NASA Earth Science Senior Review 2015

Submitted to:

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June 22, 2015

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INTRODUCTION

The 2015 Senior Review evaluated 10 NASA Earth Science satellite missions in extended operations: Aqua, Aquarius, Aura, CALIPSO, CloudSat, EO-1, GRACE, OSTM, SORCE, and Terra. The QuikSCAT mission, although invited to the Senior Review, declined to propose, and therefore was not evaluated. The TRMM mission, also in extended operations at the outset of the Senior Review, was not invited to the Senior Review because of orbital decay following exhaustion of its orbit maintenance fuel, and also was not evaluated (TRMM re-entered Earth's atmosphere June 16, 2015). All other operating Earth Science missions were still in their prime operations period, and were not included in the Senior Review for mission extension. The Senior Review was tasked with reviewing proposals submitted by each mission team for extended operations and funding for FY16-FY17, and FY18-FY19. The review considered the scientific value, national interest, technical performance, and proposed cost of extending each mission in relation to NASA Earth Science strategic plans. The Science Panel evaluated science in terms of scientific merit, relevance to NASA ESD science goals, and product quality. Subpanels were convened to provide in-depth evaluations of the national interest, technical performance, and costs of extending each mission. The Senior Review's overall conclusions were categorized as: Baseline, Augment, Reduce or Close-out; specific suggestions and justifications were provided for cases of augmentation, reduction, or close-out.

REVIEW PROCESS

The 2015 Senior Review process (Figure 1) began on December 9, 2014 when the Earth Science Directorate released a call letter inviting NASA missions in extended operation to submit proposals for continuation, due March 4, 2015. The Senior Review Science Panel first convened on February 18 via teleconference to discuss procedures and review assignments. Three reviewers were initially assigned to review each proposal. Over the next one and half months, four teleconferences were held to review status and address any issues. In parallel with this process, subpanels on National Interests, Technical, and Cost were convened and met to review proposals in these areas. These processes led to an all-day plenary meeting teleconference on April 10, in which each mission was discussed, and follow-up questions were identified for each mission. These questions were sent to each mission team on April 13, along with instructions that each mission team should prepare a presentation addressing these questions for the Senior Review Panel Meeting to be held on April 28-30 in Washington DC. Each mission was allotted a time slot of 60-90 minutes (depending on mission scope and the number of questions) for a presentation focused specifically on panelist's questions. Following these presentations and discussions, the panel developed and documented a collective evaluation of each mission.

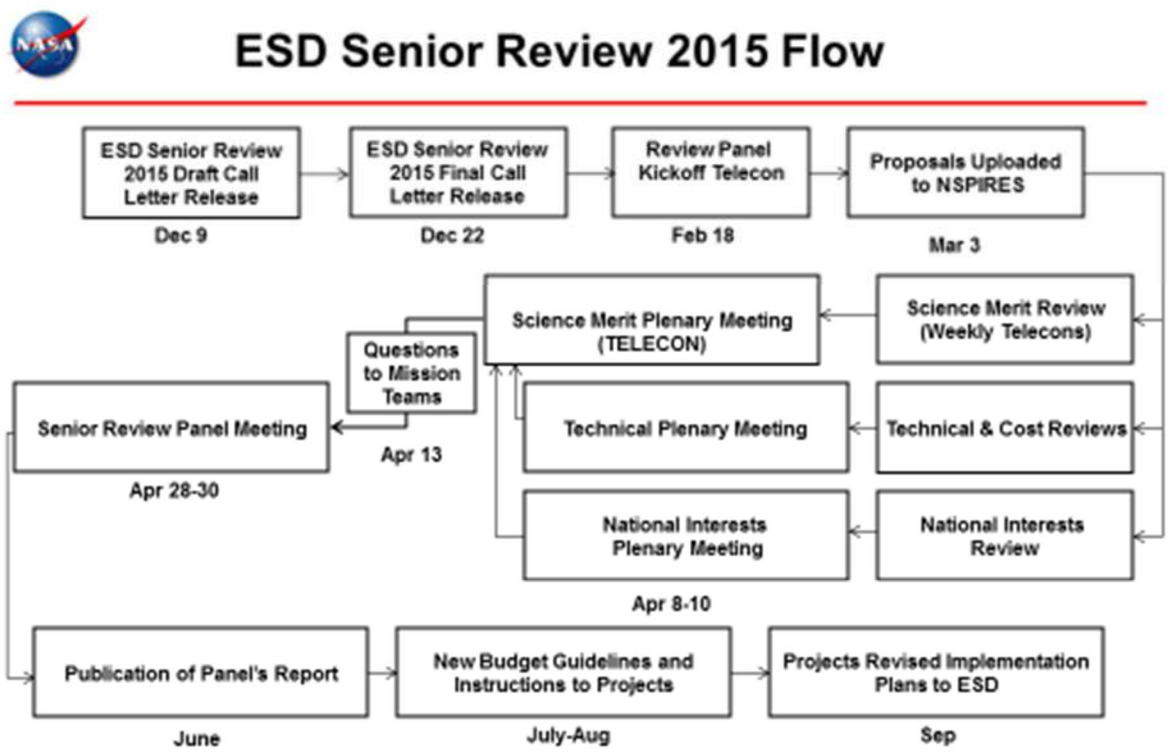


Figure 1. Working flow chart of the 2015 ESD Senior Review

GENERAL FINDINGS

The Panel was unanimously impressed that all 10 missions have made unique and important contributions to NASA Earth science objectives. Collectively, these missions constitute an unprecedented Earth observation capability that has transformed our scientific understanding of the Earth system, and they provide data for applications of extremely high societal relevance. The Panel was also impressed that these missions continue to operate beyond their designed lifetime, a fact that is a testament to high quality engineering, management, and mission execution. In the meantime, the Panel also expressed its concern that these missions are aging, and noted that the risk of loss of critical Earth observation capabilities is increasing.

Nine of the ten missions received very high marks for Scientific Merit, Scientific Relevance, and Scientific Data Product Quality, while EO-1 received a “good” rating for each of the above categories (Table 1). Scientific Merit scores ranged from 2.8 to 5.0, with 8 of the 10 missions receiving the highest score. Scientific Relevance scores ranged from 2.9 to 5.0, with 9 of the 10 missions receiving the highest score. Scientific product

Quality scores ranged from 3 to 5.0, with 7 of the 10 missions receiving the highest score. Missions received a utility score that ranged from "Some" (1 mission), "High" (7 missions), or "Very High" (2 missions). Technical Risk was distributed more broadly from "Low" (3 missions), "Medium-Low" (4 missions), "Medium" (1 mission), and "Medium-High" (2 missions), with no mission receiving "High" risk. Compared to the 2013 Senior Review, the 2015 Senior Review Panel saw a general decrease in risk because missions have been gaining experience in working with aging fleets. Cost Risk is assessed as generally low, with 6 missions receiving "Low" risk and 4 missions receiving "Medium-Low" risk.

Based on these factors, the Panel found that all missions but EO-1 would make critical contributions to enabling NASA to continue to meet its science objectives; the EO-1 mission has accomplished the science objective as a technology demonstration mission, and science value of the data is decreasing due to its degrading orbit. Nine missions were proposed for Baseline support for FY16-17; the EO-1 mission was proposed to Terminate & Close-out during FY16-17. Eight missions were selected for baseline support for FY18-19, and the budget overguide for FY18-19 sought by SORCE mission should be funded to facilitate the overlap with TSIS, pending reassessment by the next Senior Review. Mission specific findings are summarized in Table 1 below.

Table 1. Mission-specific findings

Mission	Science Scores			Numerical Science Score	Adjectival Summary Science Score	Utility Score	Technical Risk	Cost Risk	Conclusion	
	Merit	Relevance	Product Quality						FY16-17	FY18-19
Aqua	5.0	5.0	5.0	5.0	Excellent	Very High	Low	Low	Continue	Continue
Aquarius	5.0	5.0	4.0	4.7	Excellent	High	Low	Low	Continue	Continue
Aura	5.0	5.0	5.0	5.0	Excellent	High	Medium Low	Low	Continue	Continue
CALIPSO	5.0	5.0	5.0	5.0	Excellent	High	Medium-Low	Medium-Low	Continue	Continue
CloudSat	5.0	5.0	5.0	5.0	Excellent	High	Medium-Low	Low	Continue	Continue
EO-1	2.8	2.9	3.0	2.9	Good	Some	Medium	Low	Terminate & Close-out	[closed]
GRACE	5.0	5.0	5.0	5.0	Excellent	High	Medium-High	Medium-Low	Continue	Continue
OSTM	5.0	5.0	5.0	5.0	Excellent	High	Medium-Low	Medium-Low	Continue	Continue
SORCE	4.0	5.0	4.0	4.3	Very Good	High	Medium-High	Low	Continue	Continue/Augment
Terra	5.0	5.0	5.0	5.0	Excellent	Very High	Low	Medium-Low	Continue	Continue

***** All science scores are on a 1-5 scale with 1 being the lowest ranking of "poor" and 5 being the highest ranking of "excellent". Additional commentary or conditions on the Panel's scores and/or conclusions are noted in the mission-specific findings summary below.

In addition, the Panel has the following specific findings in relation to the missions:

(1) The panel found that a significant challenge to the successful continuation of the NASA missions resides in the maintenance of the health and safety of the spacecraft. Currently, several NASA missions, including Aqua, Aura, EO-1 and Terra reviewed by this Panel, are maintained by the Earth Science Mission Operation (ESMO). There are increased risks associated with old software, aging computers and operating systems, and the increased sophistication of hacking attempts on the ground-system. These increased demands on ESMO together with a flat budget, suggest that the current approach might not be sustainable if the missions continue to operate well beyond their mission prime, as currently expected. Thus, the Panel feels that a review of potential longer-term solutions to the mission operations of these missions should be done as a priority for NASA.

(2) In relation to Terra orbital change waiver (refer mission specific findings below), the Panel agrees with the mission team that if the waiver is denied, the orbital change would compromise the continuity of the stable long term climate record at some level, but feels that additional information would be necessary to fully assess the significance of this degradation. A sensor-specific or even data product-specific table of risks to data continuity resulting from waiver non-approval would have been a useful addition to the proposal. In light of this, the Panel suggests that NASA convene a workshop of data users to discuss and evaluate the trade-offs associated with the waiver decision. The Panel also suggests that such workshops should be held ahead of time if similar situations should occur for other NASA missions in the future.

MISSION SPECIFIC FINDINGS SUMMARY

Aqua

Aqua is one of NASA's flagship missions for Earth Science operating in the A-Train constellation. It was launched on May 4, 2002, and since that time has provided a wealth of information about the Earth system, generated from the 88 Gbytes per day of Earth science data being transmitted by Aqua's Earth observing instruments. Aqua observations span almost all fields of Earth science, from trace gases, aerosols and clouds in the atmosphere, to chlorophyll in the oceans, to fires on land, to the global ice cover and numerous other geophysical variables. Thousands of scientists and operational users from around the world are making use of the Aqua data to address NASA's six interdisciplinary Earth science focus areas: Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and Earth Surface and Interior. Since the 2013 Senior Review, there have been important scientific results obtained through the use of data from Aqua instruments. Among these are the followings: quantification of seasonal drawdown of atmospheric CO2 into the boreal forests, from AIRS CO2 and MODIS gross primary productivity data; quantification of the increase in moisture flux to the atmosphere in response to the decrease in Arctic sea ice coverage, from AMSR-E and AIRS data; examination of the

structure of the marine boundary layer in the northeast Pacific, from AIRS and MODIS data; and assessment of the impact of aerosol layers on southeast Atlantic stratocumulus cloud microphysics, from a combination of CERES, MODIS, and AMSR-E data, along with data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The Aqua spacecraft is still going strong after 13 years, and four of its instruments (AIRS, AMSU, CERES, and MODIS) continue to collect valuable data about the atmosphere, oceans, land, and ice. The Panel ranked this mission as the first among those missions reviewed. Based upon Aqua's high quality climate data records, the continuity of this time series is critical for the scientific community, governmental agencies and the international operational user community. Therefore, the Panel found that Aqua mission should be continued as currently baselined.

Aquarius

Aquarius is a NASA Pathfinder mission and represents the first earth observing satellite dedicated primarily to the objective of measuring sea surface salinity (SSS) over the global oceans. Aquarius successfully completed its primary 3-year mission phase in Nov. 2014, demonstrating that the hardware, mission operations, and data science and data product development approaches are combining to yield all new weekly to monthly SSS datasets that further the overall objectives of NASA's Earth Science program. The global SSS data products in swath and gridded form have already been made openly available to the broader science community in a well-documented fashion. The project calibration and validation team has been active in developing the tools needed to assess the salinity data against Argo buoy, climatology, and model products. The project has achieved success in refining the data product accuracy and *rms* errors to achieve the monthly SSS 0.2 psu *rms* error level by end of prime mission. Their new version4 datasets for science applications, reflecting latest refinements, will be released in the coming months. New scientific results are already forthcoming, with 111 publications to date, that address ocean circulation dynamics and prediction, land-ocean exchange of freshwater, cyclone impacts on the upper ocean, and atmosphere-ocean coupling associated with freshwater fluxes. The project has viable plans in place to both extend and further improve the core data products. The health of the overall satellite and the Aquarius radiometer and radar instruments indicate low risk for extended phase operations and agreements for continued collaboration between NASA and CONAE are also in place. The utility of the Aquarius data was rated "high" by government and operational communities. The Panel found that the Aquarius mission should be continued as currently baselined.

**Post-review comment: Although the SAC-D satellite platform failed June 7, 2015, ending the Aquarius mission, the data products continue to be important; an archival dataset should be processed with final calibrations and updated algorithms, documented and made available to the community for future use.*

Aura

The Aura satellite was launched in July 2004 as part of the A-Train. The three operating instruments on-board Aura (the Microwave Limb Sounder - MLS, the Ozone Monitoring

Instrument - OMI, and the Tropospheric Emissions Spectrometer - TES) provide profiles and column measurements of atmospheric composition in the troposphere, stratosphere, and mesosphere. OMI is contributed from the Netherlands Space Office and the Finnish Meteorological Institute. The suite of observations from MLS, OMI and TES is very rich, with nearly 30 individual chemical species relevant for stratospheric chemistry (O_3, HCl, HOCl, ClO, OClO, BrO, NO_2, N_2O, HNO_3, etc.), tropospheric pollutants (O_3, NO_2, CO, PAN, NH_3, SO_2, aerosols), and climate-related quantities (CO_2, H_2O, CH_4, clouds, aerosol optical properties). The Aura spacecraft is healthy and is expected to operate until at least 2022, likely beyond. There is great value in continuing the mission to (1) extend the unique 10-year record of stratospheric composition, variability, and trends as well as the chemical and dynamical processes affecting ozone recovery and polar ozone chemistry; (2) continue to map-out rapidly changing anthropogenic emissions of NO_2, SO_2, and aerosol products influencing air quality; (3) continue to develop greater vertical sensitivity by combining radiances from separate sensors; (4) use Aura data to further evaluate global chemistry-climate, climate, and air quality models; (5) extend observations of short-term solar variability overlapping with SORCE and providing a bridge to future measurements (GOME-2 TROPOMI); (6) continue the development of new synergetic products combining multiple Aura instruments and instruments from the A-Train; (7) provide continuity and comparison to current and future satellite missions (Suomi NPP, SAGE-III, TROPOMI); and (8) deliver operational products: volcanic monitoring, aviation safety, operational ozone assimilation at NOAA for weather and UV index forecasting, OMI Aerosol Index and NO_2 products for air quality forecasting. As such, the Panel concludes that Aura mission be continued as currently baselined.

CALIPSO

CALIPSO is a NASA Pathfinder mission operated jointly with the French Space Agency (CNES), measuring the three-dimensional distribution of aerosol and clouds. The CALIPSO satellite flies in formation with 5 other satellites in the A-Train constellation (Aqua, Aura, CloudSat, OCO-2 and GCOM-W), and consists of three instruments: (1) CALIOP - a dual wavelength, polarization sensitive (532 nm and 1064 nm) laser, IIR - a three-wavelength infrared radiometer, and WFC - a single visible wavelength imager. More than 500 peer reviewed publications have utilized CALIPSO data since the 2013 Senior Review. CALIPSO provides a unique set of data products that are not currently available from any other satellite platform. The L1 products have reached a level of maturity that enables climate quality analysis based on the nearly 10-year dataset. The L2 products are widely used by the scientific community, and gridded L3 aerosol and cloud products are in active development. The project continues to innovate, and has recently produced an estimate of ocean sub-surface phytoplankton concentration. Synergistic use of CALIPSO data in combination with CloudSat, MODIS, and CERES observations has led to the development of robust multi-instrument cloud, aerosol, and radiative heating products. CALIPSO aerosol vertical profiles are used in data assimilation tests at the US Naval Research Laboratory, the European Centre for Medium Range Weather Forecasts, and the Japanese Meteorological Agency. Detection of volcanic ash plumes by CALIPSO is used in support of commercial aviation operations. The US Environmental Protection Agency and several state agencies are using CALIPSO data to assess air quality and

develop strategies to mitigate pollution-induced reduction to visibility. Specifically, the EPA notes that 10-20% of its data downloads consist of CALIPSO data. The CALIPSO spacecraft and all instruments are in excellent health and the mission is supporting transformative science. Continuation of the mission will allow continued production of a valuable suite of data products, support climate data analysis activities, and allow overlap with the Cloud-Aerosol Transport System (CATS) and upcoming EarthCARE missions. In summary, the Panel concludes the CALIPSO mission be continued as currently baselined.

CloudSat

CloudSat is a single-instrument Earth System Science Pathfinder mission that flies the Cloud Profiling Radar (CPR) as part of the A-train constellation and has completed nine years of operations, which is an outstanding achievement. The CPR is a nadir-viewing W-band radar that enables detailed mapping of the vertical structure of clouds, hydrometeors and precipitation with unprecedented sensitivity, especially for snowfall and light rain. Integrated with A-train satellites (e.g. Aqua, CALIPSO, GCOM-W, OCO-2) and the recently launched GPM, CloudSat observations are instrumental for elucidating fundamental climate processes such as cloud-radiation feedbacks, including aerosol-cloud-rainfall interactions, and the linkages between the water cycle and radiative forcing. CloudSat data can also be used for the evaluation of existing parameterizations of moist processes in numerical weather prediction models, and for the development of new parameterizations of microphysical processes and convection. The continuity of these data products is highly desirable for the scientific community, governmental agencies and the international operational user community. Hundreds of science publications and millions of downloads of CloudSat products, in particular L2 products, attest to their importance and utility. Until the future launch of EarthCARE, CloudSat observations are the sole source of information on the vertical structure of precipitating and non-precipitating clouds, including liquid and ice water. The importance of CloudSat observations to elucidating the global climatology of clouds and to understand their climate role was highlighted by the IPCC AR5 report. By taking advantage of the long data records and the rich suite of L2 and L3 products, the extended mission allows the science to focus on studying moist processes in the context of multi-annual modes of climate variability, a WCRP grand challenge, and ultimately to improve their representation in numerical weather prediction and climate models. While operating in DO-OP (Daylight-Only) mode due to battery issues, the spacecraft and the radar instrument are in good health, and appear to be able to continue to work well during the proposed mission extension. The Panel found that the CloudSat mission should be continued as currently baselined.

EO-1

EO-1 was launched in late 2000 as a technology demonstration mission with a planned mission life of 1.5 yrs. EO-1 simultaneously acquires 30 m spatial resolution data from two instruments: ALI and Hyperion. EO-1 is a targeting system that is capable of imaging any particular Earth location each day, up to 5 times every 16 days. This

capability has proven to be useful for rapid response monitoring of disasters and specific events. The conclusion of the 2013 Senior Review Panel was that EO-1 be decommissioned on 30 September 2015 when the Mean Local Time (MLT) equatorial crossing would "have degraded to the point where many products will lose their usefulness." As a consequence of this finding, EO-1 was not originally included in the missions to be considered by the present 2015 Senior Review Panel. EO-1 was subsequently invited to submit a proposal following analysis that indicated that a MLT crossing of 8 AM would occur in September 2016. The EO-1 team was invited to submit a complete new 2015 proposal, or (because of the abbreviated proposal preparation time available to them) to re-submit the 2013 proposal with updates summarized as an accompanying presentation. The project chose the second option. The project was also allocated additional time in the panel presentations to ensure the mission had equal opportunity to present their proposed extension plans and to describe and justify their value.

The present 2015 Senior Review Panel finds that the mission should be decommissioned on 30 September 2016. There are three major reasons for this finding:
(1) As noted in the 2013 Senior Review Report, the early MLT would greatly limit the usefulness of the data for science research and application support.
(2) There is only limited utility of extending EO-1 mission for high latitude observations.
(3) The mission team did not provide adequate information to support their claims of the potential scientific benefit and users of the proposed Lunar Lab.

A condition of continuing the EO-1 mission into FY16 is that a detailed review be conducted of the scientific usefulness of EO-1 data to specific users based on the change in illumination conditions that will result from changes in MLT during 30 September 2015 - 30 September 2016. In addition, the mission team must provide documentation that clearly indicates how to access and use archived data to a broader community. These actions must be completed before the beginning of CY2016.

The panel was disappointed that there was not a formal 2015 proposal. It is noted however, that the panel reviewed not only all the documents the EO-1 team provided to this Panel, but also the 2011 and 2013 EO-1 proposals, plus the 2009, 2011, and 2013 Senior Review Reports. It is further noted that a key element of this review was the EO-1 team's presentation and response to the questions presented to the team prior to the panel meeting and during their presentation. In general, the Panel found their responses to be unsatisfactory and in several instances unresponsive. For example, even though the 2009, 2011, 2013 and this Panel indicated that there were concerns regarding the documentation and distribution of EO-1 products, the EO-1 team did not adequately address why these continue to be issues. Furthermore, the Panel was disappointed that the EO-1 team continued to emphasize EO-1's ability to acquire rapid imagery and potential to test future instruments rather than provide evidence of the scientific use and specific users for EO-1 data as requested.

GRACE

Since launch in 2002 the GRACE mission has produced a series of over 140 global gravity models, providing an unprecedented view of mass redistribution within the Earth system on monthly to inter-annual time scales. These gravity variations result primarily from transport of water between the oceans, land, cryosphere and atmosphere, making GRACE a unique and important component of NASA's climate measurement capability; it was designated as a Climate Mission in the 2010 ESD Climate Initiative. GRACE is a valuable resource for basic science investigations, providing a unique view of the coupled Earth system, and shedding light on fundamental oceanographic, hydrologic, and cryospheric processes and interconnections. Through assimilation, mission data are also helping to improve model hind-casts and improving predictive skill in several areas of application. A follow-on mission is planned for launch in fall 2017. A core rationale for extension of the GRACE mission is to maintain continuity of the climate record, and provide sufficient overlap with the follow-on for calibration and validation of the new mission. The value of continued data collection to both basic research and applications provides further justification for mission extension.

There are significant risks to the mission over the coming years. Many systems are single string, and a single additional battery cell failure will terminate the two-satellite science mission. Limited fuel and continuing descent of the satellite also may prevent continuation of GRACE until launch of the follow-on mission. If the K-band ranging is lost, the mission proposes to continue to produce time variable gravity fields with GPS tracking of a GRACE satellite, in combination with other LEO satellites. The mission is studying the feasibility of this approach, but preliminary assessments do not yet demonstrate that such solutions would be of sufficient quality to maintain the climate record. The mission should continue these studies, in cooperation with international collaborators and the science community, to further develop and evaluate the feasibility of the single GRACE satellite solution approach. Risks associated with this uncertainty are also reflected in the cost rating, with which the science panel concurs.

The Panel concludes the mission be continued as currently baselined.

OSTM

The OSTM mission is a Ku-band radar altimeter. It continues a legacy established by TOPEX/Poseidon and Jason-1 of providing a high-quality global record of sea surface height on a 10-day repeat reference ground track. The mission is a joint effort by NASA and NOAA in the US and by EUMETSAT in Europe and the French Space Agency, CNES. Data are used for a broad range of applications, including studies of global sea level rise and ocean circulation. The satellite altimeter and related instruments are performing well and continue to return high-quality data. The level of maturity and validation for the primary altimeter dataset deliverables, the Operational-, Interim-, and Merged Geophysical Data Records related to core altimeter sea level, wind and wave data are all found to be excellent. Data latency has been optimized for operational purposes and science data use continues to rise. Methods for updating any science algorithm changes are efficient, robust, and transparent.

A key rationale for extending OSTM is to ensure mission continuity between OSTM/Jason-2 and Jason-3, due to launch in July 2015. Jason-3 will join the same orbit as OSTM for a six-month calibration phase. Subsequently, following the science plan originally established for TOPEX/Poseidon and Jason-1, OSTM will move to an interleaved orbit to provide higher spatial/temporal coverage of oceanic eddy variability. Eventually, the project intends to move OSTM to a terminal orbit as a geodetic mission in order to improve mapping of sea floor bathymetry. Both of these subsequent mission phases will yield valuable additional data, providing further justification for mission extension. The Panel concludes the mission be continued as currently baselined.

SORCE

SORCE measures total solar irradiance (TSI) as well as solar spectral irradiance (SSI). Because the TSI instruments are not absolutely calibrated, gaps in the record can introduce important uncertainties in the long-term trend. Therefore, continuous measurements of TSI are very important. In addition, the daily SSI measurements are important operational products for NOAA and Air Force space weather operations. SORCE has played a key role in maintaining the continuity of the long-term TSI time series, and is expected to transfer the TSI calibration to TSIS TIM when it becomes operational (early 2018). SORCE has also been extending the SSI climate data record, and is expected to transfer the SSI calibration to TSIS SIM when it becomes operational. The mission listed the top four accomplishments of the SORCE mission since last Senior Review: (1) successful recovery of SORCE after a battery cell failure in July 2013 and return to daily solar measurements in February 2014, (2) overlap of SORCE TSI observations with the new TCTE TSI observations that began in December 2013, (3) critical review of the SORCE SSI measurements and solar cycle variability results by a NASA independent panel in September 2014, and (4) determination that solar cycle 24 variability is about half as much as the variability during the past few 11-year solar cycles.

