP vision specifically for the suite of gravity missions including GRACE launched in 2002, GRACE Follow On (GRACE-FO) scheduled to launch in 2018, and future GRACE-like missions. The primary goal is to promote the use of GRACE data by public and private organizations to help support decision-making activities and services as a way to increase the benefits of GRACE to society.

GRACE is a collaboration between NASA and the German Aerospace Center (DLR) in Germany. The key partners are the University of Texas Center for Space Research (UTCSR), the GFZ German Research Centre for Geosciences, and the Jet Propulsion Laboratory (JPL). DLR´s German Space Operations Centre (GSOC) is responsible for mission management and satellite operation. UTCSR and GFZ are responsible for scientific data evaluation.

Since 2002, the GRACE Mission has provided time series science data products and expertise on terrestrial hydrology and gravity to advance global science. These same data also offer the potential to improve decision making when incorporated into relevant policy, business or management tools. The most obvious opportunities are currently in the areas of water resources including surface and groundwater, climate, natural disasters and surveying and navigation. The GRACE AP has been developed to help realize the full potential. It outlines elements of an end-to-end approach to: i) Increase awareness of GRACE mission and data products through presentations at science and stakeholder meetings, and through telecons, workshops, tutorials, and town halls, ii) Identify and engage a diverse applications community of potential new GRACE data users including the international community, iii) Promote the understanding of GRACE products to potential new end users as well as understand the their requirements, iv) Facilitate contact and exchange of ideas among GRACE scientists and current application users, data experts and potential new users, through the formulation of a GRACE Applications Team that includes GRACE scientists and current users, and an expanding applied science community of new GRACE users, and v) Engage strategic government and private partners interested in bringing their own resources. The goal is to continue building broad support for using GRACE data products in applied sciences and fully exploit the more than 20-year time series of gravity anomaly observations.

1. Introduction

NASA's Earth Science Program is dedicated to developing a comprehensive scientific understanding of Earth as an integrated system. Through the design and implementation of both airborne and satellite remote sensing missions, and in conjunction with analysis and modeling, NASA addresses complex science questions that lead to improved prediction of global hydrology, weather and climate over the full range of terrestrial, atmosphere and ocean domains. The primary objectives of NASA's ASP include supporting activities that identify and demonstrate the broad range of activities that improve decision through innovative and practical application of data and modeling products, and scientific knowledge, that stem from NASA's Earth science missions.

The National Research Council report on Earth observations (NRC, 2007) emphasized that established societal needs are necessary to guide scientific priorities more effectively and that emerging scientific knowledge is actively applied to obtain societal benefits. NASA's Science Mission Directorate (SMD) ASP supports these aims by conducting research and development that enables use of NASA Earth observations and research to make better decisions and policy, mitigate risk, build resilient communities, and adapt to a changing planet (NASA, 2013).

Recent application planning for SMAP (Brown et al., 2012), ICESat-2 (Brown et al., 2013), SWOT (Srinivasan et al., 2014) and related GRACE presentations (Rodell et al., 2009) have helped formulate a model for missions applications plans. Of primary emphasis is the need for an applied science community of practice to integrate into the flight mission development life cycle from its inception (Pre Phase A) through launch and operations (Phase E). The objective of applications activities is to identify and engage with the community of practice for each NASA mission. Strategic engagement with key individuals and organizations will create strong partnerships that will identify user requirements, maximize the mission benefits, and provide strong advocacy for the mission (Brown et al., 2011). The extended time series expected with the launch of GRACE-FO would offer more than two decades of mapping of changes in the earth's gravity field, creating the first opportunity for a groundbreaking view of decadal variability and secular trends in water storage globally.

The GRACE mission has been accurately mapping variations in Earth's gravity field since the April 2002. The major time-varying signal measured by GRACE is redistribution of water mass within the Earth system. The principal dynamics causing redistribution include changes due to surface and deep currents in the ocean, changes in the water balance and ground water storage on the continents, glacier losses, and exchanges between ice sheets and the ocean, and variations of mass within the solid Earth. The intrinsic spatial scale of the GRACE observations is coarse for many local scale applications. However, when used in combination with other complementary data sets such as terrestrial hydrology models, the data have offered enhanced insights on processes at higher spatial and temporal resolutions. The chief advantage GRACE has over other space observations is completeness in capturing integrated mass changes at and beneath the land surface. These observations create the potential for applications in drought monitoring and related fire hazard assessment, flood risk evaluation, regional water budget analysis including quantification of groundwater depletion, ice sheet and glacier mass change monitoring, and non-steric sea level rise assessment.

