Mass Change Community Workshop Report
July 30, 2019 - August 1, 2019

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ACRONYMS

ACCP	Aerosols, Clouds, Convection and Precipitation
ACFT	Advanced Cusp Field Thruster
AMOC	Atlantic Meridional Overturning Circulation
ATMQS	Atomic Test Mass Quantum Sensing
BPR	bottom pressure recorder
CAI	cold atom interferometry
CAL	Cold Atom Lab
CAR	Community Assessment Report
CATE	Cost Assessment and Technical Evaluation
CCLR	Compact Coherent Laser Ranging
CNES	French National Centre for Space Studies (Centre national d'études spatiales)
DO	Designated Observables
DS	Decadal Survey
ECV	Essential Climate Variables
EGO	Earth Gravitational Observatory
ENSO	El Niño-Southern Oscillation
ESA	European Space Agency
ESAS	Earth Science and Applications from Space
ESD	Earth Science Division
ET	Evapotranspiration
FEWS NET	Famine Early Warning Systems Network
GCOS	Global Climate Observing System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GIA	Glacial Isostatic Adjustment
GNSS	Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Explorer
GRACE-FO	Gravity Recovery and Climate Explorer Follow-On
GRICE	GRadiométrie à Interféromètres quantiques Corrélés pour l'Espace (CNES)
HDR	High Dynamic Range
HGF	Helmholtz Association of German Research Centers
HQ	NASA Headquarters
IAGG	Atomic Interferometer Gravity Gradiometer
IGSWG	Interagency Gravity Working Group
IPCC	Intergovernmental Panel on Climate Change
ISS	International Space Station
IUGG	International Union of Geodesy and Geophysics
KBR	K-band Ranging
LISA	Laser Interferometer Space Antenna
LL-SST	Low-Low Satellite-Satellite Tracking
LEO	Low-Earth Orbiter
LRI	Laser Ranging Interferometer
MC	Mass Change
MCR	Mission Concept Review
MCM	Mass Change Mission
MEO	Mid-Earth Orbit
MWI	microwave instrument

NGGM	Next Generation Gravity Mission
NRT	near-real time
PBL	Planetary Boundary Layer
POD	Precise Orbit Determination
POR	Program of Record
RFI	Request for Information
RMSD	root-mean-square difference
SATM	Science and Applications Traceability Matrix
SBG	Surface Biology and Geology
SDC	Surface Deformation and Change
SDS	Southern Delivery System
SLR	Satellite Laser Ranging
SNR	Signal-to-Noise Ratio
SST	Satellite-to-Satellite Tracking
ST&V	Surface Topography and Vegetation
TO	Targeted Observables
TMA	Triple Mirror Assembly
TWS	Terrestrial Water Storage
TVG	time-variable gravity
VECSEL	Vertical-External-Cavity Surface-Emitting Laser
WHE	water height equivalent

DAY ONE - MEETING INFORMATION

DAY ONE – AGENDA

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A.3 Meeting Plan and Goals – Bernie Bienstock

A.4 The Role of MC in the Decadal Survey Report – Byron Tapley

A.5 Architecting Process – Dave Bearden

Space Agency Perspectives

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Breakout Sessions

Breakout Session Summary Presentations

- A.19 Hydrology Breakout Session Summary Presentation – Matt Rodell

DAY ONE – MEETING NOTES

A.1 WELCOME, OPENING REMARKS, INTRO (LUCIA TSAOUSSI)

NASA'S Earth Science Division's (ESD) Decadal Survey (DS) web page is available at: https://science.nasa.gov/earth-science/decadal-surveys.

Lucia Tsaoussi began the workshop by explaining that the Mass Change workshop is part of NASA's efforts to receive the DS and translate it. To do that, NASA decided the community needed to be engaged for the study to receive a wide range of feedback.

The DS was publicly released on January 5, 2018. Since the release, NASA began the communication process by creating a website to communicate with the community. The website is a place for the community to see Q&As, post questions that NASA will answer within a week, view records of progress and decisions, see solicitation announcements, and to find information regarding NASA studies.

Four observing system design studies were initiated for the five Designated Observables (DO) identified in the DS: Mass Change (MC), Aerosols, Clouds, Convection and Precipitation (A/CCP), Surface Biology and Geology (SBG), and Surface Deformation and Change (SDC).

The DO mission/observing system implementation included a "new" program element for cost-capped medium- and large-size missions/observing systems to address observables essential to the overall program. It addresses five of the highest-priority Earth observation needs, suggested to be implemented among three large missions and two medium missions. Elements of this program are considered foundational elements of the Decadal's observations. Each mission/observing system will be cost-constrained, as informed by DS. Payloads will be completed by Headquarters (HQ). Satellite bus(es) are expected to be procured. US and international partnerships are strongly encouraged. Contributions of each mission/observing system to other ESD science objectives are strongly encouraged. SBG or some combination of Aerosol/CCP will likely be the first DO mission/observing system to be initiated.

Each DO mission/observing system will be directed to a NASA center. Last summer, guidance was provided to the NASA centers. The studies were initiated in October. Each study will be specific and comprehensive in scope; especially with regards to science. Each study will describe institutional history, accomplishments, and ongoing activities. Each should include a plan for inter-center and international involvement and for involving industry; private sector and non-governmental.

The studies will examine approaches for incorporating non-traditional architectures, possible inclusion of other observing and/or sampling platforms, innovative development approaches including design of a spacecraft without knowledge of instrument interfaces, and new technologies. The studies will perform a qualitative or quantitative assessment of the impacts of the DOs on society, including specific applications.

The studies will specify several architectures, which NASA will down select. The study is not specifying requirements, but is focused on performance targets.

A.2 MASS CHANGE GENERAL STUDY PLAN (BERNIE BIENSTOCK)