Connected to the transfer of the TSI calibration to TSIS TIM (when it becomes operational early 2018), there is another TIM on TCTE, presently in orbit. So, SORCE TIM is not irreplaceable (Virgo is also in orbit, but it's value for intercalibration is not clear). Nevertheless, TSI is so important that having two TSI instruments in orbit is probably a reasonable risk reduction strategy. Given the importance of this overlap with TSIS, the panel finds that the budget overguide for FY18-19 sought by the mission to facilitate the overlap should be funded.

In summary, the Panel concludes that SORCE mission be continued as currently baselined for FY16-17, and budget overguided for FY18-19, pending reassessment by the next Senior Review.

Terra

The Terra mission is now beyond 15 years of continuous data collection, providing fundamental observations of the earth's climate system, high-impact events, and adding value to other satellite missions and field campaigns. With 5 sensors providing a unique

combination of spatial resolutions, temporal sampling, and multiple look angles, Terra is an exemplary mission that offers a tremendous long term data record capable of identifying subtle climate signals. The Terra mission is an international mission (US, Japan, and Canada) with broad participation among three NASA centers (JPL, Langley, and Goddard). The 5 sensors onboard Terra (ASTER, CERES, MISR, MODIS, and MOPPITT) collectively contribute to 81 calibrated and validated core data products. The value of Terra to the science and operational communities is unequivocal. The data distribution numbers for 2013 and 2014 exceed the combined distribution numbers for all other years combined – an indication of the continued and growing use of the data products. There were over 1,600 peer-reviewed papers in 2014, bringing the mission total to over 11,000. All of Terra's instruments are performing in exemplary fashion, except for ASTER's SWIR bands which were declared inoperable in 2009. Despite this, ASTER data have been used to produce 30 million tiles of the Global Digital Elevation Model - the most complete, consistent, high-resolution global topographic data set ever released.
One significant source of uncertainty with regards to the future of the mission, however, is the fate of the waiver to extend the Terra mission at the current 705 km altitude. If the waiver is approved, and the Terra mission team strongly endorses this position, then Terra will be able to maintain the tight 10:30 MLT for 3 additional years and continue to provide a long term uninterrupted data record. The Panel agreed that if the waiver is denied, Terra would certainly continue to collect high quality data of sufficient value to the science community to warrant extension. The Panel also agreed that the orbital change would compromise continuity of the stable long term climate record at some level, but felt that additional information would be necessary to fully assess the significance of this degradation. A sensor-specific or even data product-specific table of risks to data continuity resulting from waiver non-approval would have been a useful addition to the proposal. In light of this, the panel suggests that NASA convene a workshop of data users to discuss and evaluate the trade-offs associated with the waiver decision.

The continuity of the Terra data products is highly desirable for the Scientific and the broader user communities. As such, regardless the outcome of the waiver, the Panel concludes the Terra mission be continued as currently baselined.

APPENDIX 1. TECHNICAL REVIEW PANEL REPORT

Results from the Technical Review Subpanel
of the Senior Review 2015 of the Mission Operations and Data Analysis Program for the
Earth Science Operating Missions

Waldo J. Rodríguez
NASA Science Office for Mission Assessments

Introduction

The NASA Earth Science Division (ESD) of the Science Mission Directorate (SMD) is supporting several Earth observing missions that are operating beyond their prime mission lifetimes. Extended operations and associated data analysis activities require a significant fraction of the ESD annual budget. NASA and the ESD thus periodically evaluate the allocation of Mission Operation and Data Analysis (MO&DA) funds with the aim of maximizing within finite resources the missions' contributions to NASA's and the nation's goals. This periodic NASA comparative review for missions in extended operations is known as the "Senior Review."

The following eleven missions (in alphabetical order) were invited to propose to the 2015 Senior Review: Aqua, Aquarius, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), CloudSat, Earth Observing-1 (EO-1), Gravity Recovery And Climate Experiment (GRACE), Jason-2/ Ocean Surface Topography Mission (OSTM), Quick Scatterometer (QuikSCAT), Solar Radiation and Climate Experiment (SORCE), and Terra. Performance factors are to include quality and demonstrated scientific utility of the mission datasets, contributions to national objectives, technical status and budget efficiency.

The objective of the ESD Senior Review is to identify those missions beyond their prime mission lifetime whose continued operation contributes cost-effectively to both NASA's goals and the nation's operational needs. The primary evaluation criterion for extension of a mission is its contribution to NASA's research science objectives, but the ESD Senior Review also explicitly acknowledges (1) the importance of long term data sets and overall data continuity for Earth science research; and (2) the direct contributions of mission data to national objectives, such as the routine use of near-real-time products from NASA research missions for applied and operational purposes by U.S. public or private organizations.

The Senior Review is composed of two panels: the Science Panel and the National Interests Panel. The Science Panel is the primary panel. It will be an independent analysis group with sole responsibility to evaluate the scientific merit of each mission's datasets with respect to NASA's Earth science strategic plans and objectives. The Science Panel will be drawn from recognized expert members of the Earth Science research community, and supported by technical (Technical Review Subpanel) and cost experts from within and outside NASA to assess the health and viability of the operating satellites and the proposed MO&DA budgets.

The National Interests Panel will assess the utility and applicability of the mission's data products to satisfy national objectives by public (non-NASA) and private organizations.

The Senior Review Panel considers the results from the National Interest Panel and the Technical Review Subpanel on their final review findings and ratings.

ESD has requested the NASA Science Office for Mission Assessments (SOMA) to perform a Technical Review that partially parallels the Technical, Management, and Cost (TMC) evaluations that NASA SOMA performs on Pre-Phase A mission concepts. As the missions are proposing extensions on the Operations and Sustainment phase (extended Phase E), the review emphasizes the hardware status and performance and reliability projections, and mission operations plans.

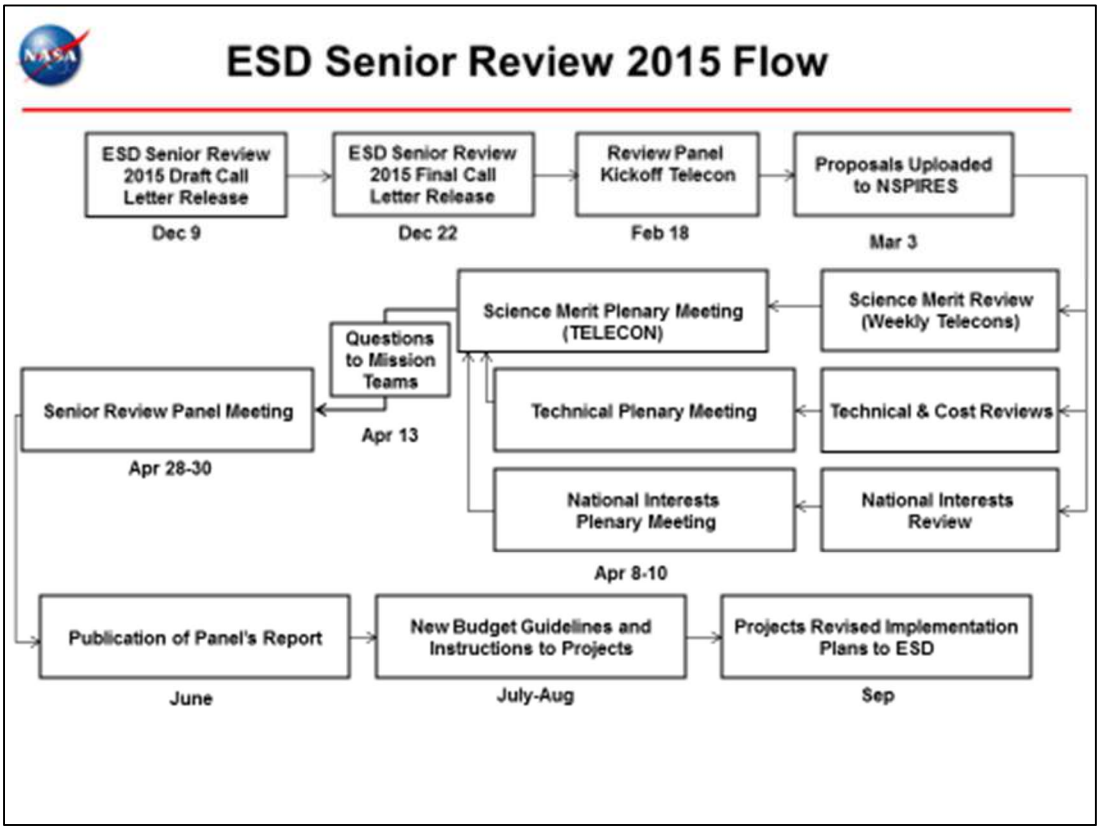


Figure 1. Senior Review Flow

Proposers were instructed in the "Call for Proposals – Senior Review 2015 of the Mission Operations and Data Analysis Program for the Earth Science Operating Missions" to: Discuss the overall technical status of the elements of the mission, and the team's approach to managing operations to optimize health and vitality of the elements. Include the spacecraft, instruments, and ground systems including spacecraft control center and science center(s). Summarize actions taken to improve the effectiveness of the mission operations tasks and describe what improvements have been accomplished. Summarize the health of the elements and point out limitations as a result of degradation, aging, use of consumables, obsolescence, failures, etc. Provide supporting data in the form of engineering data tables and figures in Appendix E. Include an estimate and rationale of mission life expectancy.

Technical Review

Technical Review Criteria

Each proposed mission extension is reviewed in detail for the feasibility of mission implementation as reflected in the perceived risk of accomplishing the extended mission as proposed.

The Technical Review Subpanel is given the task to assess each mission's performance and reliability projections for the satellite and instrument(s), the mission operations implementation plan, and the likelihood of accomplishment within the proposed cost. The technical experts will consider factors including the status of consumables and predicted utilization; spacecraft and instrument status, performance degradation, and failure risk; the proposed mission operations approach for the effective and safe management of an aging satellite; and mission and data management. The cost experts will compare the requested budget against historical expenses and allocated funds. The technical review will result in narrative text as well as a risk rating for the feasibility of the extended mission implementation.

Technical Review Principles

The basic assumption is that the mission will be extended unless significant technical weaknesses are evident that would adversely affect the proposed mission extension. The proposer is regarded as the expert on his/her proposal and therefore is given the benefit of the doubt.

On the proposal, the proposer's task is to provide evidence of the mission extension risk posture. During the review the Technical Review Subpanel's task is to try to validate proposer's assertion of risk.

All Proposals are reviewed to identical standards and they receive same evaluation treatment in all areas and are not compared to other proposals. The Technical Review Subpanel is made up of non-conflicted reviewers who are experts in the areas that they review and they review the investigations using only the review factors that apply to the specific mission.

The proposals are only reviewed on the risks that are under the control of the proposer. Inherent risks from space-based missions, e.g. space environments, are not considered on the review. Programmatic risks of mission extensions, e.g. budgetary uncertainty, are not considered on the review. Risks that the mission team can address, e.g. adequacy of resource management, are considered.

The Technical Review Subpanel develops findings for each proposal that reflect the general agreement of the entire panel. The findings can be: "Above expectations" that translates into "Strengths", "Below expectations" that translates into "Weaknesses" and "As expected" that does not generate a finding.

Technical Risk Ratings

The Technical Review is to determine, for each proposed mission extension, the level of risk of implementing the mission extension as proposed. An integral part of the Technical Review is the review of available resources to the proposer to handle problems. Resources can be redundant hardware, consumables, reserves, and margins on physical resources such as power and propellant; planned solutions; and personnel.

Technical Risk Ratings are defined as:

- Low Risk: There are no problems evident in the mission that cannot be normally solved well within the resources available. Problems are not of sufficient magnitude to doubt the Proposer's capability to continue the proposed investigation well within the available resources.
- Medium-Low: Problems have been identified, but are considered well within the proposal team's capabilities to correct within available resources with good management and application of effective engineering resources. Mission design may be complex.
- Medium Risk: Problems have been identified, but are considered within the proposal team's capabilities to correct within available resources with good management and application of effective engineering resources. Mission design may be complex and resources tight.
- Medium-High: One or more problems of sufficient magnitude and complexity have been identified that are unlikely to be solved within the available resources.
- High Risk: One or more problems are of sufficient magnitude and complexity as to be deemed unsolvable within the available resources.

Technical Review: Definitions of Findings

Each finding is identified as a:

- Major Strength: A facet of the response that is judged to be well above expectations and can substantially contribute to the ability to meet the proposed technical objectives well within the available resources.
- Major Weakness: A deficiency or set of deficiencies taken together that are judged to substantially impair the ability to meet the proposed technical objectives within the available resources.
- Minor Strength: A facet of the response that is judged to be above expectations and can contribute to the ability to meet the proposed technical objectives within the available resources.
- Minor Weakness: A deficiency that is judged to impair the ability to meet the proposed technical objectives within the available resources.

For the Senior Review all findings (major and minor) are considered on the Technical Review risk ratings.

Technical Review Process

The Technical Review Subpanel is composed of non-conflicted reviewers who are experts in the areas that they review. These areas include Instruments, Flight Systems, and Mission Design and Operations. The Technical Review Subpanel is asked to consider technical factors such as; Instruments - status of the instrument(s) and components, redundancies, projected lifetime, and instrument resource management; Flight Systems – flight systems status and health, redundancies, consumables, margins, and spacecraft resource management; Mission Design and Operations - mission operations approach, ground facilities – new/existing, and telecommunications. The Technical Review Subpanel is lead by a Technical Review Form Lead who is responsible for guiding the discussions and for the Technical Review Form development.

All Technical Review Subpanel members review the proposals and write an individual review before discussing findings with other members of the review team. Each individual finding explains the issue in detail and is identified as "Above expectations" that translates into "Strengths", "Below expectations" that translates into "Weaknesses" and "As expected" that does not generate a finding. For each proposal, these individual findings are gathered into a table that is the basis of a subpanel discussion teleconference.

Teleconferences are held for each proposal to discuss the findings by the entire subpanel. During the discussions individual findings are kept, merged with other similar individual findings, or dismissed when appropriate.

A Technical Review Panel Meeting is held to refine and finalize the forms and determine the Risk Rating. During the discussion findings are refined, merged with other similar findings, or dismissed. For each proposal, the Technical Review Form is reviewed 3 times and polling is held to determine the Risk Ratings for each proposed mission extension.

Technical Review Product

The Technical Review of the 2015 Senior Review results on a Technical Review Form for each proposal. This form is labeled with the appropriate Mission name and Principal Investigator; it contains the Risk Rating and a rationale paragraph explaining the rating; and it enumerates the Major Strengths, the Major Weaknesses, the Minor Strengths, the Minor Weaknesses, and any questions sent to the proposing mission team. This form is the product of the Technical Review process described above and for each proposal it is regarded as the report from the Technical Review Subpanel to the Senior Review Panel.

Technical Review Summary Results

Table 1 shows the Risk Ratings for each proposed mission extension. Including the Technical Review Form for each proposal in this report would be very cumbersome therefore only the risk rating and rationale are presented. If more detail on the results of the Technical Review Subpanel is required, the Technical Review Forms are available

from the NASA SOMA archive. The rationales are organized in alphabetical order and the major findings are in bold letters.

Table 1. Summary results of the Technical Review for the 2015 Senior Review

Mission \ Risk	Low	Medium-Low	Medium	Medium – High	High
GRACE				X	
SORCE				X	
EO-1			X*		
Aura		X			
CALIPSO		X			
CloudSat		X			
OSTM		X			
Aqua	X				
Aquarius	X				
Terra	X				

*Risk Rating for a 1-year extension.

Aqua

The Aqua proposed mission extension is rated as Low Risk**.** The Technical Review Panel has identified two Major Strengths, no Major Weaknesses, one Minor Strength and one Minor Weakness. **Five of Aqua's six instruments continue to perform very well, maintain redundancy, and appear able to support the proposed mission extension period. The spacecraft bus is in excellent condition and should be fully functional well past the mission extension period.** Aqua data processing uses resources shared with other Earth Observing System (EOS) Flagship missions, and benefits from ongoing modernization efforts. The risk for a four-year mission is expected to be higher.

Aquarius

The Aquarius proposed mission extension is rated as Low Risk**.** The Technical Review Panel has identified two Major Strengths, no Major Weaknesses, one Minor Strength, and one Minor Weakness. **The Aquarius radiometer/scatterometer instrument system continues to perform very well, maintains all as-designed redundancy, and shows no trends or other issues that would prevent completion of the proposed mission extension. With one exception in the power control system, the Aquarius spacecraft flight systems are operating on primary hardware with redundant systems intact and are expected to continue to perform very well throughout the proposed mission extension period.** The Aquarius Flight Operations and Satelite de Aplicáciones Científica (SAC-D) Mission Operations teams, supported by NASA Goddard Space Flight Center (GSFC) Engineering, have demonstrated exceptional responsiveness, experience and efficiency. However, failure of the Power Control Unit (PCU) Remote Terminal Unit (RTU) 1B in September 2013 (approximately 1 year after launch) has left the power supplied to the Attitude Control Electronics (ACE) single-string. The risk for a four-year mission extension is expected to remain low.

Aura

The Aura proposed mission extension is rated as Medium-Low Risk**.** The Technical Review Panel has identified one Major Strength, no Major Weaknesses, two Minor Strengths, and five minor weaknesses. **Aura spacecraft flight systems are operating on primary hardware with redundant systems intact and are expected to continue to perform very well through the proposed mission extension period.** Aura Mission Operations have been very successful. Aura data processing uses resources shared with other Earth Observing System (EOS) Flagship missions and benefits from ongoing modernization and improvement efforts. However, the pronounced downward trend in the percentage of retrieved Microwave Limb Sounder (MLS) profiles in 2013 and 2014 raises concerns about even limited operability for periodic OH measurements. The Thermal Emission Spectrometer's (TES) Interferometer Control System (ICS) motor stalled for a second time during the mission and recovery from a future stall may require weeks or months, or the stall may be permanent. The risk for the 4-year mission extension is expected to be higher.

CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) proposed mission extension is rated as Medium-Low Risk**.** The Technical Review Panel has identified one Major Strength, no Major Weaknesses, four Minor Strengths, and one Minor Weakness. **All CALIPSO flight systems, including Power, Attitude and Orbit Control, Propulsion, Command and Data Handling, Communications, and Thermal Control are fully operational and retain full redundancy**. The Wide Field-of-View Camera (WFC) continues to function well, with no dead or blind pixels, and good performance margins. The Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) instrument’s laser energy output has been stable at about 190 milli-Joules over the last two years indicating that the laser diode pump arrays have not had bar drop outs. CALIPSO may be able to restart the primary CALIOP laser to extend operations beyond the 2-year mission extension period. New hardware systems within the ground system have been added and are performing very well, increasing computing capability fourfold. However, the proposal did not adequately support claims that the pressure drop in the CALIOP instrument would allow operation over the entire two-year mission extension. The risk for the 4-year mission extension is expected to be significantly higher due to the loss of canister pressure in the operating laser.

CloudSat

The CloudSat proposed mission extension is rated as Medium-Low Risk**.** The Technical Review Panel has identified one Major Strength, no Major Weaknesses, three Minor Strengths, and three Minor Weaknesses. **Cloudsat's Cloud-Profiling Radar (CPR) is performing well, maintains full redundancy, and appears to be able to support the proposed mission extension**. The Daylight Only Operations mode, developed in response to a partial battery failure in 2011, has proven successful. Sufficient propellant remains onboard for at least 6 more years of normal operations. Full redundancy has been maintained in nearly all flight systems except the spacecraft transponder. However, failure of the remaining single string command receiver could create a risk to the other spacecraft in the A-Train constellation. Also, since April 2011, the Nickel Hydrogen

battery has effectively been restricted to 10% of its original capacity which requires power-cycling many components in eclipse that were not designed for power cycling, though none of these systems show signs of degradation. Due to continued aging of the battery and aging/power-cycling of electronics, risk for the 4-year mission extension is expected to be higher.

EO-1

The Earth Observing-1 (EO-1) proposed 1 year mission extension is rated as Medium Risk**.** The Technical Review Panel has identified no Major Strengths, one Major Weakness, three Minor Strengths, and three Minor Weaknesses. Spectral performance of the Hyperion instrument appears to be stable. The EO-1 mission ground system has continually evolved to an efficient and autonomous lights-out operation and the revised science orbit lifetime ending on 29 September 2016 is consistent with independent analysis. **However, there is insufficient data presented to support the claim that all flight systems are operating nominally.** The proposal did not provide trending and threshold data for the Hyperion pulse tube cryocooler power consumption. Items 7 and 8 on the Life Limiting Items List refer to radiation dose tolerances that reached their thresholds for life beyond 2008 and 2011. And, the operations team has not been performing standard maintenance for an aging satellite.

GRACE

The Gravity Recovery And Climate Experiment (GRACE) proposed mission extension is rated as Medium-High Risk**.** The Technical Review Panel has identified no Major Strengths, two Major Weaknesses, two Minor Strengths, and two Minor Weaknesses. The operations plan for managing consumables is very well structured and full redundancy has been maintained in nearly all flight systems except the spacecraft transponder. However, **instrument component failures have eliminated redundancy, which create multiple single point failures that could end the nominal gravity mission. The batteries on both GRACE spacecraft are severely degraded and lack redundancy; a third cell failure on either spacecraft would severely curtail science operations within the extension period.** Under worst case conditions, re-entry of the two GRACE spacecraft is predicted within the 2 year extension period. Due to the decaying orbit, risk for the 4-year mission extension is expected to be very high as even the best case prediction for re-entry is January 2019.

OSTM/ Jason-2

The Ocean Surface Topography Mission (OSTM) proposed mission extension is rated as Medium-Low Risk**.** The Technical Review Panel has identified one Major Strength, one Major Weakness, two Minor Strengths, and no Minor Weaknesses. **Performance of four of OSTM's five instrument systems continues to be very good and retain all original redundancy.** The precision orbit determination function provided for the spacecraft is a robust design which would exhibit graceful degradation and still meet level 1 Requirements despite the possible loss of both of the Global Positioning System Payload (GPSP) units. The B-side half-satellite of the OSTM bus is operating very well and retains significant margins. However, **the OSTM Data Handling Unit (DHU) A-side Processor Module (PMA) has experienced a permanent memory fault that currently**

causes a loss of redundancy to several A-side dedicated spacecraft components. The risk for a four-year mission extension is expected to be higher. However, if the software patch to PMA is successfully implemented, the risk for the two or four-year mission extension will be reduced.

SORCE

The Solar Radiation and Climate Experiment (SORCE) proposed mission extension is rated as Medium-High Risk**.** The Technical Review Panel has identified one Major Strength, one Major Weakness, two Minor Strengths, and four Minor Weaknesses. **SORCE's instruments are functioning exceptionally well, and appear able to support the proposed mission extension period.** The Daylight Only Operations mode, implemented in March 2014, has been able to provide science observations on 89% of all orbits and the spacecraft command & data handling, thermal control, and solar array subsystems are functioning well. However, **SORCE's Nickel Hydrogen (NiH_2) battery capacity is seriously degraded and is now considered a single point failure**. Any additional battery anomaly would likely end the mission. Daylight only operations power-cycle nearly all electronics during every eclipse and preclude stellar calibration for the SOLar STellar Irradiance Comparison Experiment. SORCE has lost reaction wheel and star-tracker redundancy. Due to an additional marginal battery cell, power-cycling of electronics and three single point failures, risk for the 4-year mission extension is expected to be significantly higher.

Terra

The Terra proposed mission extension is rated as Low Risk**.** The Technical Review Panel has identified two Major Strengths, no Major Weaknesses, two Minor Strengths, and three Minor Weaknesses. **The five instruments on Terra have continued to perform very well, which provides confidence that they will continue to perform at their current level through the proposed mission extension period**. **The propulsion, power, attitude determination and control, and primary communication systems continue to perform very well, maintain redundancies, and appear able to support science operations during the proposed mission extension period.** End of life planning is supported by a flight dynamics analysis that is well formulated with respect to constellation safety. The Terra mission benefits from ongoing efforts to modernize and improve ground systems, including multi-mission support modernization, operational scheduling, and IT security. However, overall data storage has been reduced by 17.2% due to the disabling of 10 of the total 58 Printed Wire Assembly (PWA) boards in the two spacecraft Data Memory Units (DMUs), thus reducing ASTER data collection significantly. The Terra batteries have two minor aging issues. The risk for the 4-year mission extension is expected to be higher.

APPENDIX 2. NATIONAL INTERESTS SUBPANEL REPORT

Report of the 2015 National Interests Sub-panel of the NASA Senior Review

Chair: John Haynes, NASA Applied Sciences Program
Co-Chair: David Green, NASA Applied Sciences Program

The 2015 National Interests Review assessed the contributions of the core data products of the 10 missions under review to national objectives by assigning a utility value to each product or group of products.

Overall, this panel conveyed to the Science Panel the value of the data sets for "applied and operational uses" that serve national interests -- including operational uses, public services, business and economic uses, military operations, government management, policy making, and nongovernmental organizations' uses. Essentially, this panel represented all users of the data for primarily non-research purposes.