The GRACE mission has produced several science data products, including Level 3 monthly gridded time series of global gravity anomalies at several hundred kilometers square spatial scales using a spherical harmonic approach. Recent improvements have been made by regional mascon techniques to recover signal more accurately (e.g. Luthcke et al., 2008, Watkins et al., 2015; Save et al., 2015). The mass anomalies allow a direct and comprehensive observation of terrestrial water storage changes at a nominal 2-3 degree latitude longitude resolution. When integrated into higher resolution model frameworks to downscale regional terrestrial water storage changes, the collective value of the integrated data product provides potential benefit to both public and private sectors for supporting decision-making activities at local management scales.

The formal AP described herein outlines the key components for extending GRACE science for societal benefit for GRACE, GRACE-FO, and future gravity missions. Its overarching purpose is to identify and initiate innovative uses and practical benefits of GRACE science data and technology. A primary goal is to promote the use of GRACE data by public and private organizations to help support decision-making activities and services as a way to increase the benefits of GRACE to society.

2. Strategic Goals and Objectives

The goals of GRACE Missions Applications are to: i) enhance GRACE applications research outcomes by identifying and supporting relevant evolving societal needs in the areas of policy-making, business, resource management and disaster response, ii) increase GRACE applied science collaborations by raising mission awareness and fostering partnerships with organizations that provide complementary resources and extend the mission’s reach, and iii) accelerate new use of mission data and information products by encouraging that NASA’s GRACE missions plan and support applications goals occur in parallel with science goals for future missions, through the entire mission life cycle.

Specific objectives for GRACE mission applications are to:

i) Increase awareness of GRACE mission and data products through presentations at science and stakeholder meetings, and through applications telecons, workshops, tutorials, and town halls,

ii) Identify and engage a diverse applications community of potential new GRACE data users including the international community,

iii) Promote the understanding of GRACE products to the community of potential new end users as well as understand the requirements of those users,

iv) Facilitate contact and exchange of ideas among GRACE scientists and current application users, data experts and potential new users, through the formulation of a GRACE Applications Team that includes a working group, GRACE scientists and current users, and an expanding applied science community of new GRACE users, and

v) Engage strategic government and private partners interested in bringing their own resources.

The goal is to continue building broad support for using GRACE data products in applied sciences and fully exploit the more than 20-year time series of gravity anomaly observations.

3. GRACE, GRACE-FO and other future GRACE Missions

3.1 Description

GRACE is a collaboration between NASA and the German Space Agency (DLR) in Germany. The key partners are the University of Texas Center for Space Research (UTCSR), the GFZ German Research Center for Geoscience Research, and the Jet Propulsion Laboratory (JPL). The mission is led by the Project and Program offices, and the GRACE Science Team (GST) guides science aspects of the mission. An overview of the mission is discussed in Tapley et al. (2004).

GRACE consists of twin satellites, separated approximately 200 km, that make measurements of Earth's gravity field by accurately measuring changes in the distance between them. Small variations in this inter spacecraft distance result from changes in the gravity signature due to mass changes on Earth. These gravity measurements, in conjunction with other data and models, provide estimates of terrestrial water storage change, ice-mass variations, ocean bottom pressure changes and sea-level variations.

GRACE-FO, scheduled for launch in 2017, is functionally identical to GRACE except that it includes an experimental laser ranging interferometer and will see a natural enhancement in data quality due to both improvement of de-aliasing models and enhanced skill in basic engineering software and hardware. See http://gracefo.jpl.nasa.gov for more information on the mission. Future GRACE missions, still in concept phase, could potentially provide higher spatial or temporal resolution data products compared to GRACE and GRACE-FO. Likely to launch after 2020, the later mission will address fundamental questions of climate-driven hydrological and cryospheric change, as it would provide an extended continuous time series more relevant for climate studies.