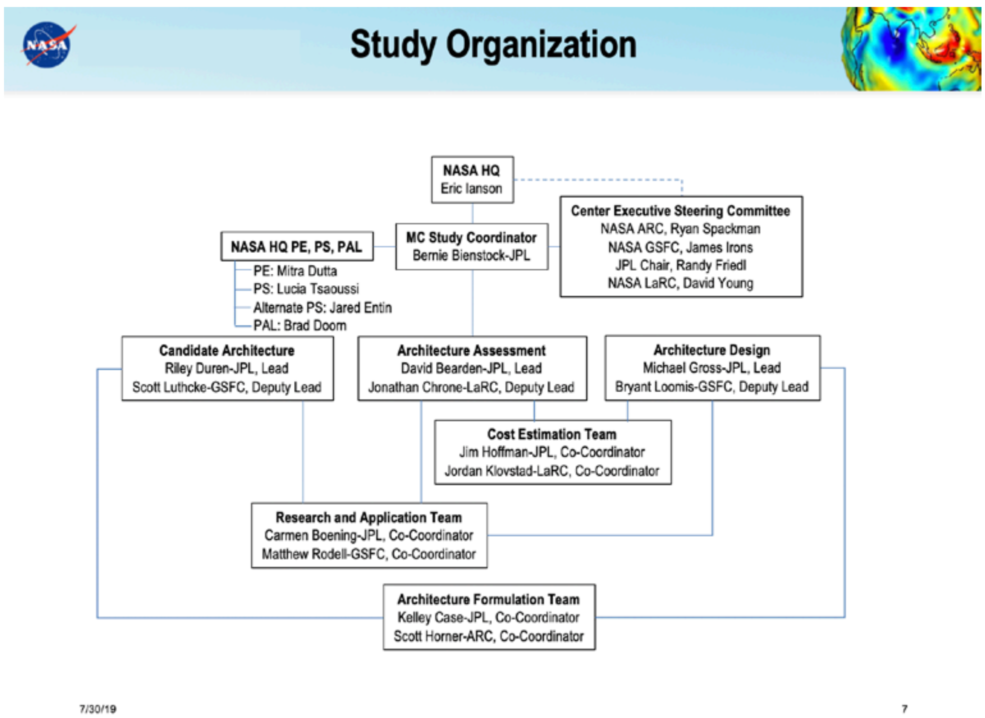
Bernie Bienstock is the MC Study Coordinator. His main objective is to ensure the MC study is completed on schedule and according to the proposed plan.

The MC study plan was approved by NASA in October, as proposed to investigate innovative, technology opportunities and technology opportunities. The main goal of the study is to identify and characterize a diverse set of high-value MC observing architectures responsive to the DS's reports to scientific and application objectives for MC. The second goal includes the cost effectiveness of each of the studied architectures. A third goal is to perform sufficient in-depth design of up to three selected architectures to enable rapid initiation of a Phase A study. The final goal is to make sure the study is cross-NASA. There is participation in the Mass Change study by four NASA centers; JPL (which is lead), GSFC, LaRC, and ARC.

Bernie stated that the workshop attendees are fully versed in MC. MC measurement techniques include changes in gravitational potential by observing the forces acting on a spacecraft. MC measurements have an intrinsic relationship between observing architectures and optimized data processing. Both of these need to work in sync.

GRACE-FO launched in May 2018 and continues GRACE measurements of tracking Earth's water movement to monitor changes in underground water storage and the amount of water in large lakes and rivers, soil moisture, ice sheets and glaciers, and sea level caused by the addition of water to the ocean. GRACE/GRACE-FO require stable platforms and have a limited life mission. Two stable platforms are needed to complete the GRACE-FO mission. The estimated end of the GRACE-FO prime mission is 2023, depending on failures and solar activity. The expected end of life is 2026.

Bernie presented the study organization to the workshop attendees to ensure that everyone understood how the study is organized to complete the work for the MC study as proposed.



The study organization is divided into various disciplines; candidate architectures, architecture assessment, architecture design, cost estimation team, research and applications team, and an architecture formulation team. It was noted, the Architecture Assessment, Cost Estimation, and Architecture Design teams have yet begin their work.

Bernie stated that the MC study is near the end of Phase 1. The study is exploring various architectures, innovations, and technologies that apply to the MC mission. The results from the MC community workshop will specify architectures that should be studied in Phase 2. Each architecture will be evaluated using a Value Framework process and will conclude with approximately three architectures to move forward into Phase 3. Phase 3 will continue with a complete evaluation of the three architectures. The goal of the MC study is to be ready for an MCR (Mission Concept Review) at the conclusion of the Pre-Phase A activity.

A.3 MEETING PLANS AND GOALS (BERNIE BEINSTOCK)

Bernie provided an overview of the MC meeting plan and goals. He noted the workshop objectives have not changed since the workshop attendees received their invitation to attend this workshop. The workshop objectives includes briefings from the community/stakeholders on study plans and progress. We are very receptive to feedback on observing system performance targets from the science and applications community, as well as from potential partners and collaborators. We encourage discussions on measurement technologies and associated observing system architectures. We also foster community discussions on potential future applications and extension of user communities. These were the four points proposed in the workshop invitation.

Every workshop attendee should decide which breakout session they wanted to attend. Of course the workshop attendees have the option to attend more than one breakout session. The session debriefs will include top level presentations meant to allow the workshop attendees to engage with the breakout session leads.

The MC meeting goals are to engage in community discussions, receive input on architecture and enabling technologies, and resulting community guidance on architectures as supported by enabling technologies. The outcome of this workshop will serve as a basis for beginning Phase 2, and to provide input to the MC final report, deliverable at the end of the study.

All presentations and conclusions today and for the next two days will be made public. If anyone has issues with this, they should communicate with Lucia and Bernie. Bernie closed this topic by providing an overview of the meeting logistics.

A.4 THE ROLE OF MASS CHANGE IN THE DECADAL SURVEY REPORT (BYRON TAPLEY)

Byron Tapley extracted information form the DS that is relevant to the MC study. He reviewed the process and focused on points and issues related to recommendations in the DS. All of these are in the context of the GRACE/GRACE-FO MC measurements.

The actual DS report was released in January 2018. This document provided a comprehensive look at the state of Earth Science. The community charge was broad-reaching and multi-agency.

Byron noted that the MCM should continue the GRACE-FO series with accuracy comparable to the GRACE/GRACE-FO performance. Measurement continuity is very important, so the MCM satellites should be launched to overlap with GRACE-FO. Given the design maturity of the GRACE-FO satellites, the mission cost should be comparable with the GRACE-FO. The implementation cost assumes international participation in the mission implementation. The primary deficiencies in the GRACE and GRACE-FO data are in spatial and temporal resolution. The technology challenges relate to deficiencies in spatial and temporal resolution and mission lifetime.

The final stage of the GRACE mission activity focused on minimizing the projected gap between the GRACE mission end and the GRACE-FO launch, but this was not achieved. An acceptable bridge for the gap between the two missions is needed. The MCM implementation should attempt to ensure mission overlap.

Riley Duren commented that avoidance of and minimizing the gap are these things that may not be achievable in one go. He also mentioned that the study team must address MC continuity and focus on deficiencies. These may also not be achievable in one go. Should the scope be focused on getting an MC mission launched to continue the record? How do we lay out the road map for doing so? What else should we be doing in the next decade for the next mission? Riley stated these are all things the study team will need to think about.

Lucia noted that everything should be considered. This study needs to address all of those questions. The better explanation and rationales the study can do; the best decisions NASA can make. If there are constraints in the budget, let the program decide how to deal with the constraints. Lucia stated if this study doesn’t do it, she doesn’t know where it will come from. The study is to address all missions together.

Byron mentioned the continuation of spatial vs. temporal resolution is his personal opinion and not in the DS. The measurement themselves have established the value. The study should look at something past MC and maintain continuity. The measurement going forward may not satisfy the community. The study team will need to ensure they get these measurements together.