The following organizations were represented on the panel: the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS); NOAA/National Ocean Service (NOS) ; the Federal Aviation Administration (FAA); the US Department of Agriculture (USDA); the Naval Research Laboratory (NRL); the US Army Corps of Engineers (USACE); the Environmental Protection Agency (EPA); the US Geological Survey (USGS); the Department of Homeland Security/Federal Emergency Management Agency (DHS/FEMA); the Centers for Disease Control and Prevention (CDC); the Alliance for Earth Observations; the International Association of Wildland Fire (IAWF); Conservation International (CI); the National States Geographic Information Council (NSGIC); the US Geospatial Intelligence Foundation (USGIF); and the Urban and Regional Information Systems Association (URISA).

The panel met April 7-9, 2015, in Washington, DC.

Pre-panel Activities

Each organization represented on the panel pre-assessed three primary factors and one overall rating for each mission during March 2015. The assessed factors included:

1) Value: Overall value of the data products to the range of applied and operational uses within the organization. Value for those times the data is used, independent of frequency of use, latency of receipt, etc. Value was qualitatively assessed as high, medium, or low.

2) Frequency of Use: Frequency the organization currently uses the data products in the range of applied and operational applications. Frequency of use was qualitatively assessed as routine, occasional, rarely, or never.

3) Latency: Current timeliness in which the organization accesses and/or receives delivery of the data products to meet the range of applied and operational uses. Latency was qualitatively assessed as near real time, within one to two days, weekly/monthly, or archival.

4) Overall rating: Utility: Overall *utility* of mission and data products to national interests. Overall utility was qualitatively assessed as very high, high, some, or not applicable.

Panel Activities

Following the pre-assessments, the organization representatives met in a formal panel session over three days in April 2015. During this panel, 45 minutes of discussion time were allocated for each mission; however, 75 minutes were allocated for the flagship missions of Terra, Aqua, and Aura.

At the start of each discussion, an assigned Primary Reviewer introduced the mission and his organization's ratings. The chair also showed a table with all the organizations' pre-panel ratings. A round-table panel discussion then commenced. By the end of each discussion, the panel reached agreement on an overall utility rating for the mission and/or sensor. The panel also determined any questions to forward to mission teams via the Science Panel. Each mission team answered these questions during the full Science Panel in late April 2015.

Following discussions of all the missions, each organization separately ranked each mission quantitatively according to its post-panel view of national interests. Each representative was asked to assign 10 points to the mission of highest priority and one point to the mission of lowest priority.

The Primary Reviewers then prepared panel summaries for each mission.

Panel Overall Summary

The following table summarizes the qualitative utility ratings determined by the panel:

NASA 2015 Earth Science Senior Review *National Interests Panel*		
Rating	**Definition**	**Missions**
Very High Utility	These missions have one or more very relevant and highly valued data products which are routinely used by one or more of the participating organizations for important activities. Loss of the data product(s) would have a significant negative impact on national agencies and organizations.	***Aqua, Terra***
High Utility	These missions have one or more data products which are routinely used by one or more of the participating organizations for their activities. Loss of the data product(s) would have a measurable negative impact on national agencies and organizations.	***Aquarius, Aura, CALIPSO, CloudSAT, GRACE, Jason-2/OSTM, SORCE***
Some Utility	These missions have one or more data products which are used by one or more of the participating organizations. Loss of the data product(s) would have a small but measurable negative impact on national agencies and organizations.	***EO-1***
Not Applicable (aka, Minor / Negilible)	These missions had no identified or significant applied or operational utility to the participating organzations. Loss of the data product(s) would have no or neglible negative impact on national agencies and organizations.	***None***

The following chart summarizes the quantitative rank of each mission according to the panel's view of national interests. A higher score indicates greater utility.

Mission	NOAA NWS	NOAA NOS	FAA	USDA	USGS	CDC	FEMA	EPA	USACE	DOD/NAVY /NRL	NSGIC	Conservati on Intl.	Alliance for Earth Observatio	IAWF	URISA	USGIF	Total
Terra	9	7	10	10	10	9	10	10	10	9	9	10	9	10	10	10	152
Aqua	10	10	9	9	9	10	9	9	9	10	10	9	10	9	9	9	150
Jason-2/OSTM	8	9	4	8	3	6	2	3	8	6	2	7	7	1	4	4	82
Aura	6	4	8	5	7	7	6	8	4	8	5	4	1	4	3	1	81
GRACE	2	8	3	4	8	3	3	5	7	3	7	5	5	2	6	8	79
CALIPSO	3	2	6	3	5	8	1	7	3	5	8	6	3	7	1	7	75
Aquarius	7	5	2	7	4	4	7	2	5	2	3	2	8	3	8	3	72
CloudSat	4	3	7	1	2	5	5	4	2	4	6	8	4	6	7	2	70
EO-1	1	1	1	6	6	1	8	6	6	1	1	3	2	8	5	5	61
SORCE	5	6	5	2	1	2	4	1	1	7	4	1	6	5	2	6	58

A detailed chart presenting each organizations' utility ranking can be found in the chart below:

Mission / Sensor	Overall Rating	Civil Agencies								Military / Intelligence Community		State & Locals	Private Sector / NGOs				
		NOAA NWS	NOAA NOS	FAA	USDA	USGS	CDC	FEMA	EPA	USACE	DOD/NAVY/NRL	NSGIC	Conservation Int	Alliance for Earth Observations	IWF	URISA	USGIF
Aqua	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility
AIRS	High Utility	Very High Utility	High Utility	Very High Utility	Not Applicable	Some Utility	High Utility	High Utility	Some Utility	Not Applicable	Very High Utility	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable
AMSR-E	Some Utility	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable
CERES	High Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable
MODIS	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility
Aquarius	High Utility	Very High Utility	Very High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Some Utility	High Utility	Not Applicable	High Utility	Some Utility
Aura	High Utility	Very High Utility	High Utility	Very High Utility	Not Applicable	High Utility	Some Utility	Some Utility	Very High Utility	Not Applicable	High Utility	High Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable
HIRDLS	High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
MLS	High Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
OMI	High Utility	Very High Utility	Very High Utility	Very High Utility	Not Applicable	High Utility	High Utility	Some Utility	High Utility	Not Applicable	High Utility	High Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable
TES	Some Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Very High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
CALIPSO	High Utility	High Utility	Some Utility	High Utility	Not Applicable	Some Utility	High Utility	Some Utility	Very High Utility	Not Applicable	Very High Utility	Very High Utility	Not Applicable	Not Applicable	Very High Utility	Some Utility	Some Utility
CloudSat	High Utility	Very High Utility	Some Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	High Utility	High Utility	Some Utility	High Utility	Not Applicable	Some Utility	Some Utility
EO-1	Some Utility	Some Utility	Some Utility	Not Applicable	Very High Utility	High Utility	Not Applicable	High Utility	Very High Utility	High Utility	Some Utility	Not Applicable	Some Utility	Some Utility	Some Utility	Some Utility	Some Utility
GRACE	High Utility	High Utility	Very High Utility	Not Applicable	Not Applicable	Very High Utility	Not Applicable	Some Utility	High Utility	Some Utility	High Utility	High Utility	Not Applicable	High Utility	Not Applicable	High Utility	Some Utility
Jason-2/OSTM	High Utility	Very High Utility	Very High Utility	Not Applicable	Very High Utility	Not Applicable	Some Utility	Some Utility	Some Utility	Some Utility	Very High Utility	Not Applicable	Some Utility	Very High Utility	Not Applicable	Some Utility	Some Utility
SORCE	High Utility	Very High Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Terra	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility
ASTER	High Utility	High Utility	High Utility	Some Utility	Not Applicable	Very High Utility	Some Utility	High Utility	Not Applicable	Some Utility	Some Utility	Not Applicable	High Utility	Not Applicable	High Utility	Very High Utility	High Utility
CERES	High Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable
MISR	High Utility	Very High Utility	Some Utility	Some Utility	Not Applicable	Not Applicable	High Utility	Some Utility	Not Applicable	Not Applicable	Very High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable
MODIS	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility
MOPITT	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable

PANEL SUMMARIES OF EACH MISSION

Terra (Very High Utility)

Easily reached consensus rating of very high utility, primarily due to the great practical utility of MODIS for a wide range of applications. The value of other sensors, particularly ASTER, added to utility rating. Uses included:

1) MISR data are assimilated in Navy global and regional weather models.

2) FAA uses MISR to distinguish sulfate/water vapor from ash-dominated plumes which can be used in volcanic air hazard mitigation.

3) CERES value was noted for general climate applications and assimilation in global weather forecast models, similar to Aqua.

4) USDA uses ASTER data for targeted analyses of agricultural droughts that may impact food security, as well as burn severity analyses during wildland fires.

5) CDC uses MOPITT for carbon monoxide profiles in major cities and long term trends.

6) The EPA uses MODIS for aerosols (as does CDC) and change detection algorithms.

7) NOAA/NOS and NWS stated MODIS is the primary data source for sea ice analysis.

8) USDA and IAWF use MODIS in monitoring fire growth, hot spots, and new fire detection. MODIS is also used to support numerous decision support tools, such as Smartfire.

Aqua (Very High Utility)
Rated very high utility by the panel. This is due to use by all groups represented on the panel and covering a broad spectrum of interdisciplinary areas. Loss of data from Aqua would have a significant negative impact on all organizations in the panel. Widespread use of MODIS alone ensured the highest rating. Uses included:

1) The importance and utility of AIRS/AMSU was widely noted. Data are of significant importance to FAA and the aviation community (sulfur dioxide, volcanic plumes). AIRS data are utilized in volcanic ash detection for the NOAA Rapid Refresh Model. AIRS profiles are assimilated in NOAA NWP and are considered to be one of their most critical NASA data sets.

2) MODIS supports diverse atmospheric, oceanic, and terrestrial applications. The NDVI product is used by USGS in FEWS NET to monitor drought conditions. MODIS data remain the most widely and broadly used NASA data set in NOAA. MODIS images have become one of the primary data sources for NOAA ice analyses. USACE uses MODIS Snow Cover products in support of military operations in CENTCOM's Areas of Responsibility (AR) -- specifically Afghanistan and Pakistan. USDA uses MODIS products to monitor global croplands for food security, cropland water use assessments, drought studies, and other natural resources assessments.

3) AMSR-E received a "some" utility rating due to its continued archival use.

Jason-2/OSTM (High Utility)
Jason-2/OSTM was rated high utility as its data products are central to the oceanographic and weather communities, but of less utility for other sectors. OSTM has extended the ability to find long term cycles that have not been seen by any other method. The OSTM mission provides heavily-used altimetry data, which has led to advances in our understanding of sea level rise and other oceanic applications, including refinement of the planet geoid. Uses included:

1) USDA stated that OSTM telemetry data are used to provide heights of inland lakes and reservoirs. In areas where these reservoirs are used for irrigating croplands, the heights can be used as one of the pieces of data in forecasting crop area.

2) NOAA assimilates OSTM data in the Real-Time Ocean Forecast System (RTOFS) and the Global Ocean Data Assimilation System (ocean component of NOAA's Operational seasonal-interannual Coupled Forecast system).

3) NRL noted that OSTM data are used extensively for model verifications and ocean circulation models. Satellite altimetry is used in sea surface wave height models along with refinement of the geoid.

4) USACE stated that the data provides a historical record of reservoir levels that may indicate normal/abnormal conditions. Additionally, OSTM data can be collected when no ground presence or in-situ data collection is possible.

Aura (High Utility)

Aura data are useful for improving our understanding for how various molecular species contribute to changes in the atmosphere and to atmospheric forcing. In recognition of this fact, and the widespread operational benefits from the mission, the panel rated the value of this mission as high. OMI observations appeared to be the most utilized. Uses included:

1) The NOAA Space Weather Prediction Center (SWPC) has developed an extended version of the Global Forecast System (GFS) model called the Whole Atmosphere Model (WAM), which extends to 600 km. The WAM Data Assimilation System (WDAS) will require data from 60-100 km altitudes, including data from OMI and MLS. Archive data from HRDLS will also be used to improve the gravity wave parameterization above 60 km.

2) The NOAA Climate Prediction Center (CPC) uses OMI in near real time to calculate total column ozone, which is currently assimilated into the NCEP GFS.

3) CDC has partnered with researchers at Emory University and the University of Nebraska to conduct a health study exploring associations between UV exposures (derived from OMI) and melanoma.

4) FAA delivers information derived from OMI regarding the presence of sulfur dioxide and airborne volcanic ash during eruptions. OMI near real time sulfur dioxide and Aerosol Index (AI) data have been integrated into the decision support system at the NOAA/NESDIS Washington Volcanic Ash Advisory Center (W-VAAC).

5) EPA uses the TES sensor to retrieve ammonia profiles so as to adjust seasonal ammonia profiles. OMI data are also utilized by the EPA for assessment of pollutants and the input is assimilated into other climate models. HRDLS is used by the EPA in an archival manner.

GRACE (High Utility)
GRACE products continue to support a wide and growing user community and, in some cases, these products are uniquely determined or enabled by GRACE such as: mass change in the polar ice sheets; monitoring continental glaciers and the permafrost; mass contribution to sea-level rise; the separation of ocean thermal expansion (heat-content) from mass changes; and the estimation of deep (> 2000 m) ocean heat content. In addition, the GRACE core mission products and user interfaces are well defined which supports an active GRACE user community. Therefore, the panel rated this mission as high utility. Uses included:

1) NOAA stated that GRACE has been, and remains, one of the most critical satellites to the physical geodesy team at the National Geodetic Survey (NGS). Its data are used as the long-wavelength control of high-resolution geoid models created at NGS. The GRACE accelerometer provides some of the best in situ data on satellite drag and atmospheric neutral density at high altitudes. GPS-RO is assimilated in the NCEP operational model suite.

2) NSGIC noted that GRACE was used to model the effects of drought on groundwater resources for the western states over the last several years.

3) NRL noted that GRACE data are unique and used for verification/validation to global models.

CALIPSO (High Utility)
CALIPSO data products are produced routinely, archived, and made available to researchers worldwide through data centers in the United States and France. Several agencies ranked CALIPSO as high or even very high utility, with others saying it had some utility for their community. Several organizations are using CALIPSO data for operational and verification purposes. The overall rating of high utility is given due to the importance of the aerosol data in operations and verification. Uses included:

1) FAA is combining CALIPSO data with CloudSat data and other weather information for development of verification methodologies. The CALIOP lidar has been of enormous utility to the FAA in validating volcanic cloud height retrievals. The FAA has used CALIPSO data in near-real-time (hours of latency) to verify cloud height in SIGMET products.

2) CDC is working with EPA to develop statistical data fusion approaches to model air quality, which use station-based measurements and predictions from the Community Multiscale Airquality (CMAQ) model. In some instances, CALIPSO aerosol measurements are being used as a reference to evaluate the performance of CMAQ.

3) NOAA utilizes CALIPSO data to monitor thunderstorm overshooting tops, cloud top height, cloud typing, and volcanic ash detection. It is also used for NWP model validation.

4) NSGIC noted that state agencies use CALIPSO data to assess the long range transport of plumes of smoke and dust, whether the source is in-state, in a neighboring state/ Canadian province, or even further afield. These data are required for daily operational decisions during such events, and also when analyzing historical events.

5) NRL stated that CALIOP and MODIS data are actively used in data assimilation. A significant improvement in forecast skill for two day forecasts was noted through the assimilation of this data.

Aquarius (High Utility)

Aquarius applications were being actively realized with very high utility noted by NOAA/NWS and NOS. As users on the panel split between four "Very High/High" votes and five "Some" votes, the panel came to a consensus utility rating of high. Applications from this mission were expected to increase in the future; however, the mission failed June 7, 2015. Prior uses included:

1) NOAA/CPC assimilates Aquarius data for the Blended Analysis of Surface Salinity (BASS) product.

2) Sea surface salinity (SSS) and sea surface temperature (SST) measurements are important for NOAA/NOS as part of their Coastal Intelligence priority. SSS affects ship buoyancy and is one factor in determining ship transit times/docking, especially for large container ships.

3) FEMA uses derivative Aquarius products to assess climatology and seasonal variance specific to Pacific El Niño predictions.

4) USGIF uses Aquarius data for monitoring sea salinity for measurement of glacial melt.

CloudSAT (High Utility)

CloudSat is the only source for combined vertical profiles of global cloud liquid content/ice. CloudSat is used widely for operational and research purposes. Operationally it is used as an independent source in model verification of clouds and cloud structures and is an uninterrupted source for aviation and weather prediction applications. Therefore, the panel determined a high utility rating. Uses included:

1) CloudSat is part of the data set being used to better understand the Madden Julian Oscillation at NRL, and is assimilated to correct model physics for routine bias due to drizzle.

2) FAA utilizes CloudSat for verification of nowcasting to assess the accuracy of cloud top height forecasts and diagnoses. Its products help diagnose and forecast the presence of high ice water content clouds. Hawaiian Airlines views CloudSat data as an important source of information for the enhancement of aviation and safety performance.

3) The NOAA Earth System Research Laboratory uses CloudSat as one of the primary data sources for evaluating the quality of aviation icing forecast products. They combine CloudSat data with CALIPSO data and other weather information for development of verification methodologies. The NOAA CPC uses CloudSat observations to validate and evaluate the vertical cloud structure in climate forecast models. The NOAA National Hurricane Center utilizes it for tropical cyclone monitoring.

EO-1 (Some Utility)

EO-1's applied and operational uses are primarily focused on disaster response for various United States Government agencies and supporting national and international relief organizations/agencies. EO-1 also supports scientific applied research as well as calibration and validation for Landsat. EO-1 was given the rating of some utility as it was primarily used following a major disaster or natural event. The majority of the panel noted that EO-1 data was otherwise not routinely used for other aspects of their missions. Overall, the panel stated that loss of the data product(s) would have a measurable but small negative impact on national agencies and organizations. Uses included:

1) NOAA NOS found some utility from EO-1 data. NOAA NOS noted that the Hyperion instrument was useful for complex shallow area waters.

2) NRL found value in EO-1 data for validation purposes, particularly for dust storms.

3) USGS uses EO-1 for geological mapping and a host of land products.

4) USDA stated that the Forest Service uses EO-1 imagery for burned area emergency response.

SORCE (High Utility)

The overall rating for SORCE was high utility. This overall rating reflects the usefulness of SORCE data within agencies' applications for monitoring solar

radiation and climate change. SORCE data products are utilized for space weather forecasting, near-real-time monitoring of solar flare events, and as inputs to various agencies' climate modeling applications. While many constituencies on the panel do not use SORCE data, the ones which do believe it is critical and necessary to continue as it provides a unique data set for understanding solar impact on climate change. Uses included:

1) NOAA noted that SORCE TIM observations are the most important reason for extending the mission. These observations form a critical component of the long-term total solar irradiance data set. UV and EUV solar energy is a primary variable input for space weather and is critical in the formation and development of upper atmosphere models (above 100 km). The data from SORCE has been and will continue to be used in space weather research and model development especially in thermosphere/ionosphere models.
2) NRL stated that SORCE data on solar irradiance variation is crucial in determining impacts on climate change and that SORCE data have been the most accurate total solar irradiance dataset ever recorded. The solar irradiance data are crucial inputs to models of solar irradiance variability that extend back in time and are used routinely for input to IPCC model simulations of climate change on multiple time scales.

APPENDIX 3. COST PANEL REPORT

COST PANEL REPORT

Mission Operations and Data Analysis Cost Team Report
May 2015

The 2015 Senior Review cost analysis team consisted of Voleak Roeum, NASA Headquarters, and Mark Jacobs, Space Systems Analysts.

INTRODUCTION

The cost team conducted their analyses from Feb-Apr 2015. The team met with the individual lead Science Panel during March-April 2015 to discuss their analysis method, rating criteria, and areas that require clarifications. The cost team adjusted their initial finding to incorporate feedback with each iteration and discussion held with each science lead as well as the initial panel discussion held on April 08, 2015. The final meeting at the end of April included presentation from each of the project teams including responses to the review panel's questions.

The cost analysis process followed was derived from the approach used to evaluate Announcement of Opportunity proposals, with necessary adjustments to incorporate unique aspects of the Senior Review. This process, represented by the "pyramid" (shown in the Figure C-1), relies on detailed analysis of many items within each proposal to form the foundation of the analysis. Findings from the proposal cost review and inputs from the full review panel are used to identify risk items, assess viability of risk mitigation plans, and define threats that could lead to cost growth. Given these missions are beyond the end of their primary mission, reserves are generally limited, and operating missions tend to rely on uncosted carryover from the prior year as reserve.

Figure C-1

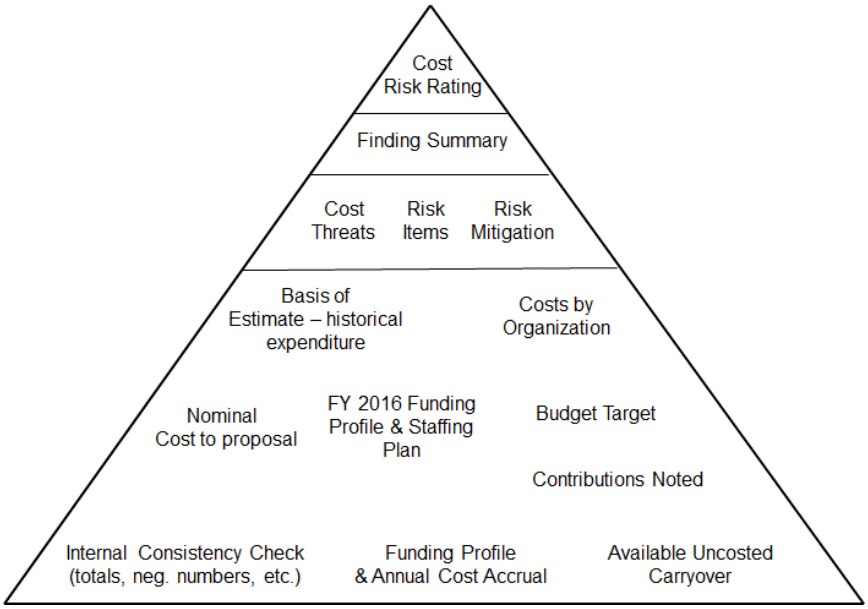


Figure C-2

Cost Risk	Definition
LOW	***Cost Envelope is adequate - expect success.*** - The proposer's estimate (with reserves) agrees closely with the work, staffing, and schedule proposed, fits within the program cap and any other budget constraints, and is verified by independent analysis. - The proposed cost reserve is adequate to address idenitified cost threats and to fund unexpected needs. - The resource management plan indicates strong, active management of resources throughout implementation.
MEDIUM-Low	***Cost Envelope is somewhat tight, but project should succeed.*** - Independent analysis identified one or more significant cost threats or weaknesses with regard to the proposer's estimate, cost reserves, and/or resource management. Overall impact of identified threats and weaknesses should be manageable.
MEDIUM	***Cost Envelope is tight. Success requires diligent oversight of resources.*** - Independent analysis identified one or more significant cost threats or weaknesses with regard to the proposer's estimate, cost reserves, and/or resource management. Cost impact of threats may be underestimated by proposer. Overall impact of identified threats and weaknesses should be manageable. - Independent analysis verifies some or most of proposer's costs.
MEDIUM-High	***Cost Envelope is very tight. It is likely the project will require more funding.*** - Independent analysis identified one or more major cost threats or weaknesses with regard to the proposer's estimate, cost reserves, and/or resource management. Cost impact of threats appears underestimated by proposer. Overall impact of identified threats and weaknesses will be challenging to manage within funding and/or schedule constraints. - Independent analysis could not verify significant elements of proposer's costs.
HIGH	***Project exceeds the Cost Envelope and is expected to require substantially more funding.*** - Independent analysis identified one or more major cost threats or weaknesses with regard to the proposer's estimate, cost reserves, and/or resource management. Cost impact of threats exceeds proposed resources and/or available resources to cover them. Threats are not acknowledged, or are underestimated by proposer. - Independent analysis could not verify proposer's costs.

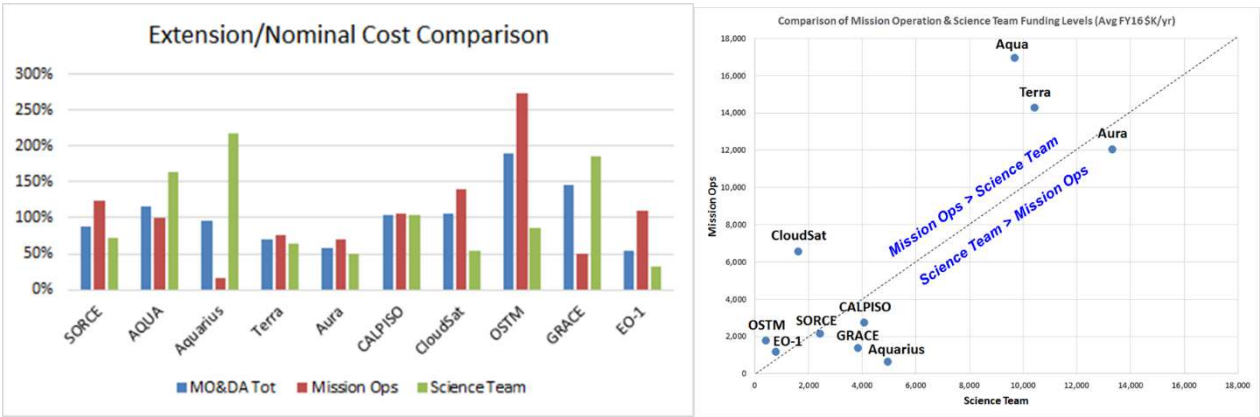
The overall risks, mitigation plans, and cost threats all contribute to the overall cost risk rating. Five categories were used and definitions for each are provided in Figure C-2. This cost risk rating is based on the proposed costs and plans during the period of performance.