3.2 Data Products

3.2.1 Grace Level 1, 2 and 3 Products

GRACE Earth gravity fields are currently officially produced at two levels. Level 1 and 2 gravity fields from GRACE’s inter-satellite range rate observations are produced by the GRACE project Science Data System (SDS). The SDS is distributed between UTCSR, JPL and GFZ. At present, the SDS delivers monthly estimates of Earth’s gravity field, and distributes them to the public via PODAAC and ISDC (links below). The Level-1A product contains raw data that are collected from satellites, calibrated and time-tagged. Two of these are publicly available (The Level-1A product requires expert-level knowledge to use). The Level-1B products refer to the collection of filtered ranging, accelerometry, attitude and related ancillary data and have been useful for scientists examining specific known targets, such as earthquakes (see Han et al., 2014). Level-2 data refer to the approximately monthly gravity field estimates reported in form of spherical harmonic coefficients. Often, one or more months of data may be combined to produce an estimated global map of gravity change, referenced to the mean over the entire observing period.

Level-3 data refer to the gridded version of these data sets, also available with higher-sampling (1-degree at writing) spatial scaling factors available following Landerer and Swenson (2012). The most current version is release RL05.

After validation, all Level-3, Level-2 and accompanying Level-1B products are released to the public through two portals; 1) the Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory, Pasadena, (http://podaac.jpl.nasa.gov/grace), and 2) Information System & Data Center (ISDC) at the GFZ German Research Centre for Geosciences, Potsdam in Germany (http://isdc.gfz-potsdam.de/grace).

As an alternative to reporting the spherical harmonics, efforts also have been made to directly compute gravity anomalies using a regional high-resolution mascon solution (Luthcke et al., 2008; Watkins et al., 2015; Save et al., 2015) and are currently a part of the data sets that may be accessed on PODAAC.

The GRACE-FO mission is also planning to produce a ‘quick-look’ product with a several day latency. This product will be directly useful for near-real-time monitoring of drought, flood, and water resources, although it will not possess the same accuracy as the stable GRACE monthly solutions released with normal latency.

3.2.2 GRACE Higher Level Products

Several users have developed value-added products from GRACE Project data products. A principal effort includes GRACE data products as water mass storage anomalies, expressed in terms of millimeters of water. Examples include Monthly Land Water Mass Grids, Monthly Ocean Mass grids, Post Glacial Rebound, and Dynamic Ocean Topography Products. Many of these are produced in gridded format and are available through the GRACE Tellus website; http://grace.jpl.nasa.gov/data/get-data.

Other data and analysis tools include NASA/GSFC’s mascon based, gridded terrestrial water storage product (http://ssed.gsfc.nasa.gov/grace/), CNES’s Marvelous GRACE plotter (http://thegraceplotter.com/), and the University of Colorado interactive tool for calculation of error-corrected mass anomalies in regional or global time series (http://geoid.colorado.edu/grace/grace.php), The University of Texas at Austin’s Center for Space Research has developed another gridded GRACE hydrology product that includes a low latency version meant to address timeliness requirements of operational applications. GRACE FO will make such a product a standard requirement.

The International Centre for Global Earth Models distributes a full range of current and historical static Earth gravity field models as well as GRACE time-variable gravity models.

It also includes tutorial and software resources for physical geodetic calculations, a GFZ GRACE Gravity Browser (G^3 Browser) for visualization of GRACE derived time variations and contains links to related gravity field services. The EGSIEM (European Gravity Service for Improved Emergency Management) project (www.egsiem.eu) will develop gravity-based indicators for extreme hydrological events and demonstrate their value for flood and drought forecasting and monitoring services and will combine the results obtained from different Analysis Centers of the EGSIEM consortium, each of which will perform independent analysis methods but will employ consistent processing standards. Additional analysis centers provide services for data download.

Further, NASA/GSFC generates weekly groundwater and soil moisture drought indicator maps for the contiguous U.S., which are distributed by the National Drought Mitigation Center. These maps are generated by integrating the GRACE data with other observations via data assimilation within a sophisticated numerical model of land surface water and energy processes. For more information, see Houborg et al. (2012), and http://drought.unl.edu/monitoringtools/nasagracedataassimilation.aspx).

4. GRACE Applications Focus Areas

GRACE science data continue to provide ongoing expertise on terrestrial hydrology and improvements to the Earth's gravity fields (E.g., See NASA Mission Directorate, 2015). They also offer the potential to improve decision-making techniques across many application areas. The most obvious opportunities are currently in the areas of water resources including surface and groundwater, climate, natural disasters and surveying and navigation.

4.1 Water Resources

Seasonal and interannual changes in water availability including water stored in surface waters, groundwater, and snow and ice can be quantified using GRACE. Hence GRACE missions have the potential to inform water resources decision-making related to surface and groundwater management, and snow and streamflow quantification, flooding preparedness, drought mitigation, irrigation management, food security and agricultural management, among many others.