A.5 ARCHITECTING PROCESS (DAVE BEARDEN)

Dave Bearden is the Phase 2 lead for the MC study. Phase 2 moves from the conceptual development into evaluating the architectures in terms of performance and cost. Phase 2 hasn’t yet begun and is fairly notional and high level, but Dave would like to expose Phase 2 to the community.

The first order is to specify the technical characteristics of the architectures. The next step is the measurement of value. Dave mentioned that it's important to have a straight forward process for the measurement of value. The study doesn't want a value framework to be dependent on an individual decision maker. The idea is to hinge value into some form of documentation. Value measures should be straight forward and logical, objective in nature, tied to threshold and baseline objectives, and limited in number to reduce the number of measures to a minimum that can discriminate between architectures.

The study must tie to threshold and basic objectives. There might be tradeoffs between threshold and baseline but affordability comes into picture. Each architecture must meet a set of objectives: ranging from "most important" to "very important" to "important." The study will need to assign "value" based on what community per DS is "willing to spend" to meet the objectives.

The next step will be to focus on the SATM and specify a number of architectures. To map back to DS, the study will focus on the most important and very important. These are 80% of the problem. This will be a logical and traceable process from DS, to the SATM, and to the architectures. It should be clear and transparent and justify which architectures were selected.

Sufficient information about the architectures will be required to cost each, create and evaluate schedules, and perform some sort of assessment.. The value framework compares the science value and science cost. Reduced cost to NASA may be enabled through strategic partnerships and/or commercial opportunities. Enhanced science return may be enabled through new technologies and/or innovation. Dave stated that architectures below the threshold mission or significantly above cost target will not be considered. Science value may be risk-rated based on technical or schedule risk.

Dave noted that the MC study is striving to come to a consensus across the community in evaluating what is most important and what matters. This is a way to budget the value and document it down the road. The study will need to make certain all is documented and that there is a rational of going from many ideas to a smaller number.

Lucia voiced a concern that there is much discussion on the continuity and the budget. The budget cap definitely is of great concern. She feels it will be useful to have options. Continuity has to be addressed by the evaluation of the science, although . at this point, Lucia feels the study shouldn't be concerned with the budget per se.

SPACE AGENCY PERSPECTIVES

A.7 ESA PERSPECTIVE (ROGER HAAGMANS)

Roger Haagmans provided an ESA perspective on the user community and their expression of needs, ESA activities beyond GOCE and GRACE, and then the prospects for the next gravity mission.

ESA proposed a Phase A study for the NGGM at the Space 19+ Ministerial conference. Opportunity for future cooperation includes flexible design, adequate choice of sampling allows to address science objective and applications, flexible launch times, possibility to add or replace any satellite pair or satellite, and ground segment coordination.

Roger stated that with looking beyond the next mission into the future of long-term monitoring, if you can convince the EC that this is a small thing to do, they might consider. The new technology can replace existing technology. A ministerial will be in November this year and the next one in 2022. ESA is now in Phase 0. 2022 is for the implementation.

A.8 CNES PERSPECTIVE (MIOARA MANDEA)

CNES is the French National Center for Space Studies. Mioara Mandea is in charge of the solid earth program at CNES. Mioara presented the MARVEL mission concept that was submitted to the CNES Scientific Prospective Seminar in October 2018 by 16 French and international societies. The idea of MARVEL was to reach one single mission with two major goals of current geodesy. The first is the monitoring of the mass transfers within the Earth system with increased precision; the second is realization of the terrestrial reference frame.

The scientific objectives include measurements of geodesy, hydrology, cryosphere, oceanography, earthquakes, clime and post-glacier rebound. All of the objectives have a high society impact. The CNES MARVEL mission is ambitious, innovative, and much needed for its scientific and societal implications.

Randy asked if there is already some established or hope for a connection between MARVEL and NGGM. Mioara responded that MARVEL is just an idea expressed with the community with international partnership. If done, this would be a nice opportunity to discuss with ESA or possibly NASA.

A.9 HGF PERSPECTIVE ON A MASS CHANGE MISSION (FRANK FLECHTNER)

Frank Flechtner is from the GFZ German Research Centre for Geosciences under the umbrella of the Helmholtz Association of German Research Centre for Geosciences (HGF). HGF is the association of the large research centers in Germany. The Helmholtz Association of German Research Centers and its core funding Federal Ministry of Education and Research (BMBF), as well as the Federal Ministry of Economic Affairs and Energy (BMWi), have significantly contributed in realizing and operating the GRACE/GRACE-FO missions (e.g., mission operations, laser ranging interferometer, and science data system). Frank expressed concern that there was nobody in attendance at the workshop from DLR.

There is a much interest in Germany to continue the time series of GRACE. There is considerable funding from the Ministries. Frank's research center is one of them. HGF is currently preparing for its fourth Program Oriented Funding period, which is 2021-2027. All proposals will be evaluated in December 2019. There are many participating centers (see slide 3), which are all contributing to this program with a total of 430 million Euros.

In the frame of this program, which will be discussed in December, are Category III (large infrastructures) proposals. These are larger than 50 MEUR. There was a suggestion recently made by the GFZ Board to HGF to contribute to the implementation of an MCM with partners from DLR and MPG. Major contributions have to be provided by DLR/BMWi. Therefore, various talks between HGF-BMBF-BMWi–MPG have to be made first. The final decision to put MCM on the national roadmap to be made by BMB. If positive, a proposal will be written and will be evaluated by the Science Council. The space agency must be the leader. Need to have talks in the next month. There is a need to be harmonize with the US side. It will take time for a proposal to be evaluated by the Science Council in German. Frank stated that HGF will try their best to keep the idea of partnerships alive, but can't provide any guaranteed.

Mioara asked when HGF will have a recommendation. Frank Flechtner stated the evaluation will be in December. This is the process. If it stays in the final program, it will be discussed in December. December is the date where we know if it becomes a mission or not.

Mioara mentioned that there needs to be a second meeting/conversation, as in the MC Community Workshop, due to the major milestones coming up in October, November and December. There are correlations and dependencies that are clear.

A workshop attendee noted that there was recently a decision by the Ministries for Economics (a funding the space agency) to establish seven new DLR centers in Germany. This is another chance to bring in DLR and have as many partners as possible. This could be an option to pull together sufficient funds to establish a US partnership.

A.10 IUGG STUDY: SCIENCE AND USER NEEDS FOR OBSERVING GLOBAL MASS TRANSPORT TO UNDERSTAND GLOBAL CHANGE AND TO BENEFIT SOCIETY (THOMAS GRUBER)

Thomas Gruber is from the Technical University of München. He is the Chair of Astronomical and Physical Geodesy. Thomas left the GRACE mission four months before launch and then moved to the GOCE mission. He is now looking at future missions.

Thomas explained that he won't provide great detail on the International Union of Geodesy and Geophysics (IUGG) study because most of the workshop attendees are aware of the IUGG study. A study was initiated by IUGG to consolidate science and user needs for future gravity missions. This was established in a large international team with different fields. There was a contribution by greater than 80 international experts in the fields of hydrology, cryosphere, oceans, and solid earth. The objective was to identify the science and user needs and discuss consolidation among user communities. This is now a real frame that can be used for future gravity missions. This is used for all mission proposals submitted to ESA.