As secondary rating, the cost evaluation then looked at project request and compared to the funding target as provided as part of the 2015 Senior Review call letter. This portion of assessment considered prior year, FY 2012 to FY2014, project's expenditures or cost accruals and compared it to the funding requested value as well as the available uncosted carryover. A green rating is given is the request is consistent with the funding target. In a couple of instances a "low with blue" were rated for on a couple of project, this rating means the project is requesting for more funding that it really needs. It will otherwise follow a similar rating shown above.

HIGH-LEVEL COMPARISONS

Comparisons of the proposed funding levels for combined MO&DA, mission operations, and the science team are summarized in Figure C-3. Most of the projects

Figure C-3



are near or below primary mission funding levels except OSTM and GRACE. OSTM increases are driven by the decommissioning of Jason-1, which shared many

services with OSTM. Efforts to reprocess data to support GRACE-FO is the primary driver for the GRACE increase. The plot on the right shows the ratio of science team funding to mission operations. Projects with higher mission operations costs (above the dashed line) may be trading science data product efforts to support mission operations to maintain science data collection (with some deferred science analysis).

SUMMARY COST RATINGS

The final cost risk ratings are shown in Figure C-4. Compliance with the budget target is also included noted. Details for each project are provided in the next section of this report.

Figure C-4

	Cost Risk Rating	Compliance w/ Budget Target	Note
Aqua	Low	**Yes**	Although there are risks associated with ESMO (IT security, debris, other), which can be covered with the available uncosted carryover, at least until the FY17 Senior Review process
Aura	Low	Yes	Although there are risks associated with ESMO (IT security, debris, other), which can be covered with the available uncosted carryover, at least until the FY17 Senior Review process
Terra	Medium-Low	Yes	ESMO risks (IT security, debris, other) and risk associated with waiver not approved
Aquarius	Low (Blue)	Yes	Reasonable cost plan and an in-guide request, but the project has a very high uncosted carryover (9 mons of work which has been agreed by HQ)
CALIPSO	Medium-Low	Yes	Driven by tight resources currently limiting data product schedule combined with potential cost growth associated with laser risk reduction efforts (current backup laser may be nonfunctional by 2017). The project's 5 month available carryover funds could be used to offset these risks.
SORCE	Low	No (FY18 and FY19)	Cost plan appears reasonable (except for an over-guide request in FY18/19 for at last 3 months overlap with TSIS); Most science data analysis handled with ROSES
GRACE	Medium-Low	Yes	Currently the project is very lean and any further degradation to the flight system performance may lead to additional funding need
OSTM	Medium-Low	Yes	Currently operating at "minimum acceptable staffing levels" with further staff reductions planned which could lead to operational risks
CloudSat	Low	Yes	Plans appear reasonable; Efficiencies from overlap with EarthCARE; All mission science data analysis are funded via ROSES
EO-1	Low (Blue)	Yes – without Lunar Lab No – with Lunar Lab included	Plans to operate in "Lunar Lab" mode cost at same levels as Earth viewing mode may be overly conservative. Note the project is asking for a lot more funding above its cost target and it will likely carrying ~ 5 months of uncosted into FY16. This assessment does not account for Lunar Lunar consistent the Science Panel recommendation, thus the Low/Blue rating.

INDIVIDUAL PROJECT COST ANALYSIS SUMMARIES

Summary details of the cost analyses for each project are included in this section, which comprises of

- Project-specific cost assessment summary.
- *Findings:* Includes significant items that may affect cost performance. These are based on details from the cost assessments covering various aspects of each proposal.
- *Evaluation Criteria Assessment*: Summarizes lower-level findings regarding selection criteria derived from the Call for Proposals.
- *Project Cost/Expenditure History and Request:* Shows funding and workforce by fiscal year for FY 2012 / 2013 through the proposed operating time. Data includes funding guidelines and uncosted carryover.
- *Cost Driver Assessment:* This analysis compares costs and technical drivers between funding levels for the primary mission and the extension. Costs comparisons include sizing of the mission operations team and science team.
- *In-Kind Support/Funding:* This area covers all significant contributions toward each project's Mission Operations (MO) & Science (DA) requirements.

Additional supporting details covering all cost analysis areas were provided to the panel and are covered in a separate presentation ("2015 Senior Review - Cost Analysis Final Assessment Rating (4.30.15).ppt").

Aqua

Aqua Summary: Aqua received a Cost Risk Rating of Low and was compliant with their budget target. The Aqua project has been performing well. The risks associated with ESMO may become more significant in the future, but appear to be within the project's ability to cover within its available funding before the next Senior Review.

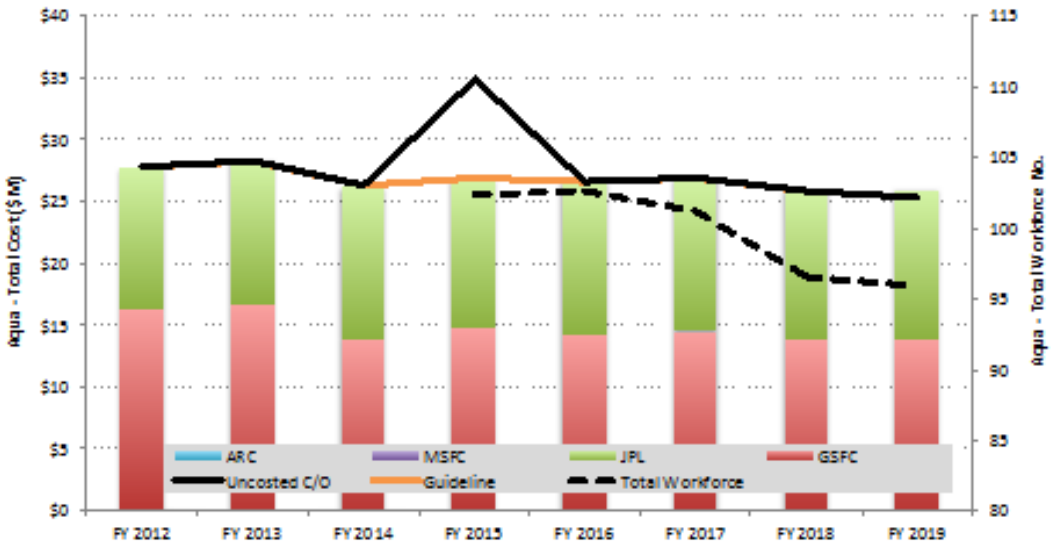
Aqua Findings:

- Request meets the mission planning, and it is within the targeted baseline budget
- Proposed cost and proposed workforce number are well correlated with each other
- Labor rate and JPL plan align well with other operating missions
- Other than CERES, there are no deviations from historical expenditures
- Instruments and other costs also appear reasonable
- Request and implementation plan appear reasonable, and align with similar/like (Terra and Aura) missions
- Recommend approval at the requested funding level, with a note that this mission relies heavily for "in-kind supports" (estimate at ~$10M/year). Also, it should also be noted that a better insight and understanding of ESMO funding requirements as well as its identified IT security, orbital debris and ground system upgrades/etc risks is needed for thorough cost assessment.

Aqua Evaluation Criteria Assessment:

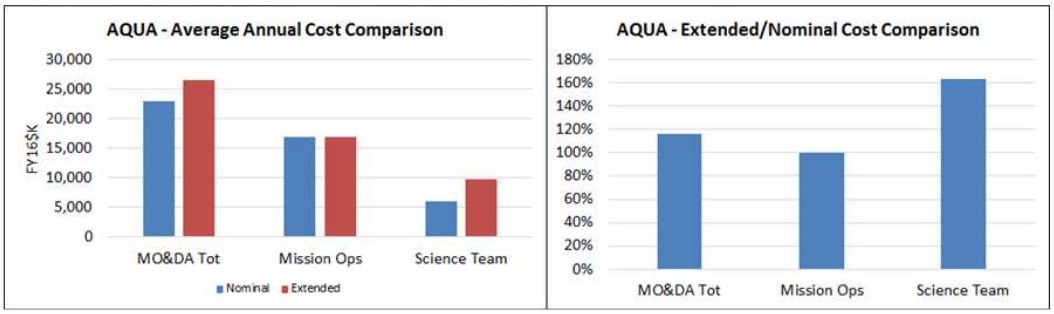
Likelihood of Accomplishing Proposed Task within Proposed Cost	**Low - Cost Risk**	Aligns within historical expenses, with available uncosted carryover that can be used to cover potential ESMO (IT Security, ground system, etc) risks
Meeting Target Baseline Budget	**Yes**	Compliance with ESD FY 2015 Senior Review call for Proposal
Demonstrated Cost Improvement Process	**Yes**	Implemented algorithm update and able to reduced AMSR-E FTE. MODIS peaked at 54 FTE/yr vs.
Trading Data Collection/Operations to save cost	**Possibly**	Ground system equipment is now beyond or near end-of-life and limited ground system staff
Request for Additional Scope	**No**	
Identification of Parallel Funding	**Yes**	ROSES and Terra, as well as many other funding sources
Reliance on External Source for Data/Resources	**Yes**	JAXA, Terra, ROSES an NISN (?)
In-Kind Support	**Yes**	CERES $5M/yr, ESDIS support, EOS project science ($283K), and JAXA for AMSR-E and RSS instrument ops/etc. Terra MODIS science team.

Aqua Cost History and Request:



Aqua Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Improvements to Backup EOS Ops Center (BEOC) ➢ Modernization of EOS Data & Ops System (EDOS) ➢ FDS/CCS enhancements	➢ Portion of CERES covered in a separate budget (covering CERES on other s/c) ➢ Budget sharing between Aqua, Terra, and Aura	➢ Loss of some solar array strings ➢ 4 of 6 instruments operating normally



Aqua In-Kind Support/Funding Summary:

- AMSR-E from JAXA
- MODIS 55 PI funded via ROSES
- MODIS – Terra 16.7 FTE, SDT and Science Team leader
- $285K for EOS project science office thru ESD Science Office
- $5M for CERES thru WBS 652528
- AIRS – algorithm refinement provided by investigator funded thru ROSES or other NASA/non-NASA funds.
- AIRS Science team member funded thru ROSES to do PGS

<u>Aura</u>

Aura Summary: Aura received a Cost Risk Rating of Low and was compliant with their budget target. The Aura project has been performing well. The risks associated with ESMO may become more significant in the future, but appear to be within the project's ability to cover within its available funding before the next Senior Review.

Aura Findings:

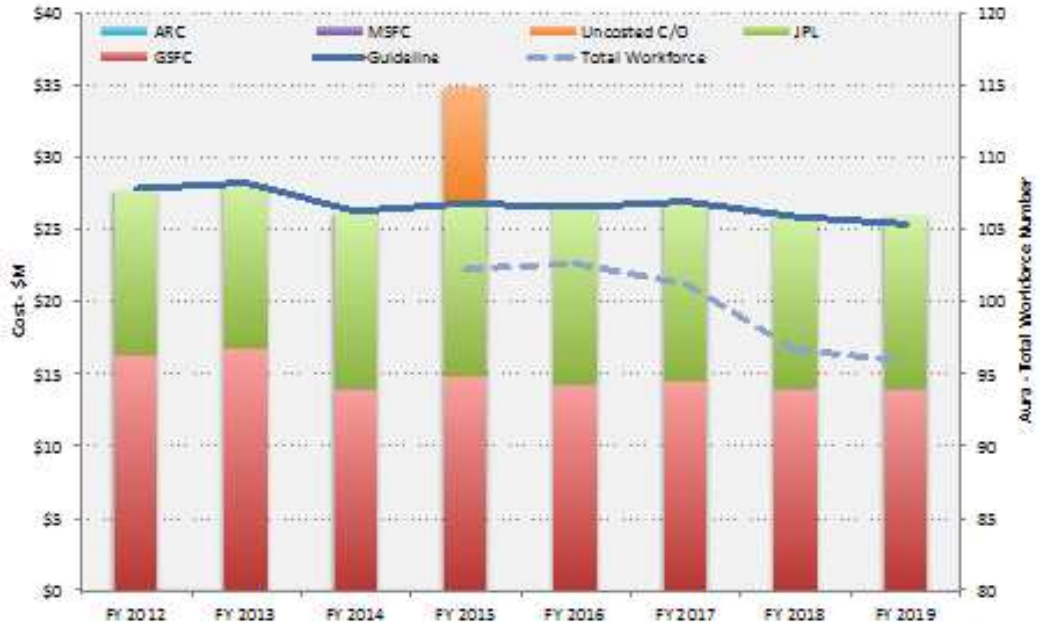
- Request meets the mission planning, and it is within its targeted budget
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Travel cost is within the norm
- FTE labor rate is higher than Aura and Terra as well as the GSFC FY 2016 composited labor rate
- While the TES effort deviates from its historical plan, but the proposal appears acceptable and aligns with the narrative plan. There are no real changes to the MLS and OMI efforts.
- Request appears reasonable, consistent with historical expenditure and about the same funding level as similar/like operating missions, Terra and Aqua
- Recommend approval at the requested funding level, but need to have an insight and understanding of ESMO funding requirements as well as its identified IT

security, orbital debris and ground system upgrades/etc risks for a thorough cost assessment

Aura Evaluation Criteria Assessment:

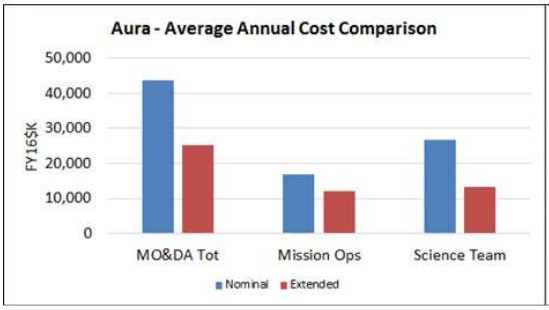
Likelihood of Accomplishing Proposed Task within Proposed Cost	Low Risk	Aligns within historical expenses, with available uncosted carryover that can be used to cover potential ESMO (IT Security, ground system, etc) risks.
Meeting Target Baseline Budget	Yes	Complies with In-guide/budget target
Demonstrated Cost Improvement Process	No	
Trading Data Collection/Operations to save cost	Yes	Trades were to buttress staffing for MO in MLS activities
Request for Additional Scope	No	
Identification of Parallel Funding	Yes	ROSES and SIP
Reliance on External Source for Data/Resources	Yes	KNMI and FMI for OMI instruments
In-Kind Support	Yes	ROSES, KNMI and FMI for OMI instrument, SIP for MLS and TES

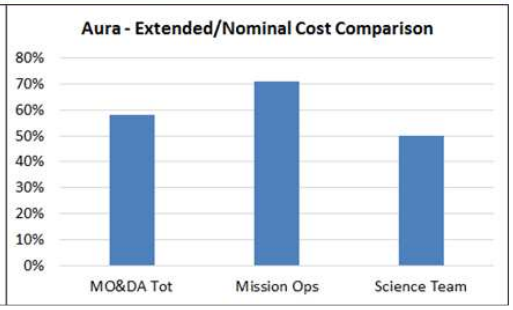
Aura Cost History and Request:



Aura Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Improvements to Backup EOS Ops Center (BEOC) ➢ Modernization of EOS Data & Ops System (EDOS) ➢ New/improved data products	➢ Budget sharing between Aqua, Terra, and Aura ➢ HIRDLS science data collection finished	➢ All instruments except 1 (HIRDLS) operating well ➢ Loss of some solar array strings ➢ FMU/SSR anomalies





Aura In-Kind Support/Funding Summary:

- OMI and TES SIPS for processing all US OMI and KNMI data products
- ROSES funding for all US developed products except TOMS heritage products
- OMI flight operations, L1B algorithm maintenance, monitoring is being provided by KNMI an FMI

Terra

Terra Summary: Terra received a Cost Risk Rating of Medium-Low and was compliant with their budget target. The Terra project has been performing well. The risks associated with ESMO may become more significant in the future, but appear to be within the project's ability to cover within its available funding before the next Senior Review. The need for a waiver to maintain the current orbit is the main contributor to the cost risk rating, and although approval of a waiver is expected, significant effort would be required to adapt to a different orbit.

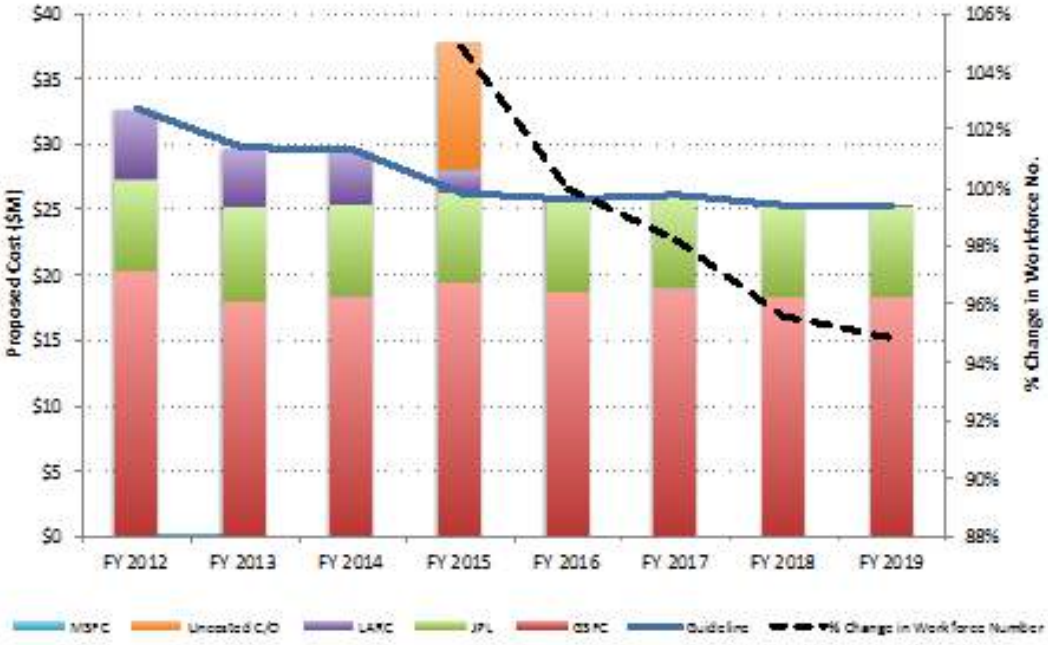
Terra Findings:

- Request meets the mission planning, and it is within the targeted baseline budget
- Proposed cost and workforce number correlate pretty well with each other as well as to other operating missions
- Labor rates are reasonable and align with other operating missions as well as GSFC composite labor rate for FY 2016
- Travel expense is within the 1% norm for extended operating missions
- In addition to CERES, there are some other minor deviations from historical expenditures, but they acceptable and align with the narrative plan
- Pending a better insight and understanding to the ESMO funding need as well as its identified IT security, orbital debris, ground system upgrades/etc risks, and a decision associated with an orbit waiver, the request appears reasonable as it aligns with similar/like (Aqua and Aura) missions as well as historical expenditures.

Terra Evaluation Criteria Assessment:

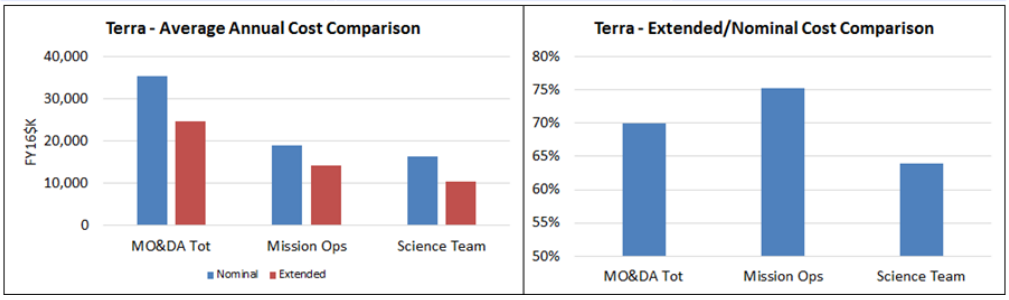
Likelihood of Accomplishing Proposed Task within Proposed Cost	Medium-Low	Aligns within historical expenses, with uncosted to cover potential cost risk items. However, the ESMO (IT Security, ESMO (IT security, debris, other) and orbit waiver risks may exceed the project's available funding.
Meeting Target Baseline Budget	Yes	Complies with In-guide/budget target
Demonstrated Cost Improvement Process	Yes	Continual improvements resulted in cost savings and more efficient operations. Total budget went from $82M in 2006 to $30M in FY 2011
Trading Data Collection/Operations to save cost	Yes	Will reduced MISR algorithm refinement and effort for "matured" areas in FY18 and FY19
Request for Additional Scope	No	
Identification of Parallel Funding	Yes	ROSES and Aqua for MODIS and CERES
Reliance on External Source for Data/Resources	Yes	JAXA for ASTER, Canadian for MOPITT
In-Kind Support	Yes	LP DAAC for ASTER, MODAPS, LANCE and ODPs for MODIS, NCAR SIP for MOPITT, and LaRC DAAC for CERES and MISR

Terra Cost History and Request:



Terra Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Improvements to Backup EOS Ops Center (BEOC) ➢ Modernization of EOS Data & Ops System (EDOS)	➢ Budget sharing between Aqua, Terra, and Aura ➢ EOS FOT automation & process improvements	➢ Fully functioning instruments except ASTER SWIR band ➢ PWA issues with SSR



Terra In-Kind Support/Funding Summary:

- Processing at SIPS and DAACs - part of ES Data System Program's Multi-Mission Operations
    - LP DAAC for ASTRE
    - MODAPSLANCE, and ODPS for MODIS
    - LaRC Atmospheric Science Center DAAC for CERES and MISR
    - NCAR SIP for MOPITT
- CERES DA > $5M
- Cost sharing between Aqua and Terra for MODIS and CERES processing facilities

Aquarius

Aquarius Summary: Aquarius received a Cost Risk Rating of Low (Blue) and was compliant with their budget target. The project is performing well. The current carryover level is equivalent to 9 work months, which seems overly conservative as well as excessive, thus the reason behind the Low (Blue) rating.

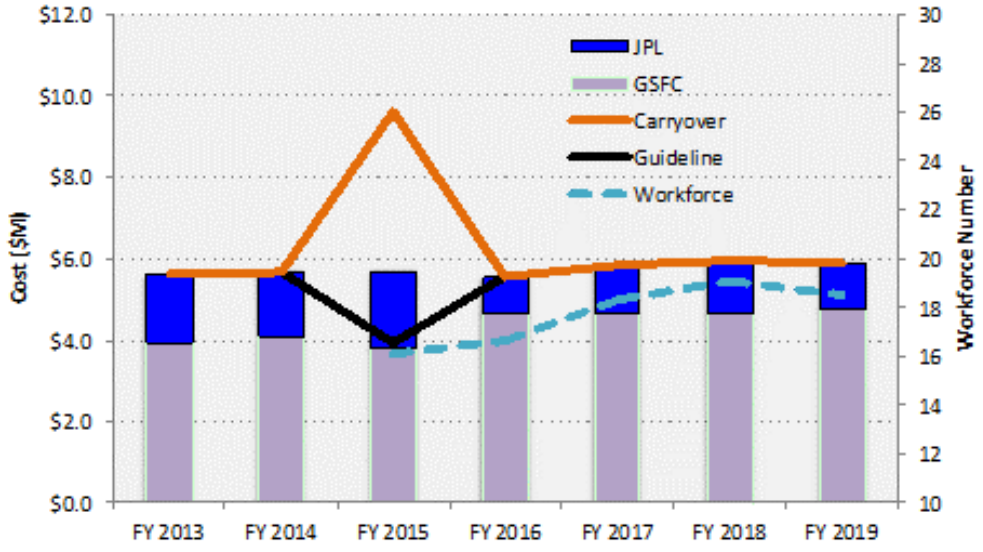
Aquarius Findings:

- Request meets the mission planning and it is within the targeted baseline budget
- Proposed cost estimate and workforce number are well correlated to each other as well as to other similar operating missions
- Although travel cost (6%) is higher than the 1% extended missions norm, but not way outside the norm
- Labor rates are consistent with other operating missions as well as GSFC composited/overall labor rate
- There are no real changes to the project's historical expenditure
- There are changes for the extended missions, now includes "producing a new salinity product with data from SMAP"
- Request appears somewhat aggressive, asking for too much funding than it needs, given the project's high uncosted carryover and the project's current and prior year monthly burn-rate

Aquarius Evaluation Criteria Assessment:

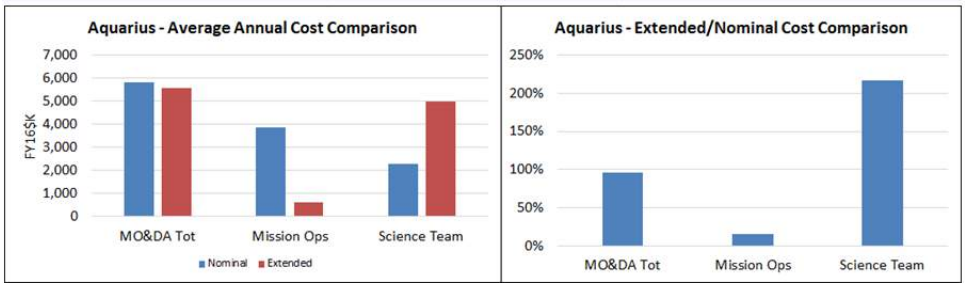
Likelihood of Accomplishing Proposed Task within Proposed Cost	Low Risk	Aligns within historical expenses, but carries a very high uncosted carryover that could be used to offset project current/future expenditures
Meeting Target Baseline Budget	Yes	Complies with In-guide/budget target
Demonstrated Cost Improvement Process	Yes	Proposes a reduced mission operations budget, by 24% from FY16 to FY17. The saving goes to science.
Trading Data Collection/Operations to save cost	No	Not discussed, no trend or info provided, and it is the opposite, where msn ops is reduced while science budget goes up
Request for Additional Scope	Yes	Producing a new salinity product data using SMAP data
Identification of Parallel Funding	Yes	ROSES for "traditional research" and adapting algorithm to SMAP observation
Reliance on External Source for Data/Resources	Yes	CONAE for mission ops and ground system
In-Kind Support	Yes	NISN, NASA Ground Network and receiving station, and CARA

Aquarius Cost History and Request:



Aquarius Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Capability to contribute to ocean dynamics knowledge ➢ Improvements for science data products ➢ Joint activities with SMAP and SMOS	➢ Joint activities with SMAP and SMOS ➢ CONAE-provided ground segment	➢ S/C subsystems are in good health ➢ Memory issue on s/c C&DH A-side ➢ MWR and TDP instruments no longer operating



Aquarius In-Kind Support/Funding Summary:

- NISN - network support GSFC/WFF/CONAE
- NASA Ground Network and receiving station
- CARA for space debris analysis
- ROSES
- CONAE

CALIPSO

CALIPSO Summary: CALIPSO received a Cost Risk Rating of Medium-Low and was compliant with their budget target. Resources are currently tight and driving schedules for data products. An additional risk exists regarding the laser risk reduction efforts may lead to addition work and costs, thus the reason behind the Medium-Low risk rating.