For instance, groundwater is a useful indicator of climate variability and human impacts on the environment. Combining GRACE data with hydrologic modeling enables water managers to quantify changes in groundwater over large regions or where monitoring well data are sparse, providing insight on groundwater withdrawals and sustainable resource planning. GRACE-FO will continue to observe global terrestrial storage anomalies leading to improved knowledge of the components of the water balance. Observations will provide information on seasonal and large-scale (>100,000 km^2) river basin water storage changes, human influences on regional water storage changes and, evapotranspiration, which may affect water management and policy decisions. Assimilation of GRACE data into land data assimilation models enables the generation of higher resolution data products. GRACE data assimilation is currently being used to generate weekly drought indicator maps as described in section 3.2.2 above.

An important example of GRACE applications research is the incorporation of GRACE-based groundwater observations within water supply decision support tools, including GRACE data assimilation within terrestrial hydrology models. These tools would be useful for responding to the combined effects of climate change and anthropogenic water consumption. Numerous end users utilize output information of these data assimilation tools in their respective decision making.

4.2 Climate

Decision support applications related to better planning and mitigating of the effects of a warming world have high potential for gravity data products. GRACE data already are used extensively to determine mass changes of the Earth's land ice including ice sheets, ice fields, ice caps and mountain glaciers. Land ice increases through precipitation but then ablates through melt-water runoff, evaporation, mass-flux across grounding lines, basal melting and calving of ice shelves into the ocean. Net losses contribute to a sea level rise of several mm/yr (Gardner et al., 2013 and Shepherd et al., 2012) which is a significant threat to coastal regions and small island nations. Changes in groundwater is a useful indicator of climate variability and human impacts on the environment. GRACE data also provide fundamental and highly reliable information that constrain ongoing seasonal and sub-seasonal variations in water transport across the continental land masses and oceans.

4.3 Natural Disasters

Applied science can take advantage of GRACE science research to better capture gravity changes that result from changes in Earth's mantle, lithosphere and crust during and after earthquakes. This information can be incorporated into operational modeling to support improved planning and mitigation activities in earthquake-prone regions. GRACE is the only space-based measurement system for imaging the long-wavelength effects of great thrust events of the circum-Pacific and Indian Ocean where earthquakes of magnitude $M_w > 8.0$ often occur directly below the sea. This unique potential GRACE may be useful for use in the area of natural hazards in coastal areas. GRACE science research on glacial isostatic adjustment (GIA) also may be useful for improved terrestrial hydrology modeling.

4.4 Surveying and Navigation

GRACE data products have led to improved knowledge of the Earth's gravity field by orders of magnitude, providing a global geoid model accurate to the centimeter level at 200-kilometer resolution. This improved capability has potential decision support applications that rely on accurate gravity fields as in surveying and navigation.

5. GRACE Applications Team

The GRACE Applications Team consists of the SMD ASP Manager for Water Resources, Deputy Program Application (DPA) Team Leads, the GRACE Applications Working Group, Future Adopters, and the GRACE Applications Community as described below.

5.1 Applications Team Leads

The role of the GRACE team leads includes oversight of the applications program, development of the GRACE Applications Plan, facilitation of discussions, tasks, meetings, workshops, etc., as well as development of communication products, collaborations with GRACE GST members on Applications-relevant topics and events, and administrative and logistical activities. GRACE DPA Leads will provide updates on the GRACE Plan at GST Meetings. The GRACE DPA Leads are assigned by the SMD ASP Manager for Water Resources.

5.2 GRACE Applications Working Group (GAWG)

The GRACE Applications program will initiate a GRACE Applications Working Group (GAWG) of about 20 members consisting of the Application Leads and interested members of the Science Team and the Applications Community. Members will be selected by the Applications Leads and the SMD Applied Sciences Water Resources Program Manager. The role of this group is to contribute guidance on a wide range of application activities. Specific contributions by an individual member are identified in Section 7.1.

5.3 GRACE Applications Future Adopters

The NASA Applied Sciences Program formally encourages groups and individuals who have an existing application or decision support tool that can potentially ingest data from future satellite missions, and would like to evaluate the concept using prototype data. For GRACE, the potential exists for using existing GRACE or other existing gravity data for testing GRACE-FO and future GRACE-like mission data within existing decision support tools. The Future Adopter works independently but will be assigned to a GRACE scientist mentor who can address occasional technical questions on the use of GRACE data products, if necessary. The goal of the Future Adopter participant is to develop pre-launch readiness in order to accelerate the integration of GRACE-FO and other future GRACE-like missions data products into their applications.