A.11 NASA/ESA IGSWG STUDY- TOWARDS A SUSTAINED OBSERVING SYSTEM FOR MASS TRANPORT TO UNDERSTAND GLOBAL CHANGE TO BENEFIT SOCIETY (DAVID WIESE)

David Wiese provided a perspective on the NASA/ESA Interagency Gravity Working Group, IGSWG), that began in June 2013. The working group concluded in May 2016 with a final report. David's intention for this portion of the workshop is to go over the working group's recommendations, perspectives, and where they are now in reference to the DS. There were eight members that were part of the working group, including David Wiese, Thomas Gruber, and Matt Rodell.

A.12 SATM OVERVIEW – CURRENT STATUS (RILEY DUREN)

Riley Duren provided an overview of the Science and Applications Traceability Matrix (SATM) and the continuity objective. The SATM working group included representatives from the three different science initiatives, climate, hydrology, and solid earth. They have been conducting bi-weekly telecoms with this group, with in-person meetings per the availability of the team. The plan is to complete the MC SATM by October, but there will be tweaks going into Phase 2.

There are three tiers to an SATM; threshold, baseline, and goal. The three performance tiers allow for quantitative prioritization across the project lifecycle. Threshold supports minimum science objectives; baseline supports full science objectives; and the goal supports additional science, potentially including priorities for technology development as well as priorities for advances in modeling, data assimilation.

A.13 SATM HYDROLOGY (MATT RODELL)

Matt Rodell spoke about the SATM and hydrology. There is a single TO for MC specified for hydrology; groundwater and water storage mass change. There must be measurement continuity. Similar to GRACE, the goal of measurements of gravity anomalies is to attain spatial resolution of 200 km at the equator (goal of 50 km or less). Matt stated this is where hydrology will see some hard numbers and may be challenging to achieve.

A.14 SATM SOLID EARTH (JEANNE SAUBER)

Jeanne Sauber started with the dynamics and hazards by acknowledging the last couple of months have been focused on discussing earthquakes.

There are two targeted observables (TOs) for MC, solid earth; glacial isostatic adjustment (GIA) and earthquake mass movement. There are some performance targets that were given. Throughout the DS, there is text similar to GRACE. When filling in some of the SATM elements, Jeanne used the minimum observable gravity anomalies received from GRACE. These will be the subject of discussions during the breakout session.

A.15 SATM CLIMATE (CARMEN BOENING)

Carmen Boening provided an overview for climate variability. Although people have questioned the spatial resolution, Carmen feels that continuing something known makes sense, without trying to do something that would be worse.

Carmen stressed that for MC, climate variability is looking at land-ice mass change and ocean mass change. There are several objectives, especially in the Questions C-1 and C-7. One is related to sea level and seven is related to oceanic variability. Some of these performance targets were ambiguous and will be up to the breakout session to better define what these numbers mean for MC.

A.16 BREAKOUT SESSION GOALS (CARMEN BOENING)

Prior to the workshop, the R&A Team agreed on questions to ask during the workshop and the desired end results of the workshop. This created a set of goals she presented and discussed for the breakout sessions.

BREAKOUT SESSIONS - SUMMARY PRESENTATIONS

A.19 HYDROLOGY BREAKOUT SESSION SUMMARY PRESENTATOIN (MATT RODELL)

Matt Rodell provided a debrief from the hydrology breakout session. Basically, the breakout session participants reviewed the SATM and noted four hydrology related objectives in the DS that were most important or very important. There were two listed as most important. The baseline should be consistent with the current capability (GRACE/GRACE-FO). Continuity also means consistency of measurements, quality, and ability to achieve performance of GRACE/GRACE-FO.

DAY TWO - MEETING INFORMATION

DAY TWO – AGENDA

Summary of Day 1/Plan for Day 2 – Carmen Boening

B.2 Classes of Mission Architectures for Mass Change Science – David Wiese

Architecture Options

- B.3 Single Satellite Pair Heritage and Limitations – Frank Flechtner
- B.4 European Initiatives and Studies on Mass Change Mission Architectures – Thomas Gruber
- B.5 Multi-Satellite Constellations in a Chain Formation – Tom Yunck
- B.6 Spire CubeSat Constellation Capabilities for Mass Change Studies – Dallas Masters
- B.7 Current and Future Capabilities of Multi-Satellite POD – Matthias Weigelt
- B.8 Single Satellite Cold Atom Gravity Gradiometry – Scott Luthcke
- B.9 Status of Quantum Sensing Studies at ESA – Olivier Carraz

Enabling Technologies

- B.10 Flight System Needs: Lessons Learned from GRACE and GRACE-FO – Albert Zaglauer & Nico Brandt
- B.11 Satellite System Studies for NGGM at ESA – Roger Haagmans
- B.12 LRI as the Prime Instrument – Bill Klipstein
- B.13 LRI Improvements from LISA – Kenji Numata
- B.14 Compact Coherent Laser Ranging – Guangning Yang
- B.15 Laser Frequency Comb Technology and SmallSat Concepts – Jennifer Lee
- B.16 GRACE3D: Exploiting LISA Pathfinder Technology for Gravity Field Recovery – Matthias Weigelt
- B.17 ONERA Accelerometers: CubSTAR, MicroSTAR, and Hybrid – Bruno Christophe
- B.18 Compact Inertial Sensors for Small Satellite Geodesy Constellations – John Conklin
- B.19 GRICE – Mioara Mandea
- B.20 Opto-mechanical Inertia Sensors – Lee Kumanchik
- B.21 Atomic Interferometer Gravity Gradiometer – Babak Saif
- B.22 New Approach to Atomic Test Mass for Earth Gravity Measurements – Nan Yu

B.23 Applications and the Community Assessment Report – Matt Rodell

B.24 Mass Change Architecture Template – Kelley Case

B.24A Architecture Breakout Questions – David Wiese

B.25 Applications Breakout Session Summary – Matt Rodell

DAY TWO - MEETING NOTES

SUMMARY OF DAY 1/PLAN FOR DAY 2 (CARMEN BOENING)

Carmen Boening provided a summary of the Day 1 discussions. Day 1 informed everyone about MC and the role of MC in the DS. Yesterday, Dave Bearden provided an overview of the architecture process. After the first break, the study heard from other space agencies. The SATM was a big part of the discussion in the afternoon and was followed by breakout sessions for hydrology, climate variability and solid earth. To close Day 1, Matt Rodell provided a debrief from the hydrology breakout session. Climate variability and solid earth will provide their debriefs in the morning of Day 3.

The focus for Day 2, now that the science is established, is to evaluate the architecture options and enabling technologies. There will be breakout sessions in the afternoon for applications, technology, and architectures.