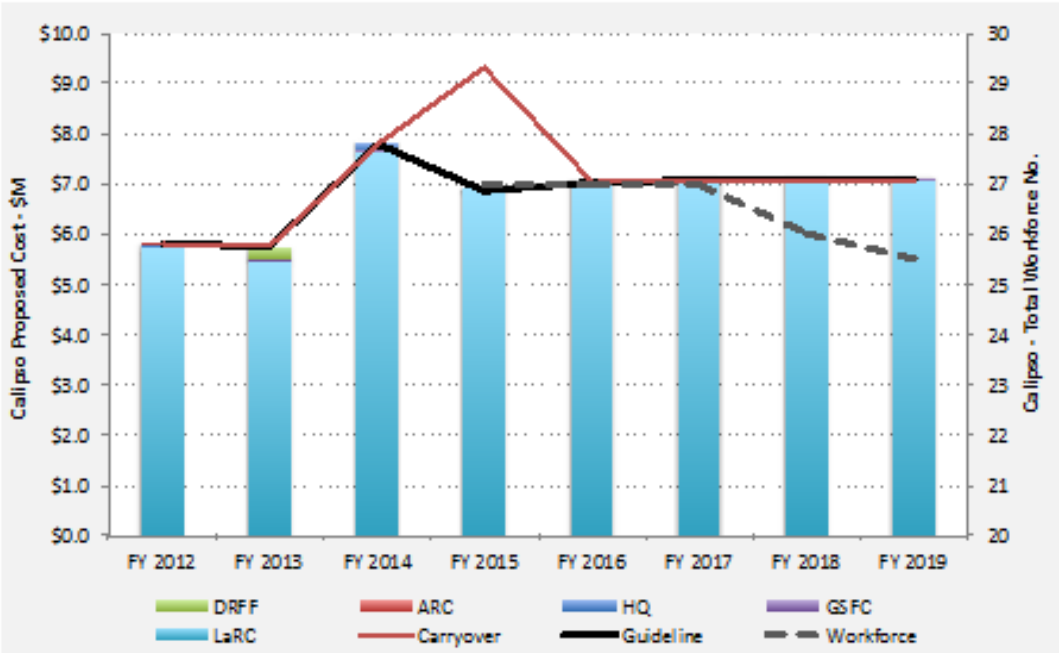
CALIPSO Findings:

- FY 2016 and FY 2017 cost proposed reflected decreasing pressure with Level 1 and threat of corona discharges at low pressure
- FY 2018 and FY 2019 estimates are placeholders pending mission longevity resulting from pressure leak rate
- The laser testing may have contributed to inconsistencies in historical expenditures, which makes it hard to judge the project's FY 2016 and FY 2017 basis of estimate. However, the proposed cost, workforce estimate, labor rate, and travel cost estimate appear to be comparable to other operating missions. Pending clarification on cost drivers associated with historical expenditures, and using comparative assessment to other operating missions, the project FY 2016 and FY 2017 estimates appear reasonable and comparable to its primary mission cost.

CALIPSO Evaluation Criteria Assessment:

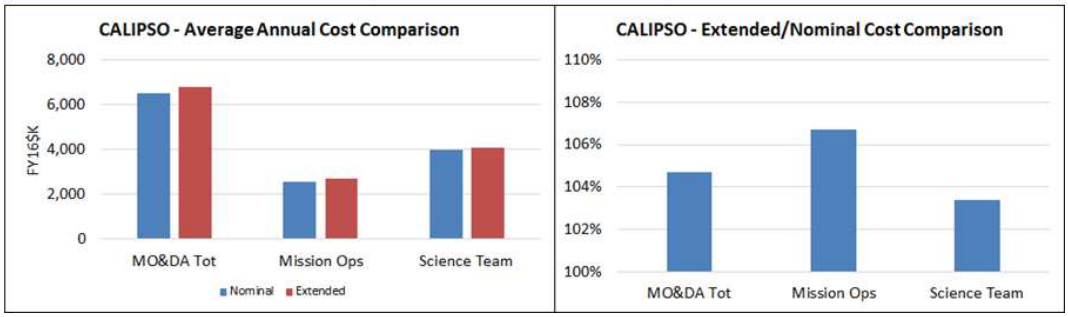
Likelihood of Accomplishing Proposed Task within Proposed Cost	Medium-Low Risk	Could not be validated against the historical (FY12, FY13 and FY14) expenditures given the pressure vessel vacuum test effort
Meeting Target Baseline Budget	Yes	Complies with In-guide budget target
Demonstrated Cost Improvement Process	Yes	Through MOCC automated and "light out" to minimize ops costs
Trading Data Collection/Operations to save cost	Yes	Already "optimized and stream lined"
Request for Additional Scope	No	
Identification of Parallel Funding	Yes	ROSES for MODIS data and aerosol product and validation supt
Reliance on External Source for Data/ Resources	Yes	CNES for IIR algorithm maintenance and instrument calibration
In-Kind Support	Yes	CNES CAESAR, NASA CARA, NOAA, and GSFC GMAO

CALIPSO Cost History and Request:



CALIPSO Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Data product improvements	➢ None identified	➢ Primary lidar laser failure (backup laser has limited life) ➢ Propulsion lien for orbit avoidance maneuvers ➢ S/C systems operating well



CALIPSO In-Kind Support/Funding Summary:

- CNES S/C & mission operations

<u>SORCE</u>

SORCE Summary: SORCE received a Cost Risk Rating of Low but was not compliant with their budget target. An over-guide funding requests for FY 2018 and FY 2019 are driven by the objective to provide at least 3 months overlap with TSIS.

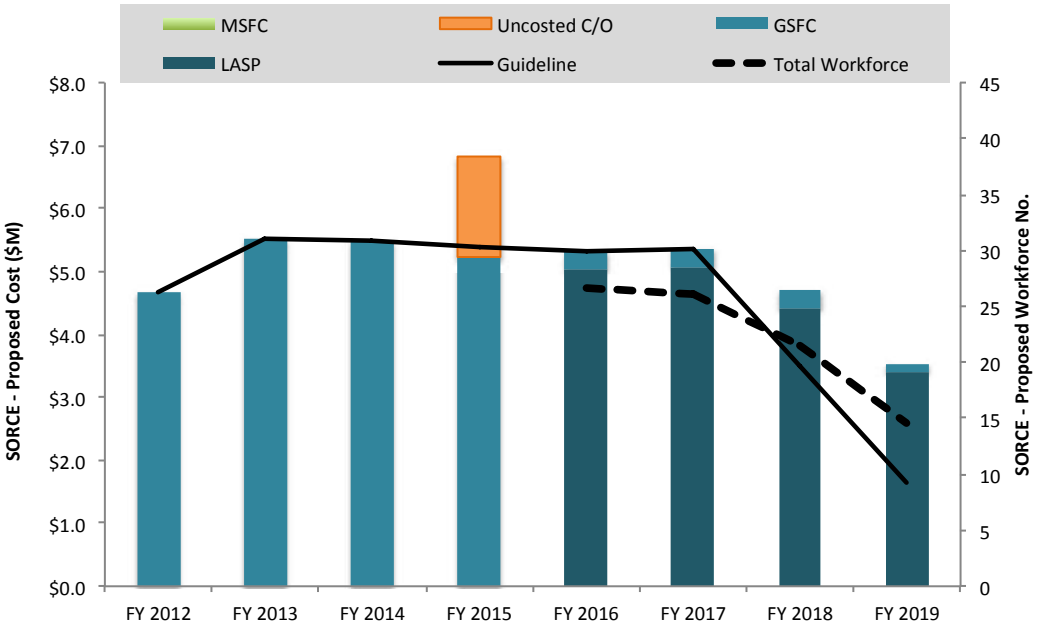
SORCE Findings:

- Proposal includes deletion of the NRL, GSFC and LASP science supports
- Using funding target identified in the 12/2/14 call letter, the project is requesting additional funding to sustain activity as well as allowing the project to assumes normal operations through the first 9 months of FY 2018 and Phase F in FY 2019
- Uncosted carryover value seems reasonable and inline with the NASA cost matrix
- Cost and labor are well correlated to each other as well as to other similar mission, showing the project moving forward with Phase F in FY 2019
- While travel cost is above the 1% norm for operating missions, but appears reasonable
- Labor rates are lower than other operating missions, but align with the NASA civil servant GSFC composite/overall labor rate as well as LASP
- Request appears reasonable, recommend approval at the requested funding level

SORCE Evaluation Criteria Assessment:

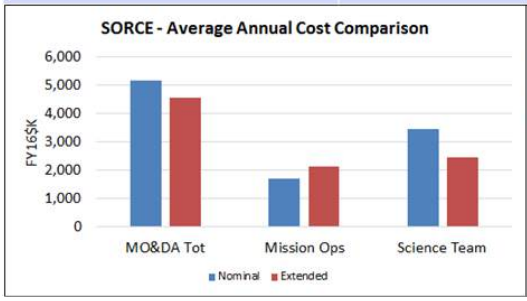
Likelihood of Accomplishing Proposed Task within Proposed Cost	Low Risk	Aligns within historical expenses, with uncosted to cover potential technical/cost risk items
Meeting Target Baseline Budget	No	The project is requesting for additional fundings in FY 18 and FY 19
Demonstrated Cost Improvement Process	No	
Trading Data Collection/Operations to save cost	No	Did not discuss or demonstrate trading operations for data collections/science
Request for Additional Scope		
Identification of Parallel Funding	Yes	ROSES and SIP
Reliance on External Source for Data/Resources	Yes	
In-Kind Support	Yes	

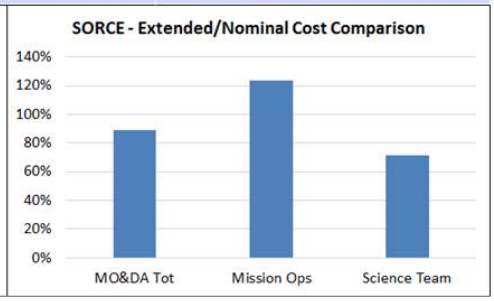
SORCE Cost History and Request:



SORCE Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Added Day-Only Op mode (deployed in Feb 2014) ➢ Data product improvements ➢ Component degradation	➢ Mature data algorithms ➢ Emphasis on supporting daily ops (with deferred data product generation)	➢ Battery degradation ➢ Loss of 1 of 4 RWs ➢ Loss of 1 of 2 star trackers ➢ All instruments are functioning well





SORCE In-Kind Support/Funding Summary:

- ROSES

GRACE

GRACE Summary: GRACE received a Cost Risk Rating of Medium-Low and was compliant with their budget target. The GRACE team is fairly lean and flight system performance appears to be degrading. Given that 91% of the requested funds are to be used for labor costs, it does not appear the project has any reserve to mitigate or cover potential anomalies, thus the reason behind the Medium-Low risk rating.

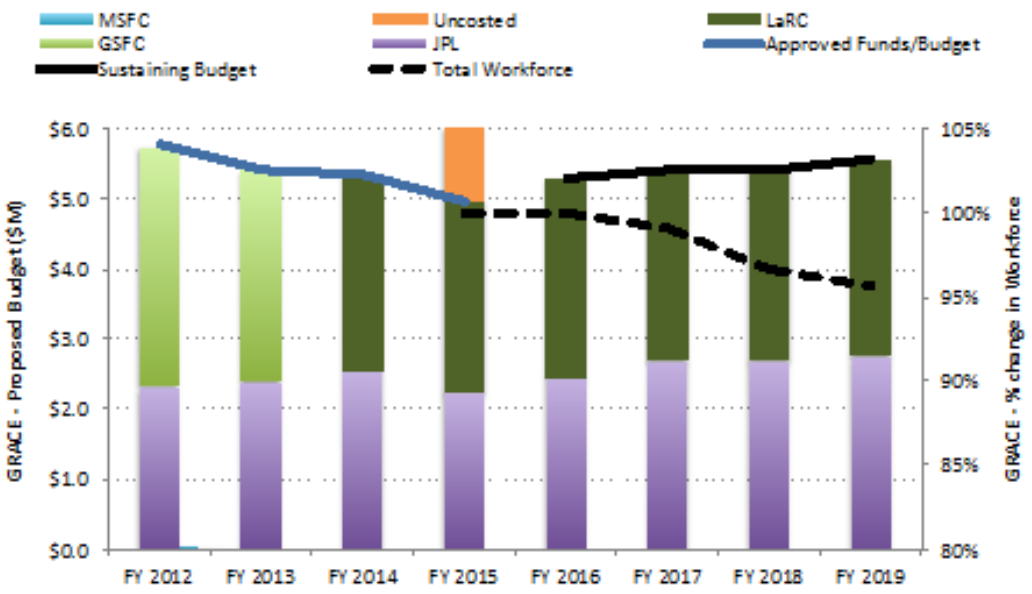
GRACE Findings:

- Uncosted carryover value is inline with the NASA matrix
- Proposed cost and workforce numbers are well correlated to each other, and are comparable to other operating missions
- The 3% travel cost is within the norm of operating mission travel expenses
- Labor rates are reasonable, and comparable to other operating missions
- Although the request appears reasonable and reflects an effective utilization of NASA funds, but it appears to be very tight.

GRACE Evaluation Criteria Assessment:

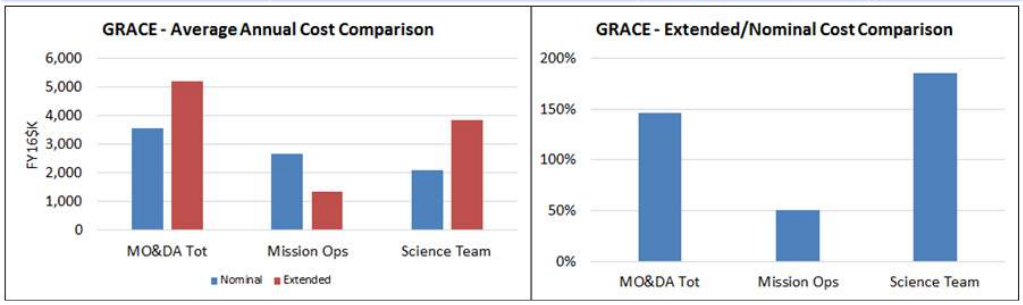
Likelihood of Accomplishing Proposed Task within Proposed Cost	Medium-Low Risk	Proposal is consistent with historical expenditures, but may not have funds to cover anomalies and/or potential mishaps
Meeting Target Baseline Budget	Yes	Proposed budget meets the provided Sustaining budget
Demonstrated Cost Improvement Process	No	Assumes no further improvements to either the flight system or the software to produce Level-1 science data
Trading Data Collection/Operations to save cost	Yes	Battery degradation issues in 2010 led to a decision to focus mission operations on life extending operations, which reduced the annual data collected to ~75%, but extended the mission life
Request for Additional Scope	Yes	The RL06 Model Solution to be initiated in FY16 and FY17
Identification of Parallel Funding	Yes	GRACE Science Team will be selected as an element in the ROSES-2015
Reliance on External Source for Data/ Resources	Yes	DLR provides funding for the flight operations at GSOC and GFZ provides funding for the Co-PI and Deputy with ESA to provide support of mission operations
In-Kind Support	Yes	GSOC - multi mission infrastructure at GSFC and MSFC, CARA for conjunction assessment, DRL provide basic ground system

GRACE Cost History and Request:



GRACE Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Data reprocessing planned in FY17 to provide compatibility with GRACE-FO	➢ ESA added to the NASA/DLR mission ops effort ➢ Power system issues reduce duty cycle for science data collection	➢ Battery degradation limits power available ➢ Atomic oxygen impacts ➢ Loss of redundancy (Xmtr, IPU, star camera, USO, others)



GRACE In-Kind Support/Funding Summary:

- GRACE Science Team will be selected as an element in the ROSES-2015
- NASA/DLR MOU, DLR provides funding for the flight operations at GSOC and GFZ provides funding for the Co-PI and Deputy Operations Mission Manager. The current MOU extends this collaboration for the life of the GRACE Mission.
- DLR provides funding for the flight operations at GSOC and GFZ provides funding for the Co-PI and Deputy, with ESA to provide support of mission operations

OSTM

OSTM Summary: OSTM received a Cost Risk Rating of Medium-Low and was compliant with their budget target. The OSTM project has been operating with minimum acceptable staffing levels and has additional staff reductions planned that has the potential to lead to operational risks. Given that 92% of the requested funds are to be used for labor costs, it does not appear the project has any reserve to mitigate or cover potential anomalies, thus the reason behind the Medium-Low Cost Risk rating.

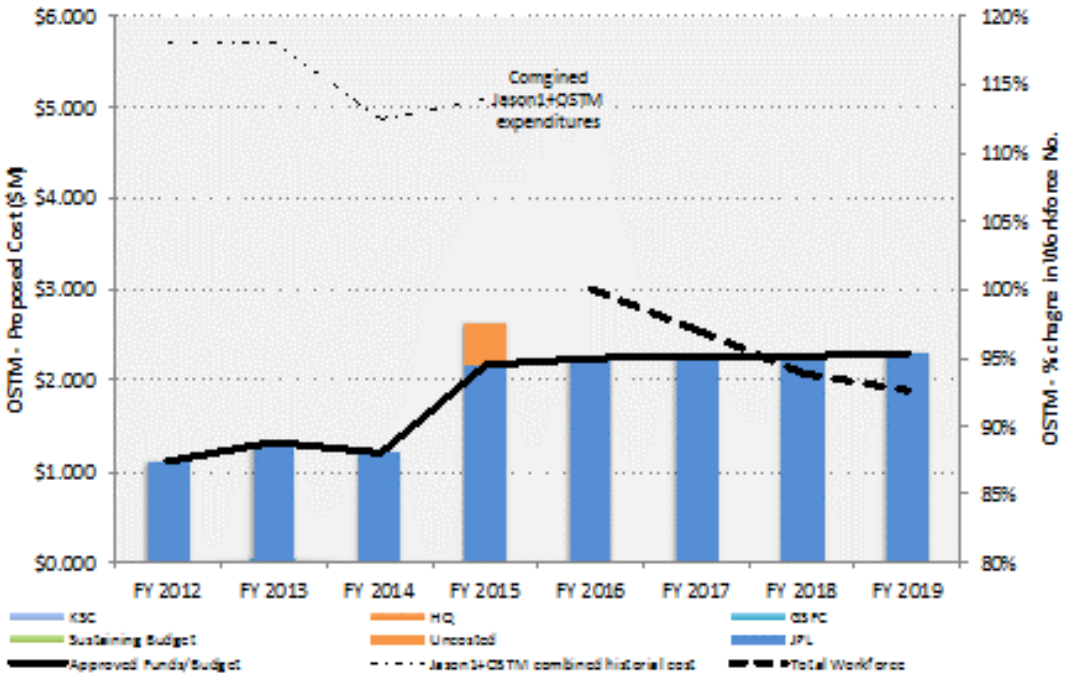
OSTM Findings:

- Uncosted carryover value is inline with the NASA matrix, which showed an effective usage of NASA funding
- Proposed cost and workforce estimates are consistent with the added scopes and plan forward
- The 3% travel cost is within the norm of operating mission travel expenses
- Although the labor rates for science is much higher than all other JPL operating missions, ~13% higher, but it appears reasonable as it indicates an effective utilization of NASA funds by possibly employing highly skill staff.

OSTM Evaluation Criteria Assessment:

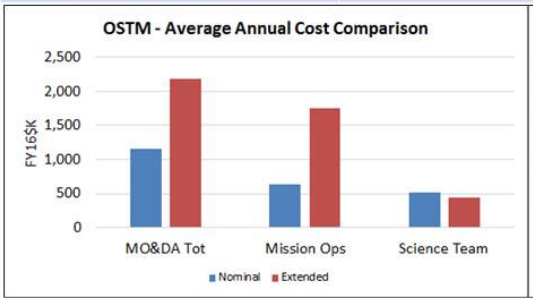
Likelihood of Accomplishing Proposed Task within Proposed Cost	Medium-Low Risk	Proposal is reasonable as it incorporates tasks that were previously shared/ leverage with the decommissioned Jason-1 mission, and the cost estimate appears to captured the Jason-1 as well as OSTM historical expenditures but does not appear to show any flexibility available to handle any anomalies that may come along
Meeting Target Baseline Budget	Yes	Proposed cost meets the targeted baseline budget
Demonstrated Cost Improvement Process	Yes	Currently operating at a low staffing level
Trading Data Collection/Operations to save cost	No	Not mentioned in the budget section, but do not believe this is viable given OSTM targeted and proposed budget and staffing level
Request for Additional Scope	Yes	Incorporated task that were leverage with Jason-1, cross-calibration with Jason-3, and increasing spatial and temporal resolution of altimetry measurements in 2016 after it has been maneuvered into the interfaced 5-day repeat orbit
Identification of Parallel Funding	Yes	ROSES and several agencies funding for the Ocean Surface Topography Science Team (OSTST) and Guest Investigators
Reliance on External Source for Data/ Resources	Yes	ROSES for science investigation and core science data product algorithm support
In-Kind Support	Yes	NOAA, CNES, EURMETSAT, ROSES

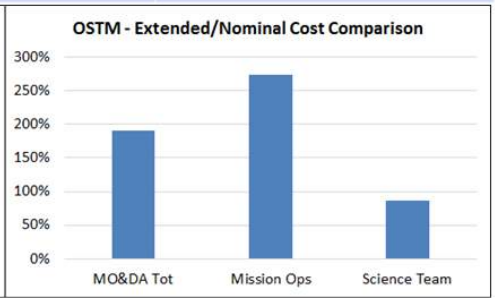
OSTM Cost History and Request:



OSTM Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Labor rate increases for mission ops org (JPL) ➢ Decommissioned Jason-1 (in July 2013) affects OSTM due to sharing	➢ None identified	➢ DHU A-side anomalies ➢ All 5 instruments operating well





OSTM In-Kind Support/Funding Summary:

- OSTM is a collaborative mission conducted by four agencies: NASA, CNES, NOAA, and EUMETSAT.

CloudSat

CloudSat Summary: CloudSat received a Cost Risk Rating of Low and was compliant with their budget target. The CloudSat project has been performing well. Some operating efficiencies are being realized from overlaps with EarthCARE. All mission science data analysis is funded through ROSES.