5.4 Applications User Community

The GRACE Applications community includes other interested research scientists, engineers, end-users, individuals, students, and policy makers, of various backgrounds and skills, who have some interest in the utility of GRACE data and have a desire to stay abreast of mission progress. Some may already use GRACE data products in their application (e.g. Community of Practice). Others may have little knowledge of GRACE capabilities, but are curious and have strong potential to ultimately benefit from the data products or information that results from them (Community of Potential). Regular updates on GRACE Applications activities will be made available to the GRACE Applications Community posted on the GRACE Applications web page. (http://grace.jpl.nasa.gov/applications). Users of GRACE data may be asked to register the type of application to which the data products may be applied.

6. Strategic Partners

In order to define the complete community that can benefit from GRACE, the Applications Team will work through partners and other organizations to identify interested individuals and institutions that should benefit from the use of GRACE data products. The goal is to establish strategic alliances with key users of satellite remote sensing data within and outside of research and government organizations. Potential partnering operational agencies include NOAA, USGS and Bureau of Reclamation.

6.1 Government, Academic, and Industry Partners

The GRACE Applications Team will identify potential models, programs and decision support tools, both in the U.S. and internationally, that may benefit from GRACE data in various public and private sectors, with the goal of developing partnerships with the interested groups. Principal U.S. partners may include groups within US Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), the Department of Interior (DoI) and the US Geological Survey (USGS). State governments and non- governmental organizations partners are equally potential partners that can benefit from the approach. Potential international partners need to be identified.

6.2 International Partners and Collaborations

As GRACE is a collaboration of NASA and DLR/GFZ, the Applications Team will promote coordination and collaboration among both domestic and international partners and GRACE scientists. It will also include communication with, assessment of, and outreach to user communities, data product and processing requirements to optimize access, and identifying applications and collaboration opportunities. Important earth science areas include climate change and impacts, water availability and redistribution, natural resources, land surface processes, and hazard and risk assessment.

International partners include principally the DLR, the GFZ German Research Centre for Geosciences and the European Space Agency (ESA). GFZ and DLR as well as ESA´s Third Party Mission Program are supporting the continuation of the measurements of mass redistribution in the Earth system, e.g., by funding of GRACE mission operations. Additional key German and other international partners will be identified throughout the implementation of this GRACE Plan.

7. Applications Initiatives

GRACE applications initiatives are aimed at fostering a community of practice interested in GRACE-FO and other future GRACE-like missions data products from inception through operations.

7.1 GRACE Applications Working Group (GAWG)

A GRACE Applications Working Group, or GAWG, will be established to support the implementation of this plan. GAWG members will be invited by the Application Leads and

SMD Water Resources Program Manager to represent the full range of potentially relevant focus areas. GAWG participation will be voluntary.

Specific initiatives within the GAWG include:

i) Identifying the breadth of potential GRACE societal benefits across a broad range of application focus areas,

ii) Providing understanding on what GRACE data products can provide to a broad user community possessing little remote sensing experience,

iii) Participating in telecons, workshops, tutorials, and town halls at science meetings,

iv) Contacting potential end-users and strategic partners, and facilitating collaborations between them and the GRACE/GRACE-FO Science Team and Project Office,

v) Writing GRACE applications manuscripts in peer-reviewed journals,

vi) Reviewing the Applications Plan and providing guidance on its future direction and implementation, and

vii) Identifying key speakers, and suggesting host institutions and venues.

Given the voluntary nature of the GAWG, contributions from an individual member may be limited to only a few activities.

7.2 Workshops, Focus Sessions and Tutorials

The following communication activities will be conducted to support this Applications Plan:

i) Workshops and\or tutorials will be organized approximately once each year. Each event will be organized to focus on a thematic topic (i.e., water resources, land ice, disasters, and oceans). The goal would be to discuss data needs, and data tools to facilitate research, and to highlight examples of other successful applications,

ii) Joint tutorials with other missions will be organized to focus on collaboration and synergies among missions (e.g. GRACE-GPM, GRACE-SMAP, GRACE-SWOT, GRACE-ICESat-2, etc.),

iii) Sponsoring GRACE applications sessions, papers and posters at organized remote sensing and relevant scientific meetings. These may include; American Geophysical Union (AGU), American Meteorological Society, International Geoscience and Remote Sensing Symposium (IGARSS), European Geosciences Union (EGU), Ocean Surface Topography Science Team (OSTST) meetings and others, and

iv) Participation in Town Halls such as at AGU meetings, to promote the GRACE AP.