B.2 CLASSES OF MISSION ARCHITECTURES FOR MASS CHANGE SCIENCE (DAVID WIESE)

David Wiese presented the classes of mission architectures for MC. David's talk set the stage to cast a wide net in considering all architectures that can measure MC. David identified five architecture classes, including ground networks, clocks and relativity, satellite-to-satellite tracking (SST), precise orbit determination (POD), and gravity gradiometry.

The MC study will only consider SST, POD, and gravity gradiometry. Ground networks have been excluded because the cost is too high to maintain a network of GPS on the ground for the global GNSS network. In addition, systematic errors are not well understood. Optical atomic clocks are now reaching precision levels of ~ 10^{-18}, and this technology is still in the future. Clocks and relativistic geodesy were excluded because the costs are too high and the technology is not yet mature enough.

ARCHITECTURE OPTIONS

B.3 SINGLE SATELLITE PAIR HERITAGE AND LIMITATIONS (FRANK FLECHTNER)

Frank stated that for GRACE/GRACE-FO, observation of gravitationally caused orbit perturbations along the common line of sight of a twin satellite pair by high-low (GPS) and low-low (K-Band) SST. A 3D accelerometer was used for observation of non-gravitational accelerations. Star cameras were used for observation of the satellite and instrument orientation. Satellite laser ranging (SLR) was used in the validation of GPS-derived orbit.

B.4 EUROPEAN INITIATIVES AND STUDIES ON MASS CHANGE MISSION ARCHITECTURES (THOMAS GRUBER)

Thomas Gruber provided a summary of accomplishments in the last ten years in terms of proposed missions at ESA. In 2007, the first ESA workshop on the future of satellite gravimetry was organized. At this time, the instrument already had a laser. The second workshop was in 2009. Geophysical modeling was significantly improved and is ongoing in terms of applications and services.

In conclusion, the next mission class should be with a multiple pair. There is real progress that can be made a will lead us to an observable system at a much sustainable class. One word about risks – no risk, no fun. No risk, no progress.

B.5 MULTI-SATELLITE CONSTELLATIONS IN A CHAIN FORMATION (TOM YUNCK)

Thomas Yunck provided information on the GeoOptics Earth Gravitational Observatory (EGO) concept. Thomas stated back in 1993, in response to an internal JPL solicitation for a small Earth probe mission. He proposed a concept which introduced the name of GRACE at the time. The idea combined precise high-low GNSS. It was proposed as 32 GHz/8GHz. GRACE was flown in 2002 at 32GHz/24GHz.

B.6 SPIRE CUBESAT CONSTELLATION CAPABILITIES FOR MASS CHANGE STUDIES (DALLAS MASTERS)

Dallas Masters presented the capabilities SPIRE CubeSat constellation for MC. SPIRE is a new, innovative satellite and data services company and has been flying under the radar for a long time. SPIRE is what you get when you mix agile development with nanosatellites. Started as a single, crowd-source nanosatellites, SPIRE is operating the second largest constellation of satellites in the world.

B.7 CURRENT AND FUTURE CAPABILITIES OF MULTI-SATELLITE POD (MATTHIAS WEIGELT)

Matthias Weigelt presented on the multi-satellite POD. Combining POD from high-low satellite-to-satellite tracking (hlSST) and SLR is the best possible candidate to bridge the gap following GRACE/GRACE FO.

B.8 SINGLE SATELLITE COLD ATOM GRAVITY GRADIOMETRY (SCOTT LUTHCKE)

Scott Luthcke began the discussion explaining that atomic interferometry was formerly termed cold atom interferometry. The goal of his team was to build a single gravity radiometer instrument, test it at high precision, and scale it for use in space and microgravity. They were focused on building the most challenging instrument possible, which could be scaled on flown on a stable platform.

The AIGG instrument build was development under NASA Earth Science Technology Office's Instrument Incubator Program (IIP) and Goddard Space Flight Center. It was a collaboration between NASA GSFC and AOSense.

B.9 STATUS OF QUANTUM SENSING STUDIES AT ESA (OLIVIER CARRAZ)

Olivier Carraz presented on the quantum sensing studies in ESA. To provide some background, the idea is to look for future concept for a gravity mission. The idea is to combine GRACE-FO with ESA's Next Generation Gravity Mission (NGGM). There will be more focus on the next generation.

ENABLING TECHNOLOGIES

B.10 FLIGHT SYSTEM NEEDS: LESSONS LEARNED FROM GRACE AND GRACE-FO (ALBERT ZAGLAUER & NICO BRANDT)

Albert Zaglauer presented the lessons learned from GRACE/GRACE-FO. There has been a long development series that started in the mid-1990's. Champ successfully launch in 2000. GRACE successfully launched in 2002 and GRACE-FO in 2018. In total, there have been 11 satellites and 74 years in orbit. GRACE turned out to have three-times the design lifetime and there was a plan to do better with GRACE-FO. Airbus met the requirements and posed questions to gain a deep understanding of the requirements and to provide the best answer to the request.

B. 11 SATELLITE SYSTEM STUDIES FOR NGGM AT ESA (ROGER HAAGMANS)

Since 2003, there have been more than a decade of ESA system and technology studies on the subject of NGGM.

ESA combined heritage from GRACE and GOCE. ESA has requirements to be compatible with an ESA launcher (Vega-C). The NGGM consolidation considers the results of the SC4MGV and ADDCON science studies and the ongoing technology developments in the laser metrology.

ESA looked at a two satellite pair (Bender pair). One pair in a near-polar orbit and the other pair in a mid-inclination orbit, with a goal of a minimal 7-year lifetime. They attempted to design a system that would fly as low as possible. ESA looked at the design that fits any orbit for the altitude and range of solar activity. The design should be able to launch in either orbit plane. Can control all six degrees of freedom, if needed. Direct ranging to the center of mass is required.

B.12 LRI AS THE PRIME INSTRUMENT (BILL KLIPSTEIN)

Bill Klipstein discussed the prospect of using a Laser Ranging Interferometer (LRI) on an operational mission. On GRACE-FOI, LRI has operated for 92 days of continuous tracking, except when there were other activities occurring. The design had an internal requirement to operate for 5 years. The laser is qualified for flight on the

15-year Tesat mission. There is a 17 db margin on the intersatellite link. Implementation has a technology demonstration, but there are things that still need to be done.

The LRI instrument is a US and German partnership. It has a triple mirror assembly and a 4-element detector. Measurement on each spacecraft are made to the location of the other spacecraft. There is remarkable precision in the science return. LRI post-fit residual RMS is approximately three times smaller than MWI.

B.13 LRI IMPROVEMENTS FROM LISA (KENJI NUMATA)

Laser Interferometer Space Antenna (LISA) is a mission to detect gravity waves. It is led by ESA and planned to launch in 2023. Gravity waves are emitted from super-massive objects. LRI improvements for LISA will be smaller, higher power, lower noise laser source. It will be available in the ~2022 timeframe for smaller, lower cost MC LRIs.