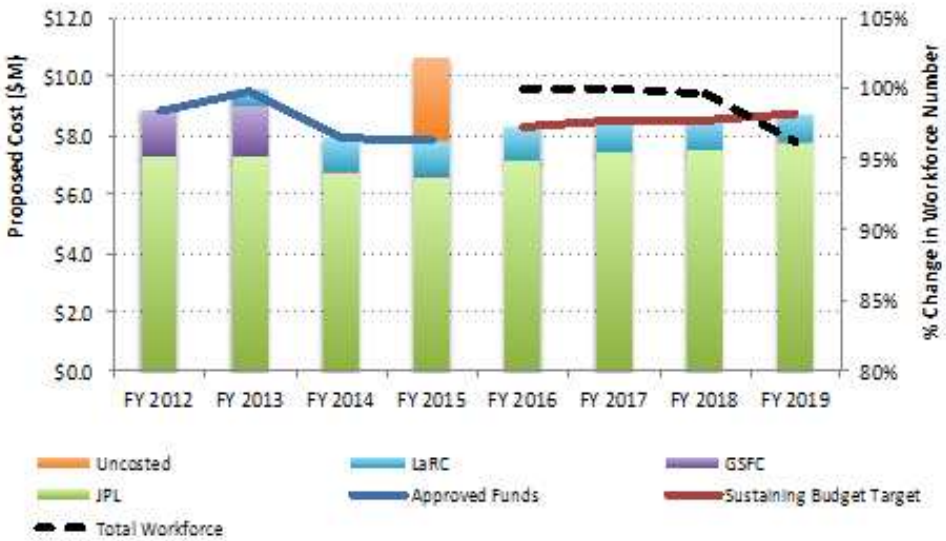
CloudSat Findings:

- Proposed funding request is consistent with FY 2014 and projection for FY 2015 expenditures
- The 3% travel cost is within the norm of operating mission travel expenses
- Labor rates for offsite science calibration and algorithm activities assumed university and/or post doc, thus it is much lower than other missions. All other labor rates (JPL science activities and mission operations) are comparable to other operating missions' rate
- Workforce estimate is comparable to other operating missions of comparable budget size and effort
- Request appears very reasonable, it showed a very effective utilization workforce, recommend approval at the requested funding level

CloudSat Evaluation Criteria Assessment:

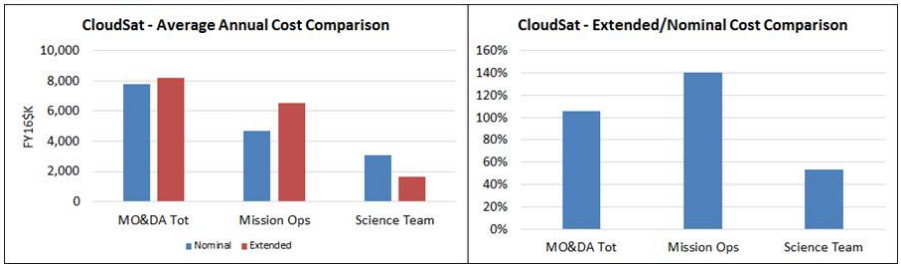
Likelihood of Accomplishing Proposed Task within Proposed Cost	Low Cost Risk	Proposal is reasonable, proposal assumed some utilization of university and postdoc for science activities
Meeting Target Baseline Budget	Yes	Proposed cost meets the targeted sustaining baseline budget
Demonstrated Cost Improvement Process	No	
Trading Data Collection/Operations to save cost	Yes	Cloud data collection at ~56% of each orbit due to Daylight-Only Operations (DO-OP) mode
Request for Additional Scope	No	
Identification of Parallel Funding	Yes	ROSES for science team research
Reliance on External Source for Data/Resources	Yes	International and interagency science team members
In-Kind Support	No	None, project is fully responsible for operations, ground system, data processing, distribution and archiving algorithm development and maintenance, validation and s/c and p/l engineering support

CloudSat Cost History and Request:



CloudSat Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ Added Day-Only Op mode (April 2011) transitions s/c from 3-axis to spinner during eclipses ➢ New data products (w/ GPM)	➢ Reliance on science data research funded by ROSES (outside CloudSat project)	➢ Battery degradation



CloudSat In-Kind Support/Funding Summary:

- There is no "in-kind" support from NASA-funded sources

<u>EO-1</u>

EO-1 Summary: EO-1 received a Cost Risk Rating of Low (Blue). EO-1 is compliant with their budget target without operating in the "Lunar Lab" mode, but would need additional funding if "Lunar Mode" is used. The cost rating is consistent with the Science Panel finding, where Lunar Lab effort is not included as part of the EO-1 project baseline task, thus the reason behind the Low (Blue) cost risk rating.

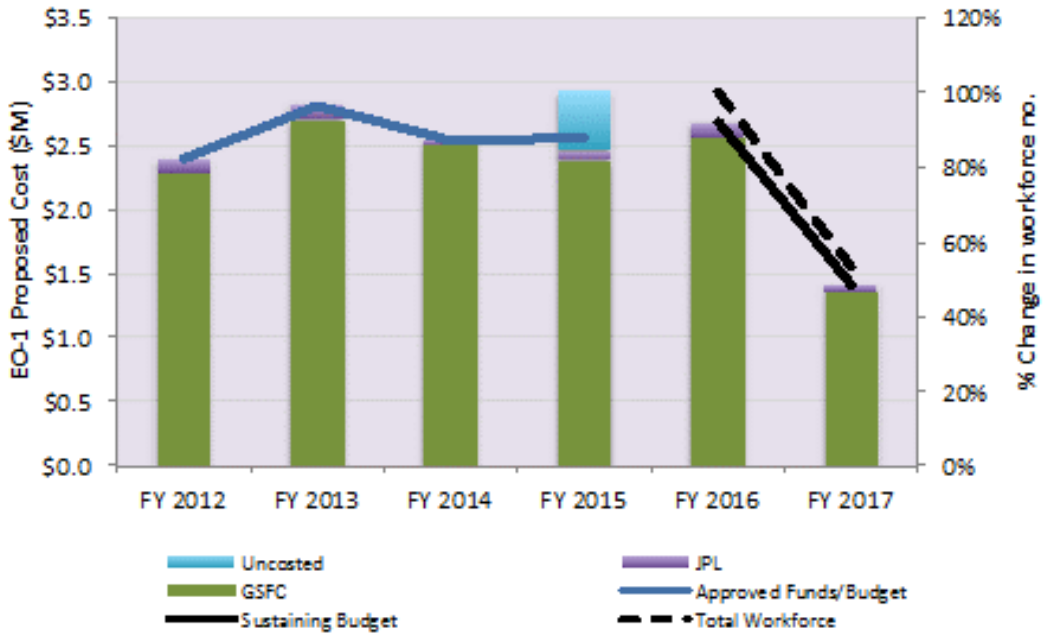
EO-1 Findings:

- Uncosted carryover value is inline with the NASA matrix, which showed an effective usage of NASA funding
- The 2% travel cost is within the norm of operating mission travel expenses
- EO-1 labor rates is within the GSFC composited labor rate, the contractor rate is about the same as other operating missions labor rate
- The proposed tasks do not line up with the cost estimate, and it is unclear why this is the case and/or the rationale behind it. However, the project is asking for a lot more funding in its April 30, 2015 presentation to the Science Panel, which was not part of its written proposal.
- While funding request for a full year operation during FY 2016 appears reasonable, and consistent with historical expenditures, the proposed outyear funding needs further definition and/or examination

EO-1 Evaluation Criteria Assessment:

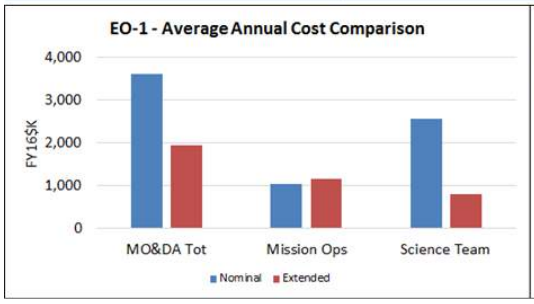
Likelihood of Accomplishing Proposed Task within Proposed Cost	Low (Blue)	Proposal is reasonable, it is consistent with historical expenditure. However, it is unclear that the proposed task align with the proposed cost The "low" rating does not consider the Lunar Lab effort consistent with the Science Panel Recommendation.
Meeting Target Baseline Budget	Yes - without Lunar Lab; No with Lunar Lab included	Proposal is consistent with the provided sustained budget and funding profile.
Demonstrated Cost Improvement Process	No	
Trading Data Collection/Operations to save cost	No	
Request for Additional Scope	Yes	Added dedicated Lunar Labor in 10/1/2016, but unclear the length/time period of the lab
Identification of Parallel Funding	No	
Reliance on External Source for Data/Resources	Yes	Working with NOAA to develop an advanced version of the current lunar-based calibration model
In-Kind Support	Yes	NOAA/LDCM

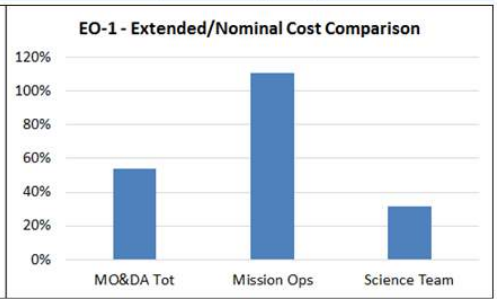
EO-1 Cost History and Request:



EO-1 Cost Driver Assessment:

Contributors to Higher Cost vs Nominal	Contributors to Lower Cost vs Nominal	Factors potentially affecting MO&DA success
➢ General increase in FOT costs	➢ None identified	➢ Orbit degradation ➢ Battery degradation





EO-1 In-Kind Support/Funding Summary:

- There is no "in-kind" support from NASA-funded sources

APPENDIX 4. DETAILED SCIENCE PANEL MISSION REVIEWS

AQUA

Conclusion: Continuation of projects as currently baselined

Aqua is one of NASA's Flag Ship Missions for Earth Science operating in the A-Train constellation. Thousands of scientists and operational users from around the world are making use of the Aqua data to address NASA's six interdisciplinary Earth science focus areas: Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and Earth Surface and Interior. The Aqua spacecraft is still going strong after 13 years, and four of its instruments (AIRS, AMSU, CERES), and the MODIS continue to collect valuable data about the atmosphere, oceans, land, and ice. The panel ranked this mission as first among those missions reviewed based upon the scientific merit, the relevance to NASA science goals, and utilization by scientist in their related research. Based upon Aqua's high quality climate data records, the continuity of this time series is critical for the scientific community, governmental agencies and the international operational user community.

Scientific merits : Excellent

<u>Major Strengths</u>

Thousands of scientists and others from around the world are making use of the Aqua data to address a wide range of scientific questions and practical applications. In each of the past 2 years, hundreds of science publications have incorporated Aqua data and thousands of citations have been made to Aqua publications, grouping these into NASA's six interdisciplinary Earth science focus areas: Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and Earth Surface and Interior.
A few of the science highlights from the past two years include:

- AIRS: quantification of marked decreases in Northern Hemisphere atmospheric carbon monoxide and an increase of 0.72 ppb/year in global mid-tropospheric nitrous oxide.
- AMSR-E precipitation data: discovery of a marked 20-30-day periodicity in the Southern Hemisphere atmospheric general circulation.
- CERES radiative fluxes: identification of shortcomings in the representation of cloud radiative effects in a major climate model.
- MODIS: mapping of extremely large interannual variability in melt over the Greenland ice sheet.

Also, there were several new and important scientific results obtained through the complementary use of data from two or more Aqua instruments that include:

- quantification of seasonal drawdown of atmospheric carbon dioxide (CO_2) by

boreal forests, resolved using AIRS CO_2 and MODIS gross primary productivity (GPP) data.

- quantification of the increase in moisture flux to the atmosphere in response to the decrease in Arctic sea ice coverage, from AMSR-E and AIRS data
- examination of the structure of the marine boundary layer in the northeast Pacific, from AIRS and MODIS data.
- assessment of the impact of aerosol layers on southeast Atlantic stratocumulus cloud microphysics, from a combination of CERES, MODIS, and AMSR-E data, along with data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

Further, Aqua mission data continue to be highly relevant and in daily use for a large variety of practical applications that include:

- U.S. National Oceanic and Atmospheric Administration (NOAA) and others for weather forecasting
- U.S. Forest Service for monitoring forest fires and appropriate deployment of fire fighters
- U.S. Department of Agriculture (USDA) for monitoring crop yields and drought
- Environmental Protection Agency (EPA) for air-quality analyses
- Federal Aviation Administration (FAA) for monitoring volcanic ash
- U.S. Coast Guard and the NOAA Coastwatch program for sea ice monitoring
- Department of Defense (DoD) for support of military operations

Minor Weaknesses

A former weakness for this mission was the termination of AMSR-E science measurements because of the loss of the antenna rotation capability in 2011. However, from a scientific merit perspective, the archived AMSR-E data set has high scientific value, and this weakness is remedied by utilizing AMSR-2 data, now collected in the A-Train since 2012 by the GCOM-W2 satellite.

Other instrument failures have reduced AQUA measurement capability, namely; AMSU has lost 3 of 15 channels; and CERES (FM-4) has a failure in the shortwave channel. Despite these losses, AQUA still meets full mission science requirements, primarily by improvements in geophysical retrieval algorithms using combined AIRS/AMSU algorithms and a fully functional FM-1 for CERES.

Value of data record and overall data continuity

Several of the key findings above demonstrate the value of Aqua mission team efforts that have been applied to creation and maintenance of the many decade-long data products now produced from each of the Aqua sensors and their respective science teams. This new proposal provides details indicating that science and data analysis activities have a continued focus on product improvements (e.g. MODIS Atmosphere Collection 6 algorithms) as well as calibration activities to assure continuity with future missions.

Core mission data product quality and maturity: Excellent

For AQUA a large number of core mission data products have reached a level of maturity that requires algorithm maintenance only. Moreover, there has been an evolution of new and improved data products for the sensors as discussed below:

- AIRS Science Team: development, integration, and validation of a new Level 2 unified retrieval algorithm that ingests Level 1 observations from AIRS/AMSU, CrIMSS, and potentially the European AMSU and IASI instruments, to produce a continuous climate data record of geophysical variables optimized for science and applications.
- AMSR-E Science Team: final reprocessing and archiving of the AMSR-E dataset, with the highest quality AMSR-E data products.
- CERES Science Team: complete the CERES Edition 4 reprocessing effort and publish Edition 4 algorithm improvements and validation results.
- MODIS Science Team: sustain the efforts needed to produce the 36 core data products, including reprocessing and on-orbit calibration activities, while at the same time coordinating MODIS Science Team members and algorithm support teams. Further, plans for 2015 include complete reprocessing of the Aqua MODIS Ocean Color and SST datasets. The focus of the Ocean Color efforts is to maintain a consistent long-term time series of ocean color products from SeaWiFS to MODIS and VIIRS.

<u>Minor Weaknesses</u>

Due to the very large constituency of data users with varying levels of familiarity and understanding of retrieval algorithms, we find that concerns expressed by the National Interests Panel regarding uncertainty characterization could be addressed by improving communication in the data portal. This is especially the case for MODIS products. Many users may not be equipped to make good use of the information provided by quality flags. Application users are generally more interested in limited area domains, where the quality of a regional subset of specific products might be substantially lower at times than that of the standard products at global scale. Providing user friendly examples and suggest resources to apply local corrections should go a long way to reduce such concerns from the national interests panel.

Relevance to NASA Science Goals: Excellent

<u>Major Strengths</u>

Thousands of scientists and operational users from around the world are making use of the Aqua data to address NASA's six interdisciplinary Earth science focus areas: Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and Earth Surface and Interior.

Weaknesses
None noted.

Technical and Cost
Concur with subpanel forms.

National Needs
Concur with subpanel forms.

Aquarius

Conclusion: Continuation of projects as currently baselined

Aquarius is a NASA Pathfinder mission and represents the first earth observing satellite dedicated primarily to the objective of measuring sea surface salinity (SSS) over the global oceans. Aquarius successfully completed its primary 3-year mission phase in Nov. 2014, demonstrating that the hardware, mission operations, and data science and data product development approaches are combining to yield all new weekly to monthly SSS datasets that further the overall objectives of NASA's Earth Science program. New scientific results are already forthcoming, with 111 publications to date, that address ocean circulation dynamics and prediction, land-ocean exchange of freshwater, cyclone impacts on the upper ocean, and atmosphere-ocean coupling associated with freshwater fluxes. The project has viable plans in place to both extend and further improve the core data products. The health of the overall satellite and the Aquarius radiometer and radar instruments indicate low risk for extended phase operations and agreements for continued collaboration between NASA and CONAE are also in place. We commend the project on successes to date and endorse extension of the mission as proposed going forward for the next operations period.

Scientific Merit: Excellent

The Aquarius project was able to deliver on their science objectives to provide new global ocean surface salinity data to the ocean and atmospheric science communities. Swath and gridded data products (versions 2 and 3) have already been distributed and in use showing first promise of the merit of these new observations consistent with NASA Earth Science priority areas including water cycle, land-ocean and air-sea exchange, and climate dynamics investigations. More than 110 publications have been produced working with these data, consistent with the young phase of past EO pathfinder-type sensors. We commend the project data system and data analysis teams for their close collaboration with NASA ROSES science team members and the overall science community during the first phase of the mission. We find that their extended mission plan should promote further use of their extended and refined datasets and represents a well-considered approach to the next years of Aquarius operation.

<u>Strengths:</u>

- Aquarius has been able to deliver on their goal to provide the science community with monthly global SSS data products with less than 0.2 psu rms error. There is a reasonable plan going forward for improving on this, for refining internal radiometer calibrations, and for augmenting the SSS data product with error estimates to better support climate science and ocean model data assimilation activities

- Key early science investigations in the tropical Pacific indicate the capability of the sensor to identify tropical instability waves and also to enhance data assimilating tropical ocean circulation prediction models
- A surprising amount of spatial structure has already been revealed in the early version SSS and surface wind products, indicating Aquarius applications near cyclones and large river plume gradients and ocean biochemistry that were not initially envisioned
- Near surface ocean processes associated with freshwater fluxes, both precipitation and evaporation, are now being addressed using latest version SSS data
- Key issues for present and future L-band earth observational factors are being investigated in great detail using the precise Aquarius radiometer and radar instruments including galactic radiation, sea surface temperature and atmospheric impacts, and a significant amount of stray radio frequency interference. We concur with their proposed approaches to address these issues further via their formal interactions with the ESA SMOS and NASA SMAP projects.
- Results indicate that the Aquarius radiometer and radar instrument calibration and pre-launch algorithm approaches are working in large part. Thus we find their extended mission algorithm refinement approaches are viable with significant improvements expected by the next senior review.
- The project will take on significant part of the activity to produce an ocean salinity product using the new NASA SMAP sensor. We support this new attempt to expand EO salinity observation capabilities.

Weaknesses:

- It appears that radio frequency interference (RFI) issue, while no fault of Aquarius, does currently degrade data utility off the coasts of the NE Atlantic and NW Pacific. The project has plans to address this in the coming period with hope to better flag out the poor measurements.
- Accuracy of the primary data deliverable, SSS, still weakly depends on use of the HYCOM ocean model within their science algorithm approach. The team will be working towards alternative methods in future data versions. Their plans for this are sound and appropriately funded.
- Quality of the monthly and weekly SSS data at polar latitudes is poor due to known geophysical limits of the L-band technique and unresolved refinements in their algorithms. The project intends to make attempts to improve on SSS retrievals, to include exacting assessment of ocean SST data.

Value of the data record and data continuity

Versions of swath and gridded SSS products have been available to the project calibration and validation teams and to the broader science community since early

in the prime mission phase. A significant number of publications have already been produced using Aquarius data.

Given the success of the prime phase of the mission in creating the core ocean salinity dataset, we concur with the mission's key extended phase objective to create a continuous 6-year data record with application to interannual and seasonal investigation of ocean circulation, water cycle, and earth climate systems.

Core mission data product quality and maturity: Very Good

The global SSS data products in swath (L2) and gridded (L3) form have already been made openly available to the broader science community in a well-documented fashion and we fully expect this to continue. The project calibration and validation team has been active in developing the tools needed to assess the salinity data against Argo buoy, climatology, and model products. Near-surface ocean salinity is independently measured across the ocean and provides a very useful metric to assess their data. The project has achieved success in refining the data product accuracy and rms errors to achieve the monthly SSS 0.2 psu rms error level by end of prime mission. Their new V4 datasets for science applications, reflecting latest refinements, will be released in the coming months.

We commend the strong data processing and archive support within this project including the capability by the GSFC team to reprocess all core data products in the entire mission dataset in less than a day's time. We also commend the ongoing close collaboration between the DAACs at GSFC and JPL and NSIDC (Aquarius ocean data are served at PO-DAAC while an add on land product is delivered to NSIDC) in support of this mission.

Their extended mission plans addresses steps they intend to take that we find should lead to an excellent rating in the next review. These include a refinement of the radiometer's internal calibration approach, refinement of geophysical corrections in tandem with SMAP and SMOS working teams, and the production of SSS uncertainty estimation with sequential steps towards a formal error assignment at the pixel level.

One new activity the project has chosen to take on is the development of a SMAP ocean salinity product that leverages the algorithms and data processing chain created for Aquarius. This is to be done within the cost of the present budget and in-kind support from a NASA ROSES competed SMAP science proposal. We find this to be a good example of synergy and efficiency and hope that it yields a useful additional science product for the community.

Relevance to NASA Science Goals: Excellent

The ocean salinity provided by Aquarius represent the first time that spatial information of SSS across ocean basins at monthly scale has been available to scientists and the data await application to core questions that NASA wishes to address as laid out in the NASA Science Mission Directorate plan of 2014. In particular, first results and the many studies to come will be focused on the earth system questions of how to utilize these ocean surface salinity baseline data and time and space SSS dynamics to address water cycle and climate change components as just two examples or focus areas within the SMD science plan. National interest and science panel evaluations indicate that SSS data are expected to provide valuable new data to numerous ocean and atmospheric prediction systems with societal benefits tied to weather and climate processes like ENSO and the Pacific Decadal Oscillation. Extending these new L-band data and this first spaceborne ocean baseline salinity time series should also lead the way for continued observation of this important ocean state climate variable. One example for such a future satellite application is already in development using NASA SMAP ocean data to derive a complementary new salinity product.

Technical and Cost

We concur with the results from the technical and cost review experts.

It does appear the Aquarius project made some adjustments to trim down their activities going into this new extended phase with reduction in mission operations and by shifting personnel over to creation of the SMAP data product.

National Needs

We concur with the panel findings.

Other Comments

We thank the team for this sound mission extension proposal and for feedback with the review panels including the well-presented technical details on mission health and operations.

Aura

The Aura satellite was launched in July 2004 as part of the A-Train. The three operating instruments on-board Aura are the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI), and the Tropospheric Emissions Spectrometer (TES) are continuing to provide profiles and column measurements of atmospheric composition in the troposphere, stratosphere, and mesosphere. OMI is contributed from the Netherlands Space Office and the Finnish Meteorological Institute. The suite of observations from MLS, OMI and TES is very rich, with nearly 30 individual chemical species relevant for stratospheric chemistry (O_3, HCl, HOCl, ClO, OClO, BrO, NO_2, N_2O, HNO_3, etc…), tropospheric pollutants (O_3, NO_2, CO, PAN, NH_3, SO_2, aerosols), and climate-related quantities (CO_2, H_2O, CH_4, clouds, aerosol optical properties).

Conclusion: Continuation of projects as currently baselined

The measurements on-board the Aura satellite provide a wealth of observations on the composition of the troposphere, stratosphere, and mesosphere. There is great value in continuing the mission to:

1) extend the unique 10-year record of stratospheric composition, variability, and trends as well as the chemical and dynamical processes affecting ozone recovery and polar ozone chemistry. In particular, most MLS data in the stratosphere is unique following the loss of ESA's Envisat in 2012;
2) continue to map-out rapidly changing anthropogenic emissions of NO_2, SO_2, and aerosol products influencing air quality;
3) continue to develop greater vertical sensitivity by combining radiances from separate sensors;
4) use Aura data to further evaluate global chemistry-climate, climate, and air quality models;
5) extend observations of short-term solar variability overlapping with SORCE and providing a bridge to future measurements (GOME-2 TROPOMI);
6) continue the development of new synergetic products combining multiple Aura instruments and instruments from the A-Train (OMI/AIRS ozone, AIRS/TES ozone comparison, OMI-MODIS aerosol colocation, OMI/MODIS reflectivity);
7) provide continuity and comparison to current and future satellite missions (Suomi NPP, SAGE-III, TROPOMI);
8) deliver operational products: volcanic monitoring, aviation safety, operational ozone assimilation at NOAA for weather and UV index forecasting, OMI Aerosol Index and NO_2 products for air quality forecasting;

MLS, OMI and TES continue to provide high-quality data. The Tropospheric Emissions Spectrometer (TES) measurement strategy has shifted in 2011 from near global coverage to directed observations due to lifetime concerns. The Aura spacecraft is healthy and is expected to operate until at least 2022, likely beyond.

Scientific merits: Excellent

Current science objectives for the mission: The three research goals for the Aura mission are to examine and quantify 1) the processes controlling tropospheric pollutants (OMI, TES), 2) chemistry-climate interactions (TES, MLS, OMI), 3) the changes in stratospheric composition and chemistry (MLS, OMI). Over the next few years, the proposed MLS contributions will further the observational record of changing upper tropospheric and stratospheric composition, with emphasis on interannual variability (ENSO/QBO), stratospheric ozone recovery and variability, and trends in composition (HCl, H_2O). OMI will continue to contribute to observations of tropospheric composition (NO_2, SO_2, O_3) as well as stratospheric composition, and solar variability. TES proposes to focus on megacity observations, regional observations over Asia and the Western US, and biomass burning monitoring during the fire season. The algorithms will continue to be improved, with an emphasis on synergetic applications within the A-train, such as OMI/AIRS ozone, AIRS/TES ozone, OMI-MODIS aerosol collocation. Aura will provide support for future and ongoing NASA field missions (KORUS-AQ and ATom). It will also allow for continuity with on-going and future non-A-Train missions (Suomi NPP, SAGE III, TROPOMI) and provide products for operational uses (aviation safety, operational assimilation of ozone, air quality).

Summary of what has been accomplished in past 2 years: Publications utilizing Aura data have made substantial contributions and have addressed a number of fundamental questions in

1) **Air quality:** OMI data has been used extensively in air quality studies, in particular focusing on using OMI NO_2 and SO_2 columns to quantify emissions and trends of surface NO_2 and SO_2 concentrations. OMI has documented the significant changes in anthropogenic emissions from point sources (power plants, smelters, etc…) and mobile sources (cars and ships) worldwide, such as the marked decreases in anthropogenic emissions over the U.S. and Europe, the decrease in ship NOx emissions over the Mediterranean, and the increases over Asia. Remarkable improvements in the OMI SO_2 retrievals have allowed detection of smaller anthropogenic sources. TES, MLS and OMI observations over Eastern China have been used to assess the trend in tropospheric ozone and attribute the O_3 changes to increases in NO_x emissions and in stratosphere-troposphere exchange. TES observations have documented vertical profile transects over 19 most polluted megacities, highlighting the different roles of biomass burning and oil/gas extraction in air quality over Mexico and Lagos.
2) **Chemistry-climate:** Aura data is extensively used to validate and improve climate models as part of NASA and DoE's Observations for Model Intercomparisons (Obs4MIPs) and the Atmospheric Chemistry-Climate Model Intercomparison (ACCMIP) project. MLS and TES observations have been used to quantify how changes in stratospheric circulation have affected upper tropospheric ozone. TES profiles were used to reduce the uncertainty

in ozone radiative forcing estimates. TES and MLS profiles of HDO and CO have helped improve the convective parameterization in the GISS GCM. OMI and MLS ozone data are now being assimilated in the NASA GMAO with improved representation of the vertical distribution of ozone.

