NASA Earth Science Senior Review 2013

Submitted to:

Dr. Michael Freilich
Director, Earth Science Division Science Mission Directorate

Elizabeth Ritchie (Chair), Ana Barros, Robin Bell, Alexander Braun, Richard Houghton, B. Carol Johnson, Guosheng Liu, Johnny Luo, Jeff Morrill, Derek Posselt, Scott Powell, William Randel, Ted Strub, Douglas Vandemark

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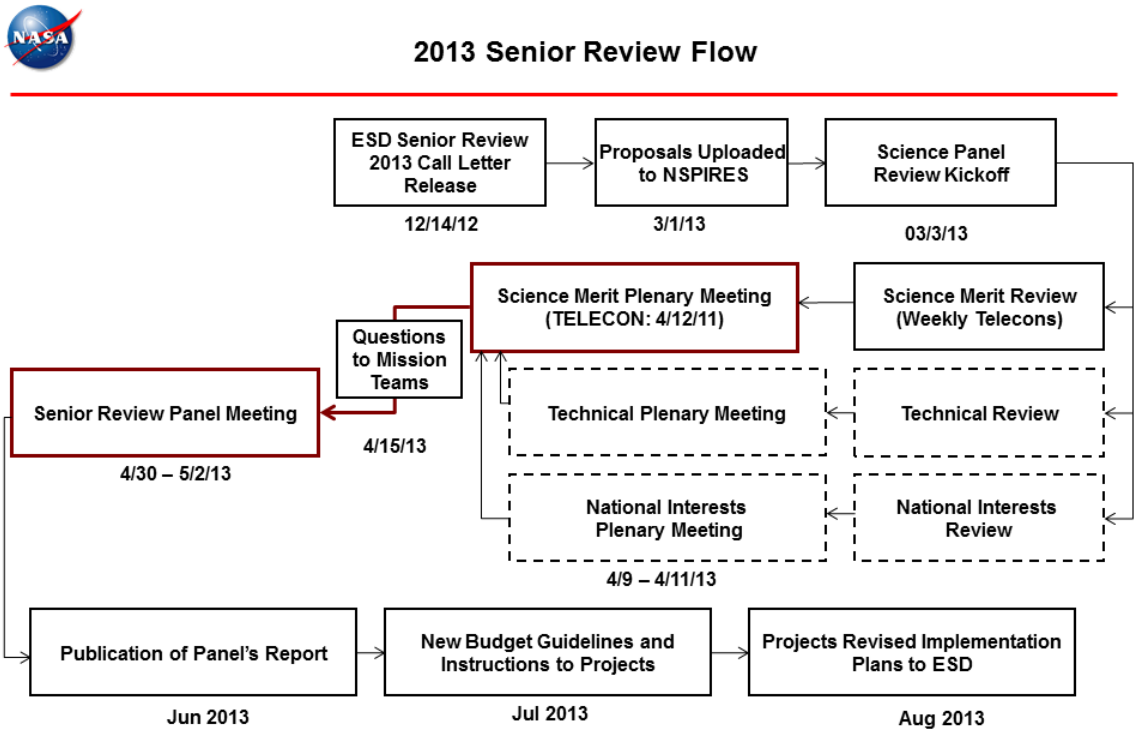
INTRODUCTION

The 2013 Senior Review evaluated 13 NASA satellite missions in extended operations: ACRIMSAT, Aqua, Aura, CALIPSO, CloudSat, EO-1, GRACE, Jason-1, OSTM, QuikSCAT, SORCE, Terra, and TRMM. The Senior Review was tasked with reviewing proposals submitted by each mission team for extended operations and funding for FY14-FY15, and FY16-FY17. 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 merit, relevance, and product maturity. 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 findings were categorized as: Baseline, Reduce, or Close-out; specific recommendations and justifications were provided for cases of augmentation or reduction.

REVIEW PROCESS

The 2013 Senior Review process (Figure 1) began on December 14, 2012 when the Earth Science Directorate released a call letter inviting NASA missions in extended operation to submit proposals for continuation, due March 1, 2013. The Senior Review Science Panel first convened on March 7 via teleconference to discuss procedures and review assignments. Three reviewers were initially assigned to review each proposal. Over the next month, two 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 12 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 15, 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 30-May 2 in Washington DC. Each mission was allotted a time slot of 45-90 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.