7.3 Applied Sciences Future Adopter Community

The NASA Applied Sciences Program formally encourages use of prototype data of new missions by selected stakeholders to understand how the eventual satellite data products can best be integrated into an organization's decision support tool. The goal is, through prior development with existing and prototype data, for that stakeholder to be ready as soon as possible after launch to incorporate the actual satellite data into the decision tool.

GRACE AP will facilitate an AS Future Adopter (FA) community focusing on GRACE-FO and other future gravity missions. Elements of this initiative include:

i) Participants are solicited based on the model currently employed by the SMAP and ICESat-2 mission APs. It includes a short 2-page proposal, submitted directly to the AP Leads, that identifies the organization, decision support tool, and applications end user. Proposals will be reviewed and selected by the Application Team leads and the GAWG.

ii) FA participants will apply their own resources (funding, personnel, facilities, etc.) to demonstrate the utility of GRACE data for their particular system or model,

iii) Participants will engage in studies ingesting GRACE data into their decision support tool. They will be asked to document data products, analyses, and models, and to provide quantitative metrics of the impact of the use of the GRACE data product. They will also be encouraged to participate in discussions with the GRACE Applications Team and provide feedback on data product attributes relevant to their application.

iv) Interested GST members will be identified based on the given application for EA contact. The GST member, whose participation is voluntary, may offer knowledgeable advice on relevant data products and other details of the data systems.

7.4 Coordination with Other Missions

The primary missions are other gravity and altimetry missions, especially those focused on surface and groundwater storage monitoring and other water cycle fluxes. These will include Jason-3, SWOT, ICESat2, CryoSat, GPM, SMAP, and other Earth missions as relevant. Application Leads or members of the GAWG will attend other mission team meetings to stay abreast of their development.

7.5 GRACE Applications Research

The following activities are envisioned:

i) Encourage Application Team members to seek opportunities to engage in capacity-building activities both within NASA (i.e., ROSES, SERVIR, DEVELOP, etc.), the U.S., and internationally,

ii) Advise the ASP on exceptional applications-oriented studies and tool development that will enable access to GRACE data products and applications,

iii) Encourage communication and collaboration between the Applications Team and GST, and

iv) Participate in related field campaigns that will enable easier access to data products.

7.6 Timeline

Qrtr	2012-2015	2016	2017	2018	2019
1	Draft Applicatons Plan	Formulate GAWG Team	Annual User Workshop	Annual User Workshop	Annual User Workshop
	Web development		GAWG/EA Quarterly Call	GAWG/EA Quarterly Call	GAWG/EA Quarterly Call
			Draft Implementation Plan		
2	Draft Applications Plan	Mtg w/GRACE-FO Mission Proj Mngmt, JPL	GAWG/EA Quarterly Call	GAWG/EA Quarterly Call	GAWG/EA Quarterly Call
	GSA Mtg 2012; GEWEX Mtg, 2013	GAWG			
	AGU 2014;Texas Water Managers Mtg, 2014				
3	Present AP at 2015 GSTM, Austin	GAWG/Formal Invite/Telecom	GSTM, Austin	GSTM Potsdam	GSTM Austin
	First GAWG Mtg, GSTM, Austin	Present AP status, GSTM, Potsdam			
		Applications Session, GSTM, Potsdam			
4	AP Poster OSTM/Coast Alt Wkshp, Reston	AGU Presentation	AGU Town Hall	AGU GRACE Apl Sci Spec Sess	AMS GRACE Apl Sci Spec Sess
	Present at ICESat2 Apl Sci Wkshop, Denver	GAWG Telecom/Implementation Plan	GAWG/EA Quarterly Call	GAWG/EA Quarterly Call	GAWG/EA Quarterly Call
		Identify Early Adopters			
		Complete Applications Plan			

8. Assessment

The overall goal of this plan is to engage GRACE end users and build broad support for the use of GRACE data products in science and societally beneficial applications. Deliverables will include successful workshops, papers, posters, and presentations at relevant science venues. The GRACE Applications program will explore ways to adequately assess the integration of GRACE data products into relevant user communities. Some strategies to evaluate the success of the GRACE Applications Program include:

i) Assess the breadth of the Applications Team at regular intervals (i.e., bi-annually), and evaluate its growth in the community,

ii) Track user community size and diversity of applications,

iii) Evaluate pre-launch (GRACE-FO and future gravity mission) applications investigations and seek formalized feedback from members of the user community on support and relevance of the program, and

iv) Identify future directions.