B.14 COMPACT COHERENT LASER RANGING (GUANGNING YANG)

Guangning Yang presented the Compact Coherent Laser Ranging (CCLR). There was discussion on the technology progress over the past 20 years. The goal was to develop optical communication and to explore size reduction to still have high performance for laser ranging. The architecture will target the performance of GRACE/GRACE-FO. The goal is to come up with 16U CubeSat scale laser interferometry. Guangning presented a CCLR flying on a CubeSat platform with ranging precision that matches the GRACE-FO performance. It enables nominal 200 km inter-satellite spacing, or tailored to specific missions. Laser ranging is insensitive to plasma (interplanetary and Earth ionosphere) noise sources. The small CubeSat-size increases the satellite body pointing capabilities.

B.15 LASER FREQUENCY COMB TECHNOLOGY AND SMALLSAT CONCEPTS (JENNIFER LEE)

Jennifer Lee presented on technology that Ball Aerospace is exploring the realm of possibility for a GRACE SmallSat mission. There were three main goals. First, to increase the temporal sampling. The more frequent revisit would provide more accurate time series data and alleviate the aliasing that occurs due to under-sampling of high frequency phenomena, such as ocean tides. Secondly, to address the North-South striping evident in the GRACE data. Smoothing is not ideal as it is limited in effectiveness and has a side effect of diminishing the spatial resolution of the data. Third, to improve the ranging accuracy, which would naturally lead to a better science product. Jennifer noted that the HDR GRACE concept would open the door to larger frequency measurements that would enable more exotic orbits.

B.16 GRACE3D: EXPLOITING LISA PATHFINDER TECHNOLOGY FOR GRAVITY FIELD RECOVERY (MATTHIAS WEIGELT)

Matthias Weigelt presented information on GRACE3D. The idea behind this concept is to use quantum metrology, quantum sensing and quantum technology for gravity field recovery. GRACE is already 3D. Need to rotational quality on ultraprecise observations of the rotation line of site. Can improve stripping.

GRACE-like missions can become a three-dimensional observation system with existing space-proven technology. Ultra-precise observation of the rotation of the line-of-sight is necessary (prad/s/√Hz). Vastly reduced stripping can be achieved. The design is under evaluation to determine if it can outperform a Bender configuration. It will not improve the temporal sampling

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B.17 ONERA ACCELEROMETERS: CUBSTAR, MICROSTAR, AND HYBRID (BRUNO CHRISTOPHE)

Bruno Christophe presented on the use ONERA accelerometers for use on future gravity missions. GRACE, GOCE and GRACE-FO used specific configurations. ONERA accelerometers are accurate with a parallepepidic proof-mass. To improve this, 3 axes of sensitivity as required. The future GRACE-FO missions could be based on CubSTAR, Micro-STAR, or a hybrid design. The MicroSTAR design has the best performance, with a high TRL. This is in line with the next gravity mission. The CubSTAR has the worst performance, but is lighter and can be used for a constellation. The HybridSTAR is not mature enough, but could be a technology demonstrator for a future mission. It's important to note that performance could be adapted to the mission.

B.18 COMPACT INERTIAL SENSORS FOR SMALL SATELLITE GEODESY CONSTELLATIONS (JOHN CONKLIN)

John Conklin spoke about the work going on in the US and the lesson learned from the LISA Pathfinder. The LISA pathfinder is a single spacecraft with two inertial sensors and a local laser interferometer. It is largely an ESA mission with a contribution from NASA. Has a 2 kg charge control system and a drag-free control system using micro thrusters. The sensor environment is critical.

CHOMPTT launched in 2018. CLICK is the next mission. This will be a first space to space laser with 3U CubeSat and is a NASA directed mission.

B.19 GRICE (MIOARA MANDEA)

Mioara Mandea presented the CNES GRadiométrie à Interféromètres quantiques Corrélés pour l'Espace (GRICE). It's important to understand the advantages and performance in stability, accuracy and dynamics.

There is measurement continuity and better space/time resolution. Think of this as a GRACE-II design. The idea was to consider two spacecraft and composite acceleration gradient measurement. When comparing this with GOCE and GRACE, it results in better mission performance.

B.20 OPTO-MECHANICAL INERTIA SENSORS (LEE KUMANCHIK)

Lee Kumanchik presented on DLR's opto-mechanical inertial sensors. The legacy (heritage) accelerometers have a performance on the 10^{-11}. It's helpful to compare the capability of an optical sensor with other devices. Have demonstrated the relative parameters. The displacement resolution assumed here is ~10^{-15} m/√Hz. There is the capability to measure the displacement resolution as high as 10^{-19} m/√Hz. The point is, there is much room for growth. As for the projected timeline, looking to have a 1-axis at TRL 4/5 by the end of 2020. Then move that to 3-axis at TRL5/6 by the end of 2021-2022. In addition, work is proceeding to improve the mechanics for low frequency sensing.

B.20A OPTOMECHANICAL ACCELEROMETERS (FELIPE GUZMAN)

Felipe Guzman presented on optomechanical accelerometers. Optomechanical gravimeters and gradiometers are ideal for space applications. They have compatible materials and simple robust geometry. They are cost effective, small and light weight. They have a lower resonance frequency. The geometry is fairly insensitive to the different axes.

Although optomechanical accelerometers are quite sensitive, they are less sensitive than that of the LISA Pathfinder system. May need to develop a caging system to make sure that it doesn't get banged/destroyed during launch.

B.21 ATOMIC INTERFEROMETER GRAVITY GRADIOMETER (BABAK SAIF)

Babak Saif presented on the Atomic Interferometer Gravity Gradiometer (AIGG). Although in development, the technology is still immature, but the technology is moving in this direction.

The effort began about 7 years ago. Needed to have a best test particle that could be used to actually measure gravity. A falling atom is isolated from other forces. The max force the atom is experiencing is the atomic field. This was the start of this technology.

The sources for atom interferometers is atoms. You are using a cloud of atoms. Basically, there are two states of the atoms. They separate the atom over Newtonian distances and bring them back together to make them coherent.

Gravimeter sensitivity based on this technology is 0.03 at worst per shot. This instrument is TRL 4 and the Germans have gone beyond that. Depending on funding, may be able to develop the out instrument further.

B.22 NEW APPROACH TO ATOMIC TEST MASS FOR EARTH GRAVITY MEASUREMENTS (NAN YU)

In order to put this into context, Nan Yu reminded the workshop attendees that in 2002, a concept was proposed to use a cold atom gravity gradiometer for earth science measurements. At the time, this was considered a crazy idea. However, the team was able to convince ESTO that the concept had merit. A functioning gradiometer instrument was developed and tested.

The latest proposal was to fly on GRACE-FO. A single-axis atomic interferometer (AI) gradiometer can provide new science data and information in each type of gradient observation over SST, at the estimated noise levels.