GENERAL FINDINGS

The Panel was unanimously impressed that all 13 missions have made unique and important contributions to NASA research objectives. Collectively, these missions constitute an unprecedented Earth observation capability that has transformed our scientific understanding of the Earth system, and provide data for applications of extremely high societal relevance. The Panel was also impressed that these missions all continue to operate beyond their designed lifetime, a fact that is a testament to high quality engineering, management, and mission execution. However, the Panel also expressed concern that these missions are aging, and noted that the risk of loss of critical Earth observation capabilities is increasing.

All missions received very high marks for Scientific Merit, Scientific Relevance, and Scientific Product Maturity (Table 1). Scientific Merit scores ranged from 4.0-5.0, with 10/13 missions receiving the highest score. Scientific Relevance scores ranged from 4.2-5.0, with 11/13 missions receiving the highest score. Scientific Product Maturity scores had more variability and ranged from 2.8-5.0, with 4/12 missions receiving the highest score. Missions received a utility score that ranged from "Some" (2 missions), "High" (8 missions), or "Very High" (3 missions). Technical Risk was distributed more broadly from "Low" (1 mission), "Medium-Low" (2 missions), "Medium" (2 missions), "Medium-High" (4 missions), and "High" (4 missions). The general increase in risk was first noted in the 2011 Senior Review. It has not changed in this Senior Review, and is broadly consistent with an aging fleet. There was no Cost Risk assessment performed in the 2013 Senior Review.

Based on these factors, the panel found that the continuation of all 13 missions would make critical contributions to enabling NASA to continue to meet its science objectives. All missions were proposed

for Baseline support in FY14-15; and eleven missions were selected for Baseline support for FY16-17, pending reassessment by the next Senior Review. One mission (Jason-1) was recommended to be re-evaluated by the next Senior Review based on whether it continued to provide necessary and essential contributions to the science community after the launch of Jason-3 in 2015. EO-1 was recommended for Terminate and Close-out in the out years based on the assessment that the mission would not provide useful measurements beyond FY15 due to its degrading orbit. Mission specific findings are summarized in Table 1 below.

Mission	Science Scores			Summary Science Score	Utility Score	Technical Risk	Conclusion	
	Merit	Relevance	Product Maturity				FY14-15	FY16-17
ACRIMSAT	4.0	4.2	2.8	3.7	Some	Medium-Low	Continue	Continue
Aqua	5.0	5.0	4.7	4.9	Very High	Medium	Continue	Continue
Aura	5.0	5.0	4.9	5.0	High	Medium-High	Continue	Continue
CALIPSO	5.0	5.0	4.9	5.0	High	Medium	Continue	Continue
CloudSat	5.0	5.0	4.9	5.0	High	Medium-High	Continue	Continue
EO-1	4.0	4.3	3.0	3.8	Some	Medium-High	Continue	Terminate & Close out*
GRACE	5.0	5.0	4.0	4.7	High	High	Continue	Continue
Jason-1	5.0	5.0	5.0	5.0	High	Medium-High	Continue	Continue & Reduce*
OSTM	5.0	5.0	5.0	5.0	High	Low	Continue	Continue
QuikSCAT	5.0	5.0	5.0	5.0	High	High	Continue	Continue
SORCE	4.9	5.0	3.2	4.4	High	High	Continue	Continue
Terra	5.0	5.0	4.8	4.9	Very High	Medium-Low	Continue	Continue
TRMM	5.0	5.0	5.0	5.0	Very High	High	Continue	Continue

Table 1: Summary of mission-specific findings. 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 findings summary below.

The Panel has several more specific recommendations to NASA Headquarters regarding the missions:

(1) The Panel recommends that there be better interaction and collaboration between and among missions, especially those where synergies are obvious. Examples include the collaborations between TRMM and CloudSat, CloudSat and CALIPSO, and ACRIMSAT and SORCE/TIM to the benefit of the community. Within the mission teams, the most obvious collaborations are for cross-calibration of instruments. However, another option might be for focused competitive calls in ROSES for focused, multi-mission, interdisciplinary projects. In addition, missions should be encouraged to hold joint mission team meetings where potential collaborations can be discussed.