9. List of Acronyms

AS	Applied Sciences
AP	Applications Plan
CNES	Centre National d'Etudes Spatiales (French Space Agency)
DLR	Deutsche Forschungsanstalt für Luft und Raumfahrt (German space agency)
DoI	Department of the Interior
ESA	European Space Agency
FA	Future Adopter
GAWG	GRACE Applications Working Group
GFZ	GeoForschungsZentrum, Potsdam (German Center for Geoscience Research)
GRACE	Gravity Recovery And Climate Experiment
GRACE-FO	Gravity Recovery And Climate Experiment Follow-On
GSFC	Goddard Space Flight Center
GST	GRACE Science Team
ICESat-2	Ice, Cloud, and land Elevation Satellite-2
JPL	Jet Propulsion Laboratory
NOAA	National Oceanic and Atmospheric Administration
ONERA	Office National d'Etudes et de Recherches Aérospatiales
SMD	Science Mission Directorate
SMAP	Soil Moisture Active Passive Mission
SWOT	Surface Water Ocean Topography
USGS	U.S. Geological Survey
UTCSR	University of Texas, Center for Space Research

10. References

Bolten, J., et al, Looking to the Future: Forming a Comprehensive GRACE FO Applications Strategy, Presented at the 2012 GRACE Science Team Meeting, 17-19 September 2012, Potsdam, Germany.

Brown, M., Escobar, V., Moran, S., Doorn, B., Friedl, L., Habib, S., Applications Activities for NASA Flight Missions, NASA White Paper, Dec 2011.

Brown, M., Moran, S., Escobar, V., and D. Extekhabi, Soil Moisture Active Passive (SMAP) Applications Plan, 2012.

Brown, M., Escobar, V., Carroll, M., Neumann, T., and M. Jasinski, Ice, Cloud and Land Elevation Satellite 2 (ICESat-2) Applications Plan, Aug 22, 2013.

Chambers, D. P: Observing seasonal steric sea level variations with GRACE and satellite altimetry, J. Geophys. Res., 111 (C3), C03010, 10.1029/2005JC002914, 2006.

Chambers, D.P. and J.A. Bonin: Evaluation of Release 05 time-variable gravity coefficients over the ocean. Ocean Science 8, 859-868, 2012. www.ocean-sci.net/8/859/2012.

Cheng, M. and Tapley, B.D.: Variations in the Earth's oblateness during the past 28 years, J. Geophys Res v109, B9, 2004.

Doorn, B., Jasinski, M., Ivins, E., and M. Srinivasan, NASA Mission Applications: Program Introduction and GRACE Plan, 201 GRACE Mission Science Team Meeting, Austin, TX, Sept., 2015.

Gardner, A.S., G. Moholdt, A. Arendt, and B. Wouters, 2012: Accelerated contributions of Canada's Baffin and Bylot Island glaciers to sea level rise over the past half century, The Cryosphere, 6, 1103-1125, 10.5194/tc-6-1103-2012.

Han, S.-C., J. Sauber, and F. Pollitz (2014), Broadscale postseismic gravity change following the 2011 Tohoku-Oki earthquake and implication for deformation by viscoelastic relaxation and afterslip, *Geophys. Res. Lett., 41,* 5797-5805, doi:10.1002/2014GL060905.

Harig, C., and F.J. Simons (2015) Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains, Earth and Planet. Sci. Lett., 415, 134-141.

Houborg, R., M. Rodell, B. Li, R. Reichle, and B. Zaitchik, Drought indicators based on model assimilated GRACE terrestrial water storage observations, Wat. Resour. Res., 48, W07525, doi:10.1029/2011WR011291, 2012.

International Group on Earth Observations: http://earthobservations.org

Ivins, E. R., M. M. Watkins, D.N. Yuan, R. Dietrich, G. Casassa, and A. Rülke (2011), On land ice loss and glacial isostatic adjustment at the Drake Passage: 2003–2009, J. Geophys. Res., 116, B02403, doi:10.1029/2010JB007607.