3) **Stratospheric composition:** MLS data is extensively used in the latest WMO Ozone depletion assessment (2014), in particular highlighting the very large 2010/11 Arctic ozone loss. High vertical resolution MLS ozone observations have documented an increase in mid-latitude upper stratospheric ozone associated with the decline in ozone depleting substances and cooling of the stratosphere. MLS HCl lower stratospheric observations have shown a decrease in HCl concentrations in most regions, except for the northern hemisphere midlatitudes, where a slow increase was attributed to a slowdown in stratospheric circulation. Combined with other platforms, OMI SO_2 observations have been used to provide an altitude-resolved record volcanic injections of SO_2 in the stratosphere. MLS stratospheric water vapor measurements have allowed an unprecedented view of interannual variability over the last decade, including a sharp decrease in water entering the stratosphere in 2012.

There is very broad community use of Aura data, with 1589 Aura-related journal articles, out of which nearly a third were published during the past 2 years. The scientific findings of these studies address key NASA research objectives related to stratospheric composition, air quality, and climate change. The three instruments continue to provide data of excellent quality, despite some signs of aging (TES) and issues with partial blocking of sunlight (row anomaly for OMI). Since the loss of Envisat in 2012, MLS has been the main source of observations of high vertical resolution profiles of ozone in the stratosphere for assessment reports.

While TES no longer has the ability to conduct global observations, the step and stare mode over Eastern Asia/Western U.S. and biomass burning regions, combined with the transects over Megacities are a good solution to continue the long-term record of observations over these specific regions. In particular the Megacities high resolution transects will lead to a unique view of air quality.

Should TES and/or OMI become no longer able to collect high quality observations, the panel finds that Aura would still be a high priority mission given the value of MLS as the most comprehensive source of stratospheric observations with high vertical resolution.

Core mission data product quality and maturity: Excellent

The Aura products have continued to improve, resulting in better support of the Aura science objectives. In particular, V4 of MLS data is providing improved retrievals of O_3, CO, and HNO_3 in the tropical upper troposphere. New methanol MLS observations are included in MLS V4. OMI UV, formaldehyde, BrO and ozone

products have been improved. There is a new near-real-time OMI Surface Solar Irradiance (SSI) product available. There have been algorithm improvements and validation for TES V6 products, in particular of O_3, H_2O, and ammonia. Four new products are included in TES V6: methanol, formic acid, joint TES/MLS CO, and ozone instantaneous radiative kernel (change of outgoing longwave radiation per unit change of ozone).

MLS operates normally with daily observations for all species except OH (only observed 1 month each year), N_2O (no longer observed on band 12, but retrieved at lower vertical resolution in the 190 GHz band), and upper stratospheric HCl (band 13 was deactivated due to aging, but HCl observations are available from the Canadian ACE-FTS team). While there is slow overall aging of spectrometer power regulators, no negative impacts on science are expected before 2020 at the earliest.

Starting in 2007, OMI products have been affected by row anomalies (30-55% of the 60 OMI rows are not usable because blockage of incoming light and reflection of earth and sun-shine in the instrument) as well as by increasing pixel degradation due to radiation damage (10% of pixels). Because of the row anomalies, OMI no longer provides 1-day global coverage, instead 2 days are need to achieve global coverage. Most OMI products maintain science- and trend-quality.

Wear on the interferometer control system (ICS) bearing has resulted in the cessation of TES global survey observations in 2011. Since then TES has only been operated in special observations mode (step-and-stare) targeting specific regions and conducting transects over megacities. The ICS has stalled twice (2011 and 2014), but the instrument recovered from the stall with good performance. The last stall event in May 2014 lead to the interruption of data collection for 52 days (compared to 100 days in 2011).

The Aura team is beginning to deliver new multi-instrument Aura and A-Train products, leading to retrievals of chemical species with greater vertical sensitivity and accuracy. The TES/MLS CO product has increased vertical sensitivity and 10-30% accuracy, and the TES/OMI ozone product allows for greater sensitivity to surface ozone. Both are being funded through ROSES.

In addition to continually improving the quality of the core data products, the Aura team has placed new emphasis on combining information from more than one sensor on Aura and/or other A-train satellites. There is great value in this effort as it leads to increase the vertical resolution, greater global coverage, and greater sensitivity to surface composition.

Significant effort has been devoted by the Aura team to develop new synergetic products combining multiple Aura instruments and instruments from other platforms on the A-Train (OMI/AIRS ozone, AIRS/TES ozone comparison, OMI-MODIS aerosol colocation, OMI/MODIS reflectivity). The Aura team also proposes to conduct special observations and provide additional products for two upcoming

field missions (NASA's KORUS-AQ and Atom missions). Finally, collaborations of Aura with Suomi NPP and the planned SAGE III mission are expected to help with validation of these instruments.

Relevance to NASA Science Goals: Excellent

Observations collected by Aura instruments have made unique and valuable contributions to NASA research objectives. These contributions on stratospheric ozone, tropospheric chemistry and emissions, as well as climate change have addressed all four of NASA Earth Science questions: How is the global Earth system changing? What causes these changes in the Earth system? How will the Earth system change in the future? How can Earth system science provide societal benefit.

Technical and Cost
We concur with the subpanel forms.

National Needs
We concur with the subpanel forms.

Other Comments
The panel notes that a significant challenge to the successful continuation of the Aura mission resides in the maintenance of the health and safety of the spacecraft. Aura, as well as Terra and Aqua are all maintained by the Earth Science Mission Operation (ESMO) project. There are increased risks associated with old software, aging computers and operating systems and the increased sophistication of hacking attempts on the ground-system. These increased demands on ESMO together with a flat budget, suggest that the current approach might not be sustainable if Aura, Terra, and Aqua continue to operate well beyond their mission prime, as currently expected. Thus the panel finds that a review of potential longer-term solutions to the mission operations of Terra, Aqua, and Aura should be a priority for NASA.

CALIPSO

Conclusion: Continuation of projects as currently baselined

CALIPSO is an Earth System Science Pathfinder mission operated jointly with the French Space Agency (Centre National d'Etudes Spatiales, CNES).

The CALIPSO mission was proposed specifically to address and reduce uncertainties in the Earth's three-dimensional distribution and properties of aerosol and clouds. In particular, CALIPSO is tasked with providing:

1. Global estimates of aerosol direct radiative forcing
2. Improved assessments of the aerosol indirect radiative forcing of climate
3. Improvements in estimates of the surface and atmospheric radiation budget
4. Assessments of cloud-radiation feedback mechanisms

The CALIPSO spacecraft flies in formation with 5 other satellites in the larger A-Train constellation (Aqua, Aura, CloudSat, OCO-2 and GCOM-W), and consists of three instruments:

1. A dual wavelength, polarization sensitive (532 nm and 1064 nm) laser (the Cloud-Aerosol LIdar with Orthogonal Polarization, CALIOP)
2. A three-wavelength infrared radiometer (the Imaging Infrared Radiometer, IIR)
3. A single visible wavelength imager (the Wide Field-of-View Camera, WFC)

The CALIPSO spacecraft and all instruments are in excellent health and the mission is supporting transformative science. More than 500 peer reviewed publications have utilized CALIPSO data since the 2013 Earth Science Senior Review. CALIPSO provides a unique set of data products that are not currently available from any other satellite platform. The L1 products have reached a level of maturity that enables climate quality analysis of a nearly 10 year dataset. The L2 products are widely used by the scientific community, and gridded L3 aerosol and cloud products are in active development. The project continues to innovate, and has recently produced an estimate of ocean sub-surface phytoplankton concentration. Synergistic use of CALIPSO data in combination with CloudSat, MODIS, and CERES observations has led to the development of robust multi-instrument cloud, aerosol, and radiative heating products. CALIPSO aerosol vertical profiles are used in data assimilation tests at the US Naval Research Laboratory, the European Center for Medium Range Weather Forecasts, and the Japanese Meteorological Agency. Detection of volcanic ash plumes by CALIPSO is used in support of commercial aviation operations. The US Environmental Protection Agency and several state agencies are using CALIPSO data to assess air quality and develop strategies to mitigate pollution-induced reduction to visibility. Specifically, the EPA notes that 10-20% of its data downloads consist of CALIPSO data. Continuation of the mission will allow continued production of a valuable suite of data products, support climate

data analysis activities, and allow overlap with the Cloud-Aerosol Transport System (CATS) and upcoming EarthCARE missions.

Scientific merits: Excellent

CALIPSO has an impressive track record of delivering stable L1 and L2 products that have been used to advance fundamental scientific knowledge in many key areas, specifically cloud and aerosol vertical profiles and aerosol direct and indirect radiative forcing. Data products have proven utility individually and in concert with other sensors, and synergy with other missions is very strong. Key synergies include: CALIPSO-CloudSat-CERES-MODIS (C3M), 2B-FLXHR-LIDAR, DARDAR, SODA. The number of publications continues to grow each year, and there is no indication that this will slow in the future.

The science objectives of the mission in the near term include:

1. Extend the record of CALIPSO core data products to better characterize the seasonal and inter-annual variability of aerosol and cloud properties at regional and global scales.
2. Maintain synergies with other A-Train sensors and provide opportunities for synergies with new sensors recently placed on orbit, including OCO-2 and CATS.
3. Provide continued measurements of stratospheric aerosol optical depth, and overlap with the SAGE III instrument to be launched in 2016.

Specific scientific advances since the 2013 review include the following:

1. CALIPSO data was used extensively in support of the 5th IPCC Assessment (AR5)
2. Calibration improvements in V4 release have resulted in L1 data products with climate quality stability.
3. Nearly 500 peer reviewed publications since the 2013 review have utilized CALIPSO data (comparable to NASA's flagship missions), with numbers increasing each year.
4. The science team has developed above-cloud and between-cloud aerosol retrievals.
5. CALIPSO now produces improved estimates of aerosol direct radiative effect in both clear and cloudy regions. The previous assumption was that the aerosol direct radiative effect was zero in cloudy regions. Earlier estimates were, as a result, too large by a factor of 2.
6. CALIPSO has produced improved estimates of stratospheric aerosol loading due to volcanic activity, leading to quantification of stratospheric aerosol direct radiative effect. As a result, the effect of stratospheric aerosol is now thought to be "well understood" in the IPCC AR5.
7. CALIPSO data is a critical part of multi-sensor studies that quantify the aerosol indirect effect.

8. CALIPSO has provided a direct contribution to increased understanding of the Arctic surface radiative energy budget, as well as the surface radiative energy budget of the Southern Ocean, a key problem area for global climate models.
9. Previous comparisons between CALIOP and MODIS showed a factor of 2 difference in cirrus cloud optical depth. Subsequent analysis led to significant changes in MODIS retrievals (included in Collection 6). Modifications to the lidar ratio of ice clouds, combined with the MODIS C6 retrieval changes have closed the gap, and the measurements now exhibit good agreement.
10. Previous biases in the V3 532 nm night-time calibration and artifacts in the 532 nm day time calibration have been eliminated (as of V4)
11. CALIPSO is also being used in evaluation of passive retrievals of cloud and aerosol, and in evaluations of models and aerosol analyses.
12. A new ocean sub-surface backscatter product has been developed that shows promise for producing estimates of ocean primary productivity, a key source of uncertainty in the global carbon cycle.

Core mission data product quality and maturity: Excellent

The core mission data products are mature, well calibrated, and thoroughly evaluated against ground measurements and aircraft under-flights. Version 4 of the CALIPSO L1 data was released on 1 April 2014, and is the end result of an extensive redesign of the lidar calibration algorithms and processing software. Previous biases in the version 3 night time 532 nm calibration have been eliminated, as have artifacts that were prevalent in 532 nm day time calibration. The 1064 nm lidar data has also been completely recalibrated, resulting in much improved intra-orbit consistency. Throughout production of the new V4 release, the algorithms were evaluated by external lidar calibration experts, and all data products are run through a comprehensive set of quality assurance tests.

Synergy with other missions is excellent, and has resulted in an extensive suite of combined data products. These include:

1. Combined CloudSat-CALIPSO profiles are used to generate a unified retrieved ice content profile and estimates of cloud occurrence (DARDAR, GEOPROF-LIDAR, AND 2C-ICE), radiative fluxes and heating rates (2B-FLXHR-LIDAR), and a Synergized Optical Depths of Aerosols (SODA) aerosol optical depth product.
2. Data from CALIOP, CloudSat, and CERES were used to create a cloud and radiation climatology of the Arctic.
3. CALIPSO data is combined with data from CloudSat, CERES, and MODIS to create a product (C3M) that includes cloud and aerosol properties, top of atmosphere radiances, and vertical profiles of shortwave, longwave, and window region radiances and heating rates.

4. CALIOP profiles have been used to create a cloud climatology at GCM resolutions (GOCCP and CALIPSO-ST).

The review panel finds that the current suite of individual and combined data products is comprehensive and mature, and encourages the CALIPSO mission to develop the version 4 L2 retrieved and L3 gridded products in a timely manner. The CALIPSO mission team noted that the release of L2 and L3 products has lagged the release of L1 products because the L2 and L3 products depend on the development of the L1 data. Version 4 of the L2 products, and the initial release of the validated L3 products are scheduled for 2016. The panel also commends the continued development of innovative new products in the spirit of a Pathfinder Mission, such as the ocean sub-surface phytoplankton product. The panel notes that the upcoming changes to laser operation, including deactivation of the current (secondary) laser and reactivation of the primary laser, will likely require additional data product evaluation and testing. Additional funding may be required in advance of and during this activity.

Relevance to NASA Science Goals: Excellent

The CALIPSO mission addresses NASA science goals in the areas of Atmospheric Composition, Climate Variability and Change, Water and Energy Cycle, and Weather. Specifically, since 2013, the CALIPSO mission has made the following contributions:

<u>Atmospheric Composition</u>

- CALIPSO observes aerosols in previously inaccessible regions such as the Arctic. It is also currently the best tool for observing global distributions of volcanic aerosol.
- CALIPSO has provided new insights into the effects of aerosols on the Earth's energy budget.
- CALIPSO provides measurements that help to assess the effects of aerosol emissions on local ecosystems, air quality, and weather patterns.

<u>Climate Variability and Change</u>

- Multilayer cloud information from CALIPSO and CloudSat have allowed the first reliable global estimates of atmospheric radiative heating profiles, and has supported investigations of the coupling between clouds and atmospheric dynamics.
- CALIPSO profiles have enabled comprehensive tests of global climate models, and have led to improved model parameterizations.

<u>Water and Energy Cycle</u>

- Multilayer cloud information from CALIPSO and CloudSat have allowed improved estimates of the surface radiation budget.

- CALIPSO data are being used to improve the representation of mixed phase clouds in weather and climate prediction models.
- CALIPSO data is being used to characterize aerosol effects on cloud brightness, cloud water content, and precipitation.

Weather

- Operational numerical weather prediction centers are beginning to produce forecasts of air quality and visibility. CALIPSO data are being used for model validation, and are being tested in aerosol data assimilation systems.
- CALIPSO data are being used to improve assimilation of cloudy-sky radiances in weather prediction models, and to evaluate cloud-track wind height assignments.

Technical and Cost

The key technical challenge in the next 2-4 years is the continued pressure leak in the currently operating laser canister. This leak is projected to cause pressures in the canister to decrease to the level at which corona discharge becomes an issue some time during summer 2017. At this time, the current laser will be deactivated and the backup (formerly primary) laser will be turned on. The backup laser's canister will at that time have near zero pressure and should be below the corona discharge region. A thorough external review of this process was conducted in February and March of 2015, and the findings indicated changing the laser from primary to backup will pose no risk to the spacecraft. Extensive tests with the CALIOP laser in the laboratory will be necessary prior to and during the transition between lasers on orbit. Additional calibration and validation of the laser may also be necessary following the switch. The panel finds that initial funding may be necessary to support laser testing and calibration/validation activities in FY16 and FY17.

In addition to the above comments, the panel concurs with the technical and cost sub-panel forms.

National Needs

The panel defers to the National Interests subpanel forms.

Other Comments

The CALIPSO mission prepared a detailed, well organized, and comprehensive proposal, and answered all of the panel's questions in a timely fashion.

CloudSat

Conclusion: Continuation of projects as currently baselined;

CloudSat is a single-instrument ESSP mission that flies the Cloud Profiling Radar (CPR) as part of the A-train constellation and has completed nine years of operations, which is an outstanding achievement. The CPR is a nadir-viewing, narrow-swath, high-spatial resolution, W-band radar that enables detailed mapping of the vertical structure of clouds, hydrometeors and precipitation with unprecedented sensitivity, especially for snowfall and light rain. Integrated with A-train (e.g. MODIS, CALIOP, CERES, GCOM-W), OCO-2 and the recently launched GPM, CloudSat observations are instrumental for elucidating fundamental climate processes such as cloud-radiation feedbacks, including aerosol-cloud-rainfall interactions, and the linkages between the water cycle and radiative forcing. CloudSat data can be used for the evaluation of existing parameterizations of moist processes in numerical weather prediction models, and the development of new parameterizations of microphysical processes and convection. The continuity of these data products is highly desirable for the scientific community, governmental agencies and the international operational user community.

Scientific merits : Excellent

<u>Major Strengths</u>

CloudSat addresses core data needs of NASA's interdisciplinary Earth Science focus areas including Atmospheric Composition, Weather, Water and Energy Cycle, and Climate Variability and Change. Hundreds of science publications and millions of downloads of CloudSat products, in particular L2 products, attest to their importance and utility. Until the future launch of Earthcare, CloudSat observations are the sole source of information on the vertical structure of precipitating and non-precipitating clouds, including liquid and ice water. The importance of CloudSat observations to elucidating the global climatology of clouds and to understand their climate role was highlighted by the IPCC AR5 report.

By taking advantage of the long data records and the rich suite of L2 and L3 products, the extended mission allows the science to focus on studying moist processes in the context of multi-annual modes of climate variability, a WCRP grand challenge, and ultimately to improve their representation in numerical weather prediction and climate models.

Some of the key recent scientific advances enabled by CloudSat observations include:

- NAM/NAO-related anomalies in tropospheric cloud incidence lead to significant TOA cloud radiative forcing anomalies that are comparable in amplitude to those associated with the NAM/NAO-related temperature

anomalies. Variations in cloud radiative forcing are large enough to suggest a two-way feedback between extratropical dynamics and cloud radiative forcing.

- By examining the linkages between the cloud vertical structure contained in multiple years of CloudSat data and various large-scale meteorological parameters, a negative relationship between static stability and cloud incidence anomalies in the upper troposphere and lower stratosphere. Because upper tropospheric cloud incidence in the storm track regions is strongly linked to the variance of large-scale vertical motion and thus the amplitude of baroclinic waves, these results can be used to evaluate the linkages among large-scale circulations and the vertical structure of cloud systems.
- Analysis of CloudSat observations provide insights into cloud physical processes and with model reanalysis they provide a basis for interpreting and improving understanding of how these processes link to the dynamics of the atmospheric general circulation, which is the essence of the cloud-climate problem. By focusing on specific phenomena such as frontal systems, tropical convection, and the Madden-Julian oscillation, much has also been learnt to understand the weaknesses improve the representation in atmospheric models.
- CloudSat observations alone and combined with other A-train observations have been intensely used to evaluate the representation of microphysics in numerical models providing a unique way of developing testable hypothesis with regard to vertical structure and links to dynamics that have not been possible before the availability of these observations.
- CloudSat observations are being used to produce snowfall rate estimates that cannot be accomplished yet by other methods, and which can be used to develop corrections and improve the calibration of snowfall estimates from less sensitive radars (e.g. DPR).
- By exploring synergies with CALIPSO observations, CloudSat observations provide unique insights into the contribution of aerosol-clouds-radiative forcing interactions to climate sensitivity. Studies have shown that thermodynamic conditions (tropospheric stability and humidity in the free troposphere) and precipitation act together to govern the cloud liquid water responses to the presence of aerosols and the strength of aerosol–cloud radiative forcing, which govern the albedo response of low level clouds.

Minor Weaknesses

CPR is operating only in daylight-only operations mode after the incidents documented in the 2011 Senior Review. Although this has reduced the volume and frequency of observations, the quality and scientific relevance and utility of the data are very high all scientific objectives proposed for the extended mission can be addressed.

Value of data record and overall data continuity

The CloudSat suite of products has continued to grow stronger in recent years, including several new L3 products that will be of great interest for an increasingly broad community of users beyond the cloud-climate science community. Especially noteworthy is the progress made in the area of numerical weather prediction and model evaluation.

Core mission data product quality and maturity: Excellent

Major Strengths

The CloudSat team has been especially creative and productive in exploring synergies with other A-Train platforms and exploring the development of unique products.
Products such as 2B-GEOPROF and 2B-GEO-LIDAR have become staples in cloud systems research, and it is expected that the continuation and evolution of CloudSat/TRMM products into CloudSat/GPM products will further increase the utility and usage of CloudSat observations.

The CloudSat team is in great position to link to the upcoming EARTHCARE mission, and the CloudSat algorithms and knowledge-base are already making an important contribution in pre-launch activities.

Minor Weaknesses

Due to the very large constituency of potential data users with varying levels of familiarity and understanding of retrieval algorithms, and given the complexity of many multi-sensor multi-platform products, implementation of systematic efforts to translate and synthesize the uncertainty CloudSat in the peer-reviewed literature into documentation readily available along with the data themselves will be essential in the near future. This will go a long way to make the CloudSat products more user-friendly and to broaden the user basis and the diversity of applications.

Relevance to NASA Science Goals: Excellent

CloudSat is highly relevant to NASA Science Goals.

Major Strengths

Thousands of scientists and operational users from around the world are making use of the CloudSat data to address four strategic focus areas of NASA's Earth

Sciences mission: Atmospheric Composition, Weather, Water and Energy Cycle, and Climate Variability and Change.

Weaknesses
None noted

Technical and Cost

The mission is doing an outstanding job with maintenance and monitoring of technical performance. Please see subpanel forms for detailed comments.

National Needs

National agencies using CloudSat data deem its relevance and utility very high. Please see subpanel forms for detailed comments.

Other Comments

Not applicable.

EO-1

EO-1 was launched in late 2000 as a technology demonstration mission with a planned mission life of 1.5 yrs. EO-1 simultaneously acquires 30 m spatial resolution data from two instruments: the Advanced Land Imager (ALI) and the Hyperion imaging spectrometer. The multispectral ALI imager has nine Landsat-type bands: six VIS/NIR (0.4–1.2 µm) and three SWIR (1.2–2.5 µm) bands, and a 10 m panchromatic band. The hyperspectral Hyperion instrument has 220 spectral bands (0.4 – 2.5 µm). EO-1 is a targeting system that is capable of imaging any particular Earth location each day, up to 5 times every 16 days. This capability has proven to be useful for rapid response monitoring of disasters and specific events.

EO-1 Conclusion: Terminate and Close-out during FY 16-17.

Earth observations using ALI and Hyperion should be collected and archived by USGS until late September 2016.

Conclusion: Close-out and finalize dataset

Scientific merits : Good

Strengths: A unique and most notable strength of the EO-1 mission is that the Hyperion instrument remains the only civilian hyperspectral imaging spectrometer in space.

Weaknesses: The mission team provided limited information of the scientific accomplishments achieved since the last Senior Review. The mission continues to operate as a technology demonstration project but desires to be funded and considered as supporting science, yet limited contribution to the NASA Earth science mission was provided.

Value of data record and overall data continuity: Overall, the panel finds that the EO-1 data has limited value to the general Earth science community.

Core mission data product quality and maturity: Good

There are limited core data products (L1 only) that are largely generated and distributed by the USGS EROS data center. As the 2009, 2011 and 2013 Senior Review Panels also noted, this panel strongly finds that a continued weakness of the EO-1 mission is a lack of level 2 product maturity and availability. The panel

Concludes that updated product definitions and user manuals be generated during this extended mission phase to enable future use of EO-1 archived data.

Relevance to NASA Science Goals: Good

Strengths: Use of Hyperion data to prototype future instruments.

Weaknesses: Limited evidence of direct support of EO-1 data to NASA Science goals; there is limited mission support to define/maintain the scientific quality of mission data.

Technical and Cost
Panel concurs with technical panel findings and cost analysis.

National Needs
National Interests Utility Score: Some. Several National Interests panel members noted that EO-1 data were very useful following a major disaster or natural event but that the data were not used routinely.

Other Comments
It is important to note that the EO-1 mission was added late to the 2015 Senior Review process and that the panel did not receive a formal proposal from the mission team. It is noted however, that the panel reviewed the 2011 and 2013 EO-1 proposals, the 2009, 2011, and 2013 Senior Review Reports, as well as all other documents the EO-1 team provided to this panel. It is further noted that a key element of this review was the EO-1 team's presentation and response to the questions presented to the team prior to the panel meeting and during their presentation. The mission team's presentation and answers to the panel's pre-meeting questions were an important element of the panel's review and findings.

Numerous panel members expressed considerable concern that the EO-1 mission team has been unresponsive in responding to the findings of previous Senior Reviews and to this panel's questions. In particular, there was concern that the distribution, usability, and maturity of level 2 products remain major issues.