(2) The panel was concerned by the number of FTEs required to support the CERES instrument, including quality control and data production on Aqua and Terra. The panel notes that the Terra project scientist, Dr. K. Thome, provided considerable detail in response to the Panel's query concerning the number of FTEs required to support the instrument. However, the Panel remains unclear as to why CERES requires such a large amount of support compared with other

instruments and recommends that NASA conducts a detailed review of the budget and personnel required to support the CERES instrument on both the Aqua and Terra platforms;

(3) The Panel notes that in the case of several missions, there was concern from the community as to whether uncertainty and error characterization of the core and/or ROSES products was either being properly accomplished or well-documented and easily found. The panel suggests that a central oversight from NASA for this process would help mitigate these concerns;

(4) The Panel is very concerned that outreach and education to new/current users and also K-12 educational components remain a mission responsibility within NASA. The Panel is deeply concerned that removing this activity from the individual missions will result in, at best, ineffective communication and, at worst, a loss of both communication and a great "hook" for young children into STEM disciplines. Moreover, one of NASA's goals is to help the nation mitigate and adapt to long-term climate change, which requires a willingness to act on behalf of the general population. This willingness depends on some understanding of the science and confidence in the scientists, emphasizing the importance of public outreach and education. Clearly, if this does not take place within NASA, it must take place elsewhere. However, we firmly believe that the best and most effective communication and outreach occurs from within the missions in particular, and NASA in general.

MISSION SPECIFIC FINDINGS SUMMARY

ACRIMSAT

The Active Cavity Radiometer Irradiance Monitor 3 (ACRIM3) experiment on the ACRIM satellite (ACRIMSAT) began in 2000 as part of the Earth Observation System (EOS) of NASA's Earth science missions. It is a key NASA component of the international effort to compile an accurate and precise total solar irradiance (TSI) database on climate timescales. ACRIM3 is capable of sustaining the 34-year satellite TSI database across a potential gap resulting from the launch failure of the Glory/TIM experiment with no loss of traceability or measurement cadence. Sustained variations in TSI of 0.1 to 0.2 percent on multi-decadal to centennial time scales are believed to have been the primary forcing of past climate changes. Thus, a precise record of TSI variability on these time scales is essential for assessing the relative significance of solar variability and other natural and anthropogenic forcings of climate change.

The primary purpose for an extended ACRIM3 mission is to ensure that there is no deterioration of the 34-year satellite TSI database across a potential gap caused by the loss of the GLORY/TIM experiment. The ACRIMSAT satellite and the ACRIM3 instrument are 100% operational and capable of continued operation with full science performance through at least FY14–15. In fact, the technical risk rating is medium-low for the extended mission. Satellite health and performance trends indicate that ACRIMSAT/ACRIM3 observations are likely to be available to support the launch and calibration phase of the next TSI monitoring experiment, JPSS1/TSIS, in 2017. In the event of a SORCE failure, ACRIM3 measurements are of the quality required to continue the TSI record and should be maintained as long as possible.

The panel notes that the ACRIMSAT is very small and supports a minimal number of FTEs to maintain satellite health, satellite data analysis, and outreach efforts. Given the value of these data for the

climate science community, and the recent success of the laboratory inter-comparisons of ground sensors that resulted agreement among the multiple TSI data records, the panel recommends that a 'TSI science team" perhaps comprised of experts within the TSI and close climate community be formed that can provide a focal point for oversight, science investigation, and collaboration.

Aqua

The Aqua mission is now 5 years into its extended mission of producing a wide array of measurements in support of addressing NASA's Earth Science mission both from the perspective of creating climate data records necessary to evaluate climate change and from the perspective of products needed to better understand fundamental Earth science processes. The Aqua mission has been extremely successful and produces a large number of critical products that are very widely used by scientists, government agencies and operational groups. The impressive list of core science products is very mature and stable. The government agencies all gave Aqua the highest ranking of all missions, and scientific citations of Aqua data now exceed 20,000, leaving no doubt that this mission should continue to be funded. One instrument – the AMSR-E – suffered a major anomaly since the 2011 Senior Review and now operates in a reduced mode that provides data for cross-calibration with other AMSR instruments. However, all other instruments are still operating nominally and the spacecraft is in excellent health and has enough fuel to operate through 2022. The reasons for extending the Aqua mission include: (1) to allow current scientific and applied benefits to continue; (2) to increase the value of the Aqua data to climate studies through increasing the length of the Aqua data sets; (3) to allow continued data overlap with NPP and GCOM-W1, and potential future data overlap with OCO-2, since all of these missions carry instruments intended to extend many of the Aqua data records; and (4) to continue to provide valuable auxiliary data for other A-Train satellite missions. Of the several instruments on Aqua, MODIS and AIRS are making extremely unique and popular measurements for science and operational applications. The continuity of these data products is highly desirable for the scientific community and the broader user community. As long as one of these two instruments is in good health (currently both are), the panel feels that the Aqua mission should be extended at baseline.