B.23 APPLICATIONS AND THE COMMUNITY ASSSESSMENT REPORT (MATT RODELL)

Matt Rodell stated that GRACE/GRACE-FO have supported numerous practical applications.

- Water resources assessments
- Drought monitoring and forecasting
- Flood vulnerability
- Fire risk
- Agricultural planning and yield forecasting
- Consequences of sea level rise

The needs of these applications communities will be further assessed during this workshop and elsewhere. They will be used to inform mission design and data processing decisions through the SATM and the value framework.

Preparation of the Community Assessment Report (CAR) will begin soon. The community assessment is a study that informs system architecture and component mission design concept and trade-off studies. It outlines the scope and potential impacts of the observables for user/applications communities, and identifies key design sensitivities having the greatest influence on the ultimate applications utility of the system.

The CAR will cover all four of the observables, not just one per mission. MC will be combined with the other three DO studies. Part of the CAR will be specific to applications.

B.24 MC ARCHITECTURE TEMPLATE (KELLEY CASE)

All presentations will be saved to the MC SharePoint site. The study team is still collecting information that drives a complete architecture in a consistent format with mechanism for people who didn't present at the workshop. This is information that may or may not apply to all architectures. Some presentations had necessary details missing.

Kelly Case provided the workshop attendees with an updated architecture template. The information to be populated on the template includes an architecture overview, mission design information, concept of operations, gravity measurement system instrumentation (the instrumentation in general, but with a focus on the gravity measurement overall), payload accommodations, technical gravity measurement system from a platform perspective, pointing accommodations, programmatics, scientific and measurement performance, ros and cons of the architecture, and a list of publications. The template was provided as a guideline for the type of content needed per architecture and will feed into the Mass Change assessment of different architectures. The workshop attendees have approval to forward this template to non-workshop attendees.

B.24A ARCHITECTURE BREAKOUT QUESTIONS (DAVID WIESE)

David Wiese presented a list of questions to be addressed in the Architecture Breakout session.

B.25 APPLICATIONS BREAKOUT SESSION SUMMARY (MATT RODELL)

Matt Rodell stated they had a very good applications breakout session with excellent discussions. The breakout session started out with a couple of presentations, and discussed the key takeaway points from these presentations as it related to applications.

FINAL COMMENTS (BERNIE BIENSTOCK)

Bernie has seen passion, serious discussions and a good community exchange. He is very impressed with all the technology, architectures and proposals. It demonstrates the knowledge of the community and the capabilities that have been developed and proposed for future MCM considerations.

DAY THREE - MEETING INFORMATION

DAY THREE – AGENDA

Breakout Session Summaries

- C.1A Climate SATM Breakout Summary – Carmen Boening
- C.1B Solid Earth SATM Breakout Summary – Eric Ivins and Jeanne Sauber
- C.1C Architecture Breakout Session Summary – David Wiese
- C.1D Technology Breakout Session Summary – Scott Luthcke

C.1E SATM Summary – Riley Duren

C.2 Mass Change Study Path Forward – Kelley Case

Workshop Summary – Carmen Boening and Lucia Tsaoussi

DAY THREE - MEETING NOTES

BREAKOUT SESSIONS DEBRIEFS

C.1A CLIMATE SATM BREAKOUT SUMMARY (CARMEN BOENING)

Carmen Boening provided a debrief of the discussion during the climate variability breakout session. The breakout session started by discussing the targets and science objectives. They determined that threshold and baseline should be consistent with the current capability. Current capabilities can fulfill all quantitative science targets for climate variability, based on the GRACE/GRACE-FO measurement error.

There was a discussion about trends and continuity. They had some general conclusions that came out of the numbers and performed online calculations to confirm those numbers. They determined that continuity and length of time series is most important for determining trends and accelerations. What was coming out of the quantitative targets from the Decadal Survey was that it should be somewhat like GRACE/GRACE-FO is currently doing. This doesn’t necessarily imply that Mass Change must fly another GRACE/GRACE-FO. Spatial resolution, temporal resolution, and accuracy are required to get close to the Decadal Survey numbers.

The breakout session included a discussion about what continuity means. Continuity also means consistency of measurement, quality and ability to achieve performance of GRACE/GRACE-FO. Continuity and length of time series is most important for determining trends and trend accelerations. This has implications on the gap analysis and length of overlap.

C.1B SOLID EARTH BREAKOUT SUMMARY (JEANNE SAUBER AND ERIK IVINS)

Erik Ivins provided a debrief for the GIA portion of solid earth. GIA has four science questions that must be addressed in an MC mission, as discussed during the breakout session.

Jeanne continued the solid earth debrief with a discussion on the DS’s questions regarding earthquake. Jeanne stated that many of these questions have been discussed before. Two questions were discussed in some detail.

C.1C ARCHITECTURES BREAKOUT SUMMARY (DAVID WIESE)

The goal going into the architectures breakout session was to come up with a concrete list of architectures that could be considered in Phase 2. The discussion started with the study time frame and expected outcomes. The nominal length is approximately three years, but could extend to five years total, if necessary.

Phase 2 will begin with a very open trade space. All architecture classes will be considered in Phase 2. Detailed and consistent simulations must be run within NASA MC team for some architectures. The team must narrow down the trade space by relying on community input, previously-published simulations and simulations performed outside the NASA MC team. The point was made that simulations can provide different results depending on the inputs. The team can't simply rely on published simulations.

The final delivery to NASA HQ is where the team will get some clarity. The timeline of observing system options includes approximately three candidate architectures for the MC observing system. It could include existing platforms, other data sets, data buys, tech demos, other agency platform(s), and contingency/gap-bridging observing system as future budget is unknown. Development of a technology road map should be included.

The architecture classes fall under the primary options of SST, Gravity Gradiometer, SmallSat/CubeSat and POD (in no particular order).

C.1D TECHNOLOGY BREAKOUT SUMMARY (SCOTT LUTHCKE)

The technology debrief started with an initial discussion regarding actions.

The first action was to define the technology "evaluation metrics". Technology should be defined. Examples include the benefit of the technology, the technology maturity level and flight mission readiness (TRL, heritage). Additional points to discuss are the necessary steps to advance the technology to flight readiness and the technology challenges and dependencies. Is there an optimal single architecture or a suite of architectures? The team will need to understand the architectures and details for the technology. One item that was stressed was the need for error models for technologies.

This led into the second action, which is to identify the studies and simulations to quantify performance in terms of time-variable gravity (TVG) improvement. This evaluation requires lead time and planning, and led to several questions. Are the fundamental technology sensitivities and performance quantifiable and ready for simulations? What are they? What are the architectures and required simulations? What error sources can be simulated, and what error sources will be ignored or not included? Measurement and error models are required for technologies.

There was a consensus among the team members that laser ranging is a path forward for SST measurements. Bill Klipstein will help lead technology summary, which will include the community.

In regards to gradiometry, further analysis and simulations including higher fidelity error models was discussed. Bruce Bills will help lead the summary of MEMS based gradiometry.