Additional panel comments: limited useful information was provided during the mission's presentation and the team was largely unresponsive to the panel's questions (content, organization and level of detail of the information presented); the mission team did not adequately provide scientific justification to continue the mission; the mission does not meet minimum requirements as a science mission in terms of scientific data evaluation, distribution, and product generation; the development of the lunar lab activity was not well justified.

The EO-1 team stated that the potential scientific benefit of the Lunar Lab to NASA

science is high by spectrally characterizing selected lunar features at a variety of lunar phase angles, to facilitate cross-calibration among imaging satellites. For example: if EO-1 Lunar Lab is in operation to overlap CLARREO Pathfinder (2019), the coincident lunar measurements will allow the entire EO-1 ALI and Hyperion archive to be put on the CLARREO radiometric scale, along with the other sensors that have and will image the moon. Unfortunately, the panel was disappointed in the depth of the EO-1 proposal to provide information required to evaluate this claim and others relating to the Lunar Lab utility to other non-NASA users. As a result the panel finding could not support this justification for the extended mission beyond 2016.

GRACE

Conclusion: Continuation of projects as currently baselined;

Since launch in 2002 the GRACE mission has produced a series of over 140 global gravity models, providing an unprecedented view of mass redistribution within the Earth system on monthly to inter-annual time scales. These gravity variations result primarily from transport of water between the oceans, land, cryosphere and atmosphere, making GRACE a unique and important component of NASA's climate measurement capability; it was designated a Climate Mission in the 2010 ESD Climate Initiative. GRACE is a valuable resource for basic science investigations, providing a unique view of the coupled Earth system, and shedding light on fundamental oceanographic, hydrologic, and cryospheric processes and interconnections. Through assimilation, mission data are also helping to improve model hind-casts and improving predictive skill in several areas of application. A follow-on mission is planned for launch in fall 2017. A core rationale for extension of the GRACE mission is to maintain continuity of the climate record, and provide sufficient overlap with the follow-on for calibration and validation of the new mission. The value of continued data collection to both basic research and applications provides further justification for mission extension.

Scientific merits : Excellent

<u>Strengths</u>

GRACE has proven value in multiple NASA Earth Science focus areas. These include:

Climate: GRACE is revealing spatiotemporal patterns of mass change for the large polar ice-sheets (Greenland and Antarctica) and for the world's ice caps and large mountain glacier systems. These studies are improving our understanding of the dynamics that control the flow of both ocean- and land-terminating glaciers, as well as impacts of atmospheric and surface processes, such as precipitation and melting, on the cryosphere. GRACE is also playing a key role in large-scale oceanographic studies relevant to climate. As examples: The precise mean gravity field, which GRACE makes a substantial contribution to, allows improved estimates of mean dynamic topography, and hence average ocean circulation. GRACE-derived maps of ocean bottom pressure variations, which reflect baroclinic (depth-dependent) processes, shed light on open questions such as Earth's energy imbalance and the current so-called warming 'hiatus'. GRACE data have allowed separation of mass and steric components of sea level rise mapped by altimetry. In combination with in situ Argo data, GRACE and altimetry have been used to infer that over the past decade, heat content of the deep ocean has not increased significantly.

Hydrology: Estimates of variations in the total land water storage from GRACE have helped distinguish variations in the water cycle that arise from natural climate

variability from those due to human water consumption. Exchanges between the oceans and land, which explain some anomalies in sea level rise, have been documented with GRACE data. Changes in soil moisture and groundwater storage have been instrumental in documenting the evolution of droughts at regional scales (e.g. California) as well as patterns of water use for irrigation globally. A wide variety of hydrological processes continue to be observed globally, from the tropics to the polar latitudes. Recent advances in the methods for assimilating GRACE data into hydrological models have also been demonstrated to be useful for regional scale hydrology.

Earth Surface and Interior: Most obviously, GRACE data have greatly improved our knowledge of Earth's large-scale gravity field. Trends in the GRACE data are providing important new constraints on glacial isostatic adjustment (GAI). An accurate estimate of GAI is critical for interpreting some climate signals such as spatial variations in sea level, and is also important for understanding the viscosity (or more broadly rheology) of the solid Earth mantle. GRACE data is also providing information about Earth rheology through studies of post-seismic deformation after large earthquakes.

Weather/atmosphere: Some ancillary data products produced by the GRACE mission have proven valuable in this area. Over 150 atmospheric moisture profiles/day, obtained from GRACE radio occultations (ROs), are assimilated into operational weather forecast models. Because GRACE carries an ultra-stable oscillator, the GRACE ROs are very accurate, and can be used to calibrate RO data from other satellites. Neutral density of the upper atmosphere derived from accelerometer, and TEC obtained from the microwave radiometer are important data for upper atmosphere studies, and for understanding drag on low-earth orbit satellites.

Weaknesses

No significant weaknesses were identified.

Value of data record and overall data continuity

The data record has been of high value to a broad group of users. The mission has steadily improved data processing and product quality, within limits imposed by some issues with batteries and the power system. From 2011-2015 monthly solutions were produced for roughly 10 months of every year. Due to further declines in power system capabilities, it is now anticipated that solutions will be available for roughly 9 months of every year. At this point the continuity of the record remains sufficient to separate the very large annual cycles from longer term trends, and to thus maintain the value of the climate data records. The missing months of data have some impact on users interested in studies of events, some of which will no longer be captured.

Core mission data product quality and maturity: Excellent

There are two core mission GRACE data products:

Level 2: Monthly and long term spherical harmonic models of gravity field. "Quick look" versions of lower accuracy are provided for operational users. As of May 1, 2015, alternative mascon solutions are available as standard mission products (two versions). These differ primarily in providing the monthly estimates in a spatially localized form, which many potential users will find simpler to understand and use.

Level 1: inter-satellite range, geocentric position, attitude and accelerometer measurements. For most purposes use of these products requires a very high level of sophistication, essentially requiring capability to do orbit calculations.

In general the quality of these data is excellent. The current release of the widely used Level 2 gravity solutions is RL05, the fifth release. All mission data have been reprocessed to this common standard. The data have been thoroughly evaluated and widely used. Significant improvements in quality and reductions in noise have been achieved with each release, and quality is widely considered by the community to be excellent. The mission proposes a new RL06 reprocessing during the continuation. This will be a relatively minor upgrade, using new background solutions, but not reprocessing at level 1, as was done for the RL05 update. A major motivation for the RL-06 upgrade is to prepare a consistent data product for comparison to GRACE-FO in the initial phases of this mission.

Relevance to NASA Science Goals: Excellent

The science section should explain how the proposed science program contributes to the ESD research objectives and focus areas as stated in the SMD Science Plan.

<u>Strengths</u>

GRACE estimates of the time-variable gravity field are highly relevant to the ESD research objective to characterize and understand "*How is the global Earth System changing?*" The mission specifically addresses four ESD focus areas including: Climate Variability and Change; Water and Energy Cycle, Earth's Surface and Interior, and Weather. For Climate Variability GRACE supports applications in ice sheet mass balance, sea-level rise, ocean dynamic topography and the transport of heat and mass in the upper ocean and ocean processes. In the water and energy cycle focus area GRACE addresses the global water balance and provides inputs for evapo-transpiration for weather models. In the Earth Surface and Interior GRACE has facilitated the development of gravity and geoid models, ultimately contributing to an improved national geodetic reference system, improved understanding of

glacial isostatic adjustment and determination of mantle rheology, and imaging of lithospheric mass adjustments after large earthquakes. In support of the Weather focus area GRACE radio occultations provide input into atmospheric models.

Weaknesses

No significant weaknesses were identified.

Technical and Cost

We concur with the technical sub-panel. As this panel finds, there are significant risks to the mission over the coming years. Many systems are single string, and a single additional battery cell failure will terminate the two-satellite science mission. Limited fuel and continuing descent of the satellite also may prevent continuation of GRACE until launch of the follow-on mission. If the K-band ranging is lost, the mission proposes to continue to produce time variable gravity fields with GPS tracking of a GRACE satellite, in combination with other LEO satellites. The mission is studying the feasibility of this approach, but preliminary assessments do not yet demonstrate that such solutions would be of sufficient quality to maintain the climate record. The mission should continue these studies, in cooperation with international collaborators and the science community, to further develop and evaluate the feasibility of the single GRACE satellite solution approach. Risks associated with this uncertainty are also reflected in the cost rating, with which the science panel concurs.

National Needs

Concur with sub-panel.

Other Comments

The proposal and presentation were generally clear, and the mission responded thoughtfully and fully to all panel questions.

OSTM

Conclusion: Continuation of projects as currently baselined;

The OSTM mission is a Ku-band radar altimeter. It continues a legacy established by TOPEX/Poseidon and Jason-1 of providing a high-quality global record of sea surface height on a 10-day repeat reference ground track. The mission is a joint effort by NASA and NOAA in the US and by EUMETSAT in Europe and the French Space Agency, CNES. Data are used for a broad range of applications, including studies of global sea level rise and ocean circulation. The satellite altimeter and related instruments are performing well and continue to return high-quality data.

A key rationale for extending OSTM is to ensure mission continuity between OSTM/Jason-2 and Jason-3, due to launch in July 2015. After launch Jason-3 will join the same orbit as OSTM, for a six-month calibration phase. Subsequently, following the science plan originally established for TOPEX/Poseidon and Jason-1, OSTM will move to an interleaved orbit to provide higher spatio/temporal coverage of oceanic eddy variability. Eventually, the project intends to move OSTM to a terminal orbit as a geodetic mission in order to improve mapping of sea floor bathymetry. Both of these subsequent mission phases will yield valuable additional data, providing further justification for mission extension.

Scientific merits: Excellent

<u>Strengths</u>

The project team has documented numerous examples of cutting edge science enabled by this extended record. The proposal provides demonstration of scientific data usage and exploitation by reference to the 4000 publications produced to date with NASA's ocean altimeter data records, as well as specific examples of recent and emerging results.
OSTM-based research spans a range of topics extending from physical oceanography to geodesy and hydrology. OSTM measurements have been used to study patterns of regional sea level rise; to study circulation, including allowing direct comparisons with in situ mooring data; to evaluate surface geostrophic velocities in the ocean; for multi-sensor studies of climate processes contributing to heat storage and transport in the ocean, and to evaluate emerging climate patterns, such as the recent appearance of a high sea level, warm "blob" off the west coast of North America. The proposal provides detail sufficient to show that extending this mission is vital to ensure NASA's participation in enabling new science and climate data record continuity for the ocean surface topography long-term dataset.

A key goal in extending OSTM is to ensure mission continuity between OSTM/Jason-2 and Jason-3 (due to launch in July 2015). This will provide a well-documented inter-calibration for the full altimetric sea level record that began with the launch of TOPEX/Poseidon in 1992. NASA, CNES, and the international ocean surface topography science have developed a proven method for tandem (dual-satellite) mission calibration phase data collection over a 6-month period, applied most recently to cross-calibrate OSTM against Jason-1. After launch, Jason-3 will be cross-calibrated with OSTM. OSTM will then be moved to an interleaved orbit, doubling the spatial coverage achieved by the OSTM and Jason-3 constellation. This follows an established approach used for TOPEX/Poseidon after the Jason-1 launch and for Jason-1 after the OSTM launch. These are well established and useful goals for the OSTM extended mission data collection with a high level of maturity, operational, and scientific merit.

Weaknesses

No major weaknesses were identified.

Value of data record and overall data continuity

The data record is part of an extended climate record and is critical to a wide range of applications and science users. The two-decade-plus record is of excellent value and should be continued to provide a reference baseline for studies of sea level rise and oceanographic variability. Data are widely available from multiple sources, and an active user community is supported through the Ocean Surface Topography Science Team, which is jointly supported via a ROSES call for proposals and also an analogous call for proposals by CNES. Through this process, OSTM has a healthy group of users and a strong mechanism for supporting innovative new science.

Core mission data product quality and maturity: Excellent

The level of maturity and validation for the primary altimeter dataset deliverables, the Operational-, Interim-, and Merged Geophysical Data Records (OGDR, IGDR, MGDR) related to core altimeter sea level, wind and wave data are all found to be excellent. This is in large part due to ongoing science team activities in calibration/validation as well as instrument and science team heritage tied to this specific radar altimeter data record. Data latency has been optimized for operational purposes and science data use continues to rise. Methods for updating any science algorithm changes are efficient, robust, and transparent.

The only potential future data quality weakness identified is in the GPS tracking system, and there are efforts to patch this to improve the quality. The project team reports that this sensor is not critical to maintaining high data quality, although it helps. The GPS system was switched to side B in August 2014. At the time that the

senior review proposal was submitted, the GPS system was not receiving a full complement of GPS satellite signals, but patches were implemented after proposal submission, and the project reports that the GPS side B system is now receiving from a full complement of 12 GPS satellites.

Relevance to NASA Science Goals: Excellent

Strengths

The proposal does a nice job of connecting use of OSTM to climate change process, monitoring and prediction goals of the NASA earth science program. The project reports that OSTM directly addresses NASA questions:

1. How is the global Earth system changing?
   OSTM measures sea level and circulation changes, continuing a multi-decade record of ocean variability.
2. What causes these changes to the Earth system?
   OSTM detects patterns of variability in the ocean, allowing researchers to evaluate the dynamics underlying ocean changes.
3. How will the Earth system change in the future?
   OSTM provides temporal and spatial sampling allowing it to help with questions of physical processes and attribution that, for example, guide our understanding of future regional sea level rise. As an example, the OSTM oral presentation noted that the recent development of a warm "blob" off the US West Coast may be a sign of a shift in the Pacific Decadal Oscillation and a reversal of regional sea level rise patterns that might bring heightened sea level changes to the US West Coast.
4. How can Earth system science provide societal benefit?
   OSTM has the potential to help provide warnings for coastal systems. Altimeter data have been used, for example, to study likely circulation pathways for oil spilled in the Gulf of Mexico, and OSTM is used to help identify likely sources of oceanic heat to feed hurricane development. Increasingly, OSTM is being used to monitor river flow

Weaknesses

None identified

Technical and Cost
We concur with technical and cost analyses.

National Needs

We concur with National Interest Panel findings.

Other Comments

The senior review panel recognizes the potential value of the end-of-life phase of the OSTM mission. In light of the time that may be required to develop a clear end-of-life plan, the panel finds that OSTM should now establish a working group and develop a well-defined consensus plan for end-of-life science.

SORCE

SORCE measures total solar irradiance (TSI) as well as solar spectral irradiance (SSI).

Conclusion: Continuation of projects with augmentations to the current baseline; Augmentation: funding to extend mission to allow 6 month overlap with TSIS

The most important measurement that SORCE makes is TSI. Because these TSI instruments are not absolutely calibrated, gaps in the record can introduce important uncertainties in the long-term trend. Therefore, continuous measurements of TSI are a high priority for NASA. SORCE has played a key role in maintaining the continuity of the long-term TSI time series, and is expected to transfer the TSI calibration to TSIS TIM when it becomes operational (early 2018).

SORCE has also been extending the SSI climate data record, and is expected to transfer the SSI calibration to TSIS SIM when it becomes operational. In addition, the daily SSI measurements are important operational products for NOAA and Air Force space weather operations.

Scientific merits: Very Good

Strengths:

The main strength of the mission is the maintenance of the long-term TSI time series, which plays a key role in climate change research. Connected to this is the crucial transfer of the TSI calibration to TSIS TIM when it becomes operational (early 2018). Given the importance of this overlap with TSIS, the panel finds that the budget overguide sought by the mission to facilitate the overlap should be funded.

A less important, but nonetheless valuable scientific merit comes from the SIM suite of instruments, which have extended the SSI data record. Continuing SORCE operations will continue extending the record and transfer the calibration to TSIS SIM.

The mission lists the top four accomplishments of the SORCE mission: (1) successful recovery of SORCE after a battery cell failure in July 2013 and return to daily solar measurements in February 2014 (battery is stable now), (2) overlap of SORCE TSI observations with the new TCTE TSI observations that began in December 2013, (3) critical review of the SORCE SSI measurements and solar cycle variability results by a NASA independent panel in September 2014, and (4) determination that solar cycle 24 variability is about half as much as the variability during the past few 11-year solar cycles.

It's worth commending the mission for their success in keeping the mission functioning in the face of many spacecraft difficulties: battery problems, star tracker problems, and reaction wheel issues. As part of the solution to battery problems,

the satellite now runs in day-only mode, which has successfully extended the mission.

Weaknesses:

There is another TIM on TCTE, presently in orbit, so SORCE TIM is not irreplaceable (Virgo is also in orbit, but it's value for intercalibration is not clear). That said, TSI is so important that having two TSI instruments in orbit is probably a reasonable risk reduction strategy. This is particularly important given that TCTE is controlled by the US Air Force, so NASA's ability to control its destiny is in question.

The panel would have liked to have seen a quantitative justification for the requirement of a 3-6 month overlap with TSIS being long enough to transfer the calibration.

SORCE SIM has calibration problems, with different wavelengths measured by multiple instruments showing different trends. The SORCE team is working on this, but it's unclear when this will be resolved. Until resolved, this will detract from the utility of the SSI data produced by SIM.

Value of data record and overall data continuity

As discussed above, the TSI data record is incredibly important and its maintenance should be a very high priority. The SSI data record is less important, but it has definite value and should be maintained, if possible.

Core mission data product quality and maturity: Very Good

SORCE produces several core data products for the community: daily and 6-hour TSI and SSI, 5-minute XUV and several times per day Mg II. These latter two are for the space-weather community.

SORCE TSI measurements are mature and stable. There was an unexplained shift with respect to Virgo during the time when the instrument was shut down due to battery problems. This introduces some uncertainty into the long-term trend. Despite this, these data make up a key part of our long-term TSI record.

SORCE SSI is not as mature and has calibration problems, with different wavelengths measured by multiple instruments showing different trends. This was identified in the 2013 Senior Review and the SORCE team is working on this, but it's unclear when or if this will be resolved. Until resolved, this will detract from the utility of the SSI data produced by SIM.

The XUV and Mg II data are used operationally for space-weather applications.

Relevance to NASA Science Goals: Excellent

The mission clearly addresses key components of NASA's climate and solar physics missions.

Technical and Cost
We concur with the subpanel forms.

National Needs
We concur with the subpanel forms.

Other Comments
None

Terra

Conclusion: Continuation of projects as currently baselined

The Terra mission is now beyond 15 years of continuous morning-orbit data collection providing fundamental observation of the earth's climate system, high-impact events, and adding value to other satellite missions and field campaigns. With 5 sensors providing a unique combination of spatial resolutions, temporal sampling, and multiple look angles, Terra is an exemplary mission that offers a tremendous long term data record capable of teasing out subtle climate signals. It's an international mission (US, Japan, and Canada) with broad participation among three NASA centers (JPL, Langley, and Goddard). The 5 sensors onboard Terra (ASTER, CERES, MISR, MODIS, and MOPPITT) collectively contribute to 81 calibrated and validated core data products. The value of Terra to the international science community is unequivocal.

One significant source of uncertainty with regards to the future of the mission, however, is the fate of the waiver to extend the Terra mission at the current 705 km altitude. If the waiver is approved, and the Terra mission team strongly endorses this position, then Terra will be able to maintain the tight 10:30 MLT for 3 additional years and continue to provide a long term uninterrupted data record. The panel agreed that if the waiver is denied, Terra would certainly continue to collect high quality data of sufficient value to the science community to warrant extension. The panel also agreed that the orbital change would compromise continuity of the stable long term climate record at some level, but felt that additional information would be necessary to fully assess the significance of this degradation. A sensor-specific or even data product-specific table of risks to data continuity resulting from waiver non-approval would have been a useful addition to the proposal. In light of this, the panel suggests that NASA convene a workshop of stakeholders to discuss and evaluate the trade-offs associated with the waiver decision.

Scientific merits: Excellent

<u>Strengths:</u>

The strengths of Terra's science mission are easy to point out with 15 years of continuous data products providing fundamental observation of the earth's climate system, high-impact events, and adding value to other satellite missions and field campaigns. The data distribution numbers for 2013 and 2014 exceed the combined distribution numbers for all other years combined – an indication of the continued and growing use of the data products. In terms of publications, there were over 1,600 peer-reviewed papers in 2014, bringing the mission total to over 11,000. In terms of citations, there were over 38,000 for 2014 alone and over 180,000 over the mission lifetime.

All of Terra's instruments are performing in exemplary fashion, except for ASTER's SWIR bands which were declared inoperable in 2009. Despite this, ASTER data have been used to produce 30 million tiles of the Global Digital Elevation Model (GDEM) - the most complete, consistent, high-resolution global topographic data set ever released.

Weaknesses:

The Science Panel did not note any significant weaknesses with regard to the scientific merits of the Terra mission.

Value of data record and overall data continuity

As stated previously, Terra's long term data record is invaluable for teasing out subtle climate signals, including Earth's radiation budget, cloud properties, GPP, NPP, air pollution, radiative forcing, atmospheric composition, and aerosols. Mission continuation through 2022 is expected based on battery and fuel, however, the status of the waiver approval has significant implications for the consistency of some of the long term data products. No spacecraft or instrument trends indicate that a major component is predicted to fail in the next 5 years. Normal on-orbit degradation is not expected to significantly limit the lifetime of any major spacecraft subsystem or component on-board within the next 5 years. Sufficient propellant is available to maintain the L1 requirement to keep the MLT between 10:15 and 10:45 through Jan. 2022. If the waiver is approved to extend the Terra mission at the current 705 km altitude, then Terra will be able to maintain the tight 10:30 MLT for 3 additional years. If the waiver is not approved, then an orbit-lowering maneuver will be performed in 2017 and Terra will slowly drift to 10:15 MLT by 2022. Prior to MLT drift, the science teams will need to re-develop algorithms for the lower altitude.

Core mission data product quality and maturity: Excellent

With 81 core data products (ASTER: 11; CERES: 13; MISR: 12; MODIS: 37; MOPITT: 7), Terra has excellent core mission data product quality and maturity. Key accomplishments since the 2013 Senior Review and proposed activities for the next 2 years for each of the 5 sensors are as follows:

- ASTER:
  - *Accomplishments in last 2 years:*
    - V3 GDEM released in 2015
    - ASTER data products available in orthorectified format in 2015
  - *Proposed activities:*
    - Maintain calibration/validation of instrument performance
    - Maintain/verify algorithms
- CERES:
  - *Accomplishments in last 2 years:*

        - Operational support
        - Intercalibration campaigns and leading ARISE field experiment over Artic Ocean
    - *Proposed activities:*
        - Instrument operations support
        - Continued algorithm development and improvement
- MISR:
    - *Accomplishments in last 2 years:*
        - 80 peer reviewed papers
        - Release of NRT products
    - *Proposed activities:*
        - Instrument maintenance and calibration
        - core data product generation
- MODIS:
    - *Accomplishments in last 2 years:*
        - Improved calibration of ocean color bands and VIS spectral bands
        - Enhancements integrated into MODIS L1B and Look-up table deliveries have been incorporated in collection 6 reprocessing of L1 products
    - *Proposed activities:*
        - Land Collection 6 algorithms reprocessing to be completed by 2016
        - Continued production and staging of core data products
- MOPITT:
    - *Accomplishments in last 2 years:*
        - Operational processing and deliveries of MOPITT V5 and V6 products
        - Significant increases in data download and peer-reviewed publications
    - *Proposed activities:*
        - Continue processing and delivering V5 and V6 L1, L2, and L3 products
        - Release of V7 products in FY16

Relevance to NASA Science Goals: Excellent

The relevance to all 6 of NASA's Earth Science Research Focus Areas is excellent. Examples of notable findings based on Terra observations in each of these areas are as follows:

- *Climate variability and change:*
    - CERES observations show a 10 Wm^{-2} increase in absorbed solar radiation during summertime over the Arctic Ocean between 2000 and 2014

    - Long-term trends in cloudiness from MODIS (morning (Terra) vs. afternoon (Aqua))
- *Atmospheric composition*
    - Long-term trends in CO emissions from megacities (MOPITT)
    - MISR Plume Height Climatology expanded 3 times since 2013 SR (to 38,000 plumes)
- *Carbon cycle and ecosystems*
    - MODIS – role of ENSO in strength of terrestrial C sink
    - MISR data can serve as a proxy for sparse, discontinuous lidar data
- *Water and energy cycle*
    - Global emissivity database from entire ASTER TIR archive
    - Surface roughness on the Greenland ice sheet from MISR
- *Weather*
    - MODIS-derived polar winds improve forecasts
    - MODIS-derived moisture information for tropical cyclone forecasting
- *Earth surface and interior*
    - Flood mapping with MODIS
    - Lava flows with ASTER

Technical and Cost

The Science Panel concurs with the Cost Panel findings of "Medium-Low" risk for the Terra mission.

The Science Panel also concurs with the Technical Panel findings of "Low risk" for the Terra mission.

National Needs

The Science Panel review concurs with the overall utility rating given by the National Interests Panel to the Terra mission of "Very High Utility."

The Terra mission supports a large number of applied and operational uses, including:

- Typhoons
- Fires
- ASTER: Emergency needs (volcanoes, field campaigns, floods, landslides, etc…)
- CERES: NRT products for energy sector uses – building energy system performance
- MISR: global time-series of near-surface fine particulate matter concentration from 1998-2012
- MODIS: NRT fire mapping; NRT NDVI/EVI and corrected reflectance

Other Comments

The proposal was complete and of very high quality and, therefore, sufficient for review. The panel noted some concern with regard to ESMO and the ground-system hardware given reduced personnel, increased IT security risks, and aging systems. It is not clear to the panel how this seemingly unsustainable issue will be managed into the future.