Aura

Aura's primary scientific missions are stratospheric chemistry and dynamics related to ozone depletion, tropospheric chemistry, and climate change issues. These missions are central to core NASA research objectives. The scientific output from Aura is substantial, with over 1100 journal publications and over 450 publications since the 2011 Senior Review. There is a large and active scientific community utilizing the Aura data. With regards to developing and utilizing data products related to tropospheric chemistry and climate, Aura has continued to make important strides since the 2011 Senior Review. The satellite is in excellent health. The Aura MLS, OMI and TES instruments are showing signs of aging, but are still producing science data of excellent quality, and there is an excellent chance of extending measurements beyond the current proposal cycle. The data are highly utilized in the research and operational communities.

The reasons for extending the Aura mission include: (1) to allow current scientific and applied benefits to continue; (2) to increase the value of the Aura data for climate studies through increasing the length of the Aura data sets; (3) to allow continued collection of data that are unique since the loss of the European Envisat satellite; and (4) to continue to generate synergistic products by combining different Aura and measurements from other A-Train satellite missions.

CALIPSO

CALIPSO's primary scientific mission is to reduce uncertainties in the Earth's three-dimensional distribution and properties of aerosol and clouds, which are key components in understanding and quantifying climate change. The scientific output from CALIPSO has increased substantially from the 2011 Senior Review with over 800 publications compared to 330 in 2011. CALIPSO provides a unique set of data products for the research community that is not currently available from any other platform. In addition, synergistic use of CALIPSO, CloudSat, MODIS, and CERES observations has led to the development of robust combined aerosol, cloud, and radiative heating rate products. Continuation of the mission will allow extension of the data record of these products as well as enable critical overlap with soon-to-be launched cloud/aerosol (e.g., EarthCARE) and stratosphere (e.g., SAGE III) missions.

Data products are mature, well validated, and widely used by the scientific community and the science team has been responsive to the recommendations of the 2011 panel, having: resolved discrepancies between CALIPSO and MODIS cloud optical depth; produced a global gridded aerosol vertical profile product; and begun production of a near real time L1.5 attenuated lidar backscatter product. The technical review panel rated a mission extension as Medium Risk for a two-year extension, because the spacecraft and all subsystems and instruments continue to function well, with an increased risk for a four-year extension. The national interest panel rated CALIPSO as high utility, and loss of the products would have a measurable negative impact on many national agencies and organizations. The reasons for extending the CALIPSO mission include: (1) to characterize processes that control seasonal and inter-annual variability on global scales by increasing the length of the CALIPSO data sets; (2) to better quantify relationships between aerosols and clouds and cloud-radiation-climate feedbacks; (3) to maintain existing synergies with other A-Train instruments; and (4) to establish links with the next generation of spaceborne lidar missions (e.g., EarthCARE), develop synergies with the new SAGE III instrument, and take advantage of joint retrievals with the new Orbiting Carbon Observatory (OCO)-2 mission, which will fly at the front of the A-Train starting in 2014. The Panel conclusion is that the project should be continued at Baseline.

CloudSat

CloudSat carries a single instrument - a w-band (94 GHz or 3 mm) cloud profiling radar (CPR) that is sensitive to both cloud and precipitation-size particles. It provides the science community with the first global survey of the vertical precipitation structure of clouds. The vertical dimension of cloud is particularly novel information, considering that decades of satellite observations in the past since 1960s have only looked at clouds horizontally. This novel observation from CloudSat has spurred a range of new research including critical evaluation of global model representation of clouds and new insights into cloud and precipitation processes. CloudSat is also a member of the A-Train constellation. Synergistic use of CloudSat and other A-Train measurements (e.g., CALIPSO, MODIS, AMSR-E) have enabled new science in the area of aerosol-cloud-precipitation interactions.