Landerer F.W. and S. C. Swenson, 2012: Accuracy of scaled GRACE terrestrial water storage estimates. Water Resources Research, Vol 48, W04531, 11 PP, doi:10.1029/2011WR011453.

de Linage C., L. Rivera, J. Hinderer, J.-P. Boy, Y. Rogister, S. Lambotte and R. Biancale: Separation of coseismic and postseismic gravity changes for the 2004 Sumatra–Andaman earthquake from 4.6 yr of GRACE observations and modelling of the coseismic change by normal-modes summation. Geophys. J. Int. (2009) 176, 695–714, doi: 10.1111/j.1365-246X.2008.04025.

Luthcke, S. B., A. A. Arendt, D. D. Rowlands, J. J. McCarthy, and C. F. Larsen. (2008). Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. Journal of Glaciology 54 (188): 767-777.

(NASA, 2013) NASA Earth Science Division, Applied Sciences Program, Program Strategy, 2010-2015.

NASA Science Mission Directorate, Research Opportunities in Space and Earth Sciences NNH15ZDA001N-GRACE, A.27 GRACE and GRACE-FO Science Team; https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=493116/solicitationId=%7B32341583-0080-3E21-AB78-CC2051C58E22%7D/viewSolicitationDocument=1/GRACE15selections.pdf, Oct, 2015.

National Academies Press: http://www.nap.edu/catalog/11820.html

NRC Space Studies Board, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, National Academies Press, 2007.

Jacob, T., J. Wahr, W. T. Pfeffer and S. Swenson, (2012) Recent contributions of glaciers and ice caps to sea-level rise, Nature, 482, 514-518, doi:10.1038/nature10847.

Jasinski, M., Srinivasan, M., Ivins, E., Bolten, J. and B Doorn. (2015). Applied Sciences Plan for the Gravity and Climate Experiment (GRACE) Missions: GRACE, GRACE-FO, and GRACE-II, Coastal Altimetry Workshop, Reston., October 18-19, 2015.

Joodaki, G., J. Wahr, and S. Swenson (2014), Estimating the human contribution to groundwater depletion in the Middle East, from GRACE data, land surface models, and well observations, Water Resour. Res., 50, 2679–2692, doi:10.1002/2013WR014633.

Rodell, M., Houborg, R., Li, B., Zaitchik,. B., Reichle, R., Bolten, J., Nigro, J., Velicogna, I., Famiglietti, J., Practical Applications of GRACE and Future Satellite Gravity Missions, ICGP 565, FGW 2009.

Rodell M, P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D.

Toll (2004) : The Global Land Data Assimilation System. Bulletin of the American Meteorological Society, vol 85 (3), pp 381-394.

Save, H., S. Bettadpur and B. Tapley (2015) Evaluation of global equal-area mass grid solutions from GRACE, Geophysical Research Abstracts Vol. 17, EGU2015-6747, 2015 EGU General Assembly 2015

Shepherd et al., A Reconciled Estimate of Ice-Sheet Mass Balance. *Science* 30, Vol. 338 no. 6111 pp. 1183-1189. Nov 2012.

Srinivasan, M., Peterson, C., Andral, A., Dejus, M., Hossain, F., Creteaux, J-F., and E. Beighley, E., SWOT Applications Program Plan, July 2014.

Srinivasan, M. E.R. Ivins, and M.F. Jasinski, Mission Applications Support for NASA The Gravity Recovery and Experiment (GRACE) Missions, 2014 GSA Annual Meeting in Vancouver, British Columbia, Oct. 2014.

Swenson, S. C. and J. Wahr, Post-processing removal of correlated errors in GRACE data, Geophys. Res. Lett., 33, L08402, doi:10.1029/2005GL025285, 2006.

Swenson S.C, D. P. Chambers, and J. Wahr: Estimating geocenter variations from a combination of GRACE and ocean model output. J Geophys. Res.-Solid Earth, Vol 113, Issue: B8, Article B08410. 2008.

Tapley et al., 2004, *Geophys. Res. Lett*. 31, L09607, doi:10.1029/2004GL019920).

U.S. Group on Earth Observations: http://www.usgeo.gov

Wahr, J., M. Molenaar, and F. Bryan, Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, J. Geophys. Res., 103, 32,20530,229, 1998.

Watkins, M. M., D. N. Wiese, D.-N. Yuan, C. Böning, and F. W. Landerer (2015), Improved methods for observing Earth’s time variable mass distribution with GRACE using spherical cap mascons, J. Geophys. Res. Solid Earth, 120, 2648–2671, doi:10.1002/2014JB011547.