Other technologies that were briefly discussed were drag free, attitude control, and reference frames.

The technology performance assessment items that everyone thought were important are:

- Optimal architecture implementation, S/C resources, dependencies, challenges, risk, and schedule
- Relevant SNR advancement as performance assessment before and perhaps in addition to full TVG simulation.
- Providing measurement and error models
- Identify what errors are not included/assessed
- Heritage, TRL, NRE. It may not be possible to assess or be provided with the TRL
- Reliability
- Different types of risk (e.g. vendor, system, long lead technologies, and limited non-spaceflight validation)
- Breakpoints with architecture implementation and other technology dependencies
- Relative Complexity
- Cost and Development Schedule
- Potential for future advances beyond MCM and other applications. Some of these technologies while risky show significant improvement, maybe beyond the MC missions.
- Potential for enabling future advances in performance and/or continuity, and other applications

The team felt that it's important to fully evaluate performance of new measurements and implementations/architectures. During the discussion, one point was brought up that it's difficult to separate architecture from technology. Technologies should specify implementation needs, assumptions, and dependencies.

It was also noted that there are significant differences in measurements from GRACE/GRACE-FO that may introduce systematic errors that jeopardize continuity. In addition, a tech demo provides opportunities for advances in CubeSat/SmallSat, gradiometry, and quantum sensing technologies.

The technology team will look at this information to see if there is something that was missed or redundant. The information from the debrief will be used as guidance.

C.1E SATM DISCUSSION (RILEY DUREN)

Riley Duren provided the team with the major steps for completion in Phase 1, and items that must be addressed in Phase 2. He reminded the workshop attendees that the study plans calls for MC to complete the SATM in Phase 1.

In Phase 1, the study must finalize the science performant targets, which includes the space-time resolution, accuracy, and duration of the overarching gravity products. This is a Level 1 science target. He mentioned the study team should think about adding quantitative targets for applications to the goal performance targets. David Wiese mentioned early, the study team will need to complete the flow down to architectural components (e.g., instruments, spacecraft, orbits). The study team must also come up with a position and consensus on continuity objective/strategy. The study team should be specific about what this actually means.

Early in Phase 2, the study team has to support assignment of weights and sensitivity analysis for value framework. This actually came up on the first day of the workshop. How the weights are set will be key. In addition, the study team will need to update performance targets on architectures. To echo David Weise's point, the study team will need to define minimum targets for contingency plans and gap-bridging.

Riley also reminded the team that in the architectures that are put forward to meet the Decadal Survey objectives include a suite of fourteen objectives. There must be some sort of adjudication and weighting. There are two updates, input form the work and duration. He advised the team to think critically how duration should be defined. In addition, the study team will need a strategy that address continuity.

Going back to what was presented on day one, Riley discussed the science performance targets for resolution and accuracy. Threshold, baseline, and goal have ≤ 30-day average, absolute performance with a specified reference center. An additional goal is to have a higher resolution.

The MC science performance targets are:

- Threshold: 2-year mission duration
- Baseline: 5-year mission duration
- Goal: 10-year mission duration

The last point Riley wanted to make was regarding the timing. To exercise the thought process, JPL, Langley and Goddard creating a timing analysis about a year ago. The study team should be mindful of the construct when putting together the plan and architectures.

They looked at the potential end of life in terms of orbit and looked at observed reliability. The primary mission for GRACE-FO is planned for 2023. The dashed line is the extended mission, which isn't unusual. The questions mark has to do when the study team falls below a certain altitude. There is an orbit end of life that will be updated. There is a broader red bar that is unpredictable. Realistically, this is the path the study team is on for the study now. If they meet their targets and the down select happens quickly, the earliest they can launch is 2026. That's a 43 months development. If the study team accelerated this and considered a 48 month development, the launch could be accelerated up to 2025. However, they would need to down select to one architecture rather quickly. During the workshop, potential partners spoke and provided their timelines. With partners, the range of dates could be 2026-2027.

Riley stated that there must be a contingency plan for gap filling. The study team must define targets on the SATM front.

A single satellite is a single element system. GRACE/GRACE-FO are Class C missions. Management of mission life and reliability at the constellation level will shift things.

C.2 MASS CHANGE STUDY PATH FORWARD (KELLEY CASE)

Kelley Case spoke about the MC path forward and the plan that was originally put together. She reviewed the study phases, as discussed in presentation A.5. Kelley also reviewed the Phase 2 architectures assessment process and the Value Framework studies where the Science Value will be evaluated as a function of the Science Cost.

WORKSHOP SUMMARY (CARMEN BOENING & LUCIA TSAOUSSI)

Carmen Boening provided the workshop paticipants with a summary of their actions after the workshop.

- Presenters will be requested to send an email to Bernie Bienstock (Bernard.Bienstock@jpl.nasa.gov) to indicate whether their presentation can be published as is or they should send updated presentation by Aug. 9, 2019.
- Presenters discussing architectures will be requested to provide summaries to Kelley Case (Kelley.E.Case@jpl.nasa.gov) by Aug. 23, 2019
- Scott Luthcke will work with those presenting technology options to provide summaries for their concepts.
- Matt Rodell, Carmen Boening, Jeanne Sauber will work with community to update the SATM. Completion of the SATM will be a high priority and the pre-SATM groups will need to complete their work.
- A workshop report will be completed by August 16, 2019 (at the end of the month at the latest).

Carmen noted that there may be another workshop in Spring, 2020.

Lucia Tsaoussi noted there are two websites; an ESD website (https://science.nasa.gov/earth-science/decadal-surveys) and a MC website (https://science.nasa.gov/earth-science/decadal-mc). The approved presentations and SATM will be made public. However, the architecture summaries and technology summaries requested of presenters on will not be made public and will be for use by the NASA/JPL MC team. Only the study team will have access to the MC SharePoint site.

Carmen stated the schedule is tight, but the study team must close the action items discussed above as soon as possible. If anyone requires more time, they should indicate the date of when they can provide the information.

Kelley is hoping to receive the architecture summaries by the end of August to allow enough time for questions. In addition, she will need to understand if one of the technologies will need a maturity plan and schedule, if it's near term or needs to be put on a roadmap. She would like to create a programmatic roadmap where the study team can improve MC even if it's not the next mission.

Carmen mentioned that it is important to work with the workshop attendees and the community to determine the important measurements on the value framework. Dave Bearden may plan another workshop on the MC Value Framework.

Lucia noted that the DO study teams have been tasked to take a broad view. The link to altimetry is critical. The idea of improving the reference frame is one of the requirements in the Decadal Survey. Thus far, the link to ground networks was briefly addressed, but there is also a specific recommendation for the ground network in the Decadal Survey.

The study teams are having science working groups and the workshop attendees may hear from them. In addition, the study team will try to get international partners brought into the study.

Lucia mentioned there is a planned Mass Change town hall meeting at AGU in December, 2019.

It's important for the workshop attendees to understand that it doesn't stop here; there needs to be additional engagement.