Continuing the CloudSat mission carries a number of benefits: 1) allowing for new science in the context of weather and climate variability and also enabling new products, 2) uninterrupted applications to aviation and weather forecasting, 3) improved understanding of seasonal and inter-annual variations in cloud behavior, 4) enhanced data for evaluating model behavior, and 5) providing calibration for future missions such as EarthCARE (2016) and GPM (2014). There is also strong synergy with the future OCO-2 mission as the oxygen A-band from OCO-2 provides complementary information on clouds.

Since the 2011 Senior review, CloudSat has begun operating in a new "Daylight-Only-Operation" mode that relies on the solar panel to power the satellite. A consequence of this "DO-Op" mode is that only the sun-lit portion (~ 56%) of the whole orbit has data. Thus, the satellite can no longer observe clouds in the polar night. However, the Senior Review Panel concludes that the overall CloudSat data quality is not compromised by this reduced operation and the mission objective can still be met, namely, surveying the vertical structure of clouds. In summary, the panel recommends that CloudSat mission be continued as currently baselined.

EO-1

The 12 ½ year old EO-1 mission continues to make numerous valuable contributions to the Earth Science community. It serves as a model for advanced technology capabilities, including spacecraft agility, on-board intelligent processing, reliable support technologies, and unique passive optical imagery. The mission also delivers and tests new technologies and strategies for satellite acquisition, algorithms for terrestrial environmental monitoring, calibration and validation, data synergy, and continuing technology advancements for data volume throughput, autonomous operations, and on-board processing. The two instruments onboard EO-1, the Advanced Land Imager (ALI) and Hyperion, are high spatial resolution sensors capable of imaging any spot on earth up to 5 times every 16 days (plus 5 nighttime images over the same period).

The EO-1 mission is central to NASA's strategic Earth Science plan: to advance Earth system science related to climate and environmental change, and to characterize, understand, and predict how the earth is changing, with consequences for life on Earth. Though originally designed as a technology demonstration project (ALI to inform Landsat 8 and Hyperion as the first grating-based, hyperspectral, civilian sensor in orbit), the mission continues to serve that purpose but has also made significant progress as a contributor to science and applied science investigations as well as national and international disaster monitoring efforts. Despite the small team size (<10 part time) in the Mission Science Office and Missions Operations, the EO-1 mission supports an impressive array of activities.

Over the past 2 years, significant progress has been made on improving communication to the broader community of how data should be tasked and acquired, and improving the Level 2 products, as well as on other fronts. These improvements have strengthened the relevance of EO-1 to NASA's science goals. In particular, the EO-1 Mission Science Office (MSO), in partnership with the USGS EROS has made data processing improvements and continues to advocate for science-quality products. The panel also notes significant improvements to data tasking and acquisition and the mission is highly commended for these changes. The EO-1 website provides mission information, a reference list, user support tools, and links to data. In addition, through its web-based task management system (GeoBPMS), the user community can submit task requests, which could likely serve as a model for future sampling missions.

The panel recommends continuing the mission for the next two years as baselined at the very low requested support level and then closes out in FY16-17. By this time the EO-1 Mean Local Time (MLT) will have degraded to the point where many products will lose their usefulness. The science team has set a decommissioning date of September 30th 2015 and the Senior Review Panel concurs with this plan.

GRACE

GRACE (the Gravity Recovery and Climate Experiment) mission has delivered unique, global datasets on the global gravity field and the large-scale temporal changes in mass distribution within the Earth system since it was commissioned in 2002. The GRACE data have provided novel insights on critical planetary processes such as ice sheet mass balance, the flux of melt water into the global oceans, mass exchanges within the oceans and seasonal and inter-annual variability in groundwater storage at the regional scale, which has been used to detect and map major water use patterns. GRACE data have been used in operational settings including the radio occultation data that are assimilated into atmospheric models. Furthermore, the GRACE accelerometer provides some of the best *in situ* data on satellite drag and atmospheric neutral density at high altitudes. The mission has provided critical contributions to the development of a global gravity field complementing terrestrial gravity, CHAMP and GOCE. The health of the mission continues to be an issue as there are few components left with any redundancy.

GRACE is presently producing data of extremely high value to the scientific community, and the panel has little doubt that the mission should be extended as long as both satellites continue to operate nominally. However, this situation could well change before the next Senior Review, even without a complete "catastrophic" failure. In the event of failure of one of the GRACE satellites, NASA should be prepared to review the utility of data collected by only one satellite and make appropriate adjustments as such data would most likely be of very limited value.

Jason-1

For the past eleven years, the radar altimeter Jason-1 has extended the record of global sea surface height (SSH) observations. It has bridged the gap between TOPEX/Poseidon and its follow-on Ocean Surface Topography Mission (OSTM), and it has sharpened our image of the oceans by providing high resolution data during its mission. Due to several safe holds early in 2012 and the potential risk of a collision with OSTM or its successor Jason-3 (to be launched 2015), Jason-1 was successfully moved to a lower geodetic orbit. The new geodetic orbit extends the repeat period from 9.9 days to 406 days and leads to significantly greater observation density at the cost of temporal resolution. As a consequence, Jason-1's contributions to extend the sea level change time series along the established track has switched to providing SSH observations along a new track pattern. Despite the change, Jason-1 continues to provide very valuable observations for mesoscale oceanography, which requires 2-3 operational altimeters. The SSH product from the geodetic mission shows only minor degradation in sea surface anomaly variance and is still assimilated into operational models by several agencies.

In addition to making fundamental progress in the science of oceanography and climate change, Jason-1 products benefit society in ship navigation and safety, offshore operations, and fisheries management. In its geodetic orbit, Jason-1 continues to provide important data for these applications and paving the way for the next generation of high resolution altimetry, beginning with the SWOT mission in 2020.

The reasons for extending the Jason-1 mission include: (1) providing revolutionary improvements to estimates of the marine geoid and ocean bottom topography; (2) improving the oceanographic utility of SSH data from other non-repeat missions and future high-resolution altimeters such as the SWOT, and allow retrospective improvement of SSH data from other non-repeat missions; (3) continue to observe large-scale oceanographic signals and globally averaged sea level rise; and (4) help resolve mesoscale oceanographic features by combining with OSTM and (later) Jason-3 (2015).

A further consideration is the need for cross-calibration with the future Jason-3 mission (2015). In its current geodetic orbit, Jason-1 can detect and correct large errors in sea-surface heights from Jason-3 in

the absence of OSTM. In the event of an unanticipated failure of OSTM, Jason-1 may add value to overall calibration and validation activities and NASA should plan to review the potential value Jason-1 might have for these activities in the event of such a failure.

Assuming no failure of OSTM, the panel recommends that the project should be continued at Baseline for FY 14-15, and then pending review by the 2015 Senior Review Panel, recommends terminate and closeout in FY-16-17.

OSTM

OSTM is the 3rd in a series of satellite-borne altimeters to occupy the 10-day repeat (TOPEX/Poseidon, T/P) "reference" orbit, while measuring ocean circulation and its effects on climate. In this orbit, OSTM serves as THE reference satellite for the other altimeters in orbit at the same time (these are now Cryosat-2 and Altika), improving the accuracy of their products by comparing heights during orbit "crossovers." This series has been highly successful in meeting all of its goals and providing a high quality time series of global sea surface topography for the past 19 years. Barring an unexpected failure of OSTM, its continuation will extend this important time series for climate change until, at a minimum, the launch of the next altimeter Jason-3 in the series. After its replacement by Jason-3, it will move to an interleaved orbit to contribute to an even higher spatial resolution of the SSH fields.

OSTM altimeter observations are also playing a key role in the analysis of other upper ocean processes in physical oceanography and the science panel supports continuation. In addition, the overall rating for OSTM by the National Interests Panel was Very High, the Technical Review of OSTM ranked the overall risk as Low. The Panel conclusion is for Baseline support of the OSTM mission.

QuikSCAT

QuikSCAT addresses several NASA science objectives primarily related to ocean winds. The proposed extended mission is to use QuikSCAT in its non-spinning mode to provide consistent calibration for the Indian Space Research Organisation (ISRO) Ku-band scatterometer (OSCAT) whose calibration loop is defective. It is clear that continuous calibration of the OSCAT scatterometer is necessary because of instabilities in the OSCAT radar that has led to unpredictable step jumps in the sigma0 measurements. The extended mission will also continue to use and improve adapted QuikSCAT algorithms to produce climate quality OSCAT ocean vector winds and ice products that continue the high quality QuikSCAT time series. This approach is viewed as the optimal way to continue the science- and climate-quality data record, since the ISRO mission is directed at near real time operational applications. Without appropriate calibration and data processing, these data will not be useful for climate and cryosphere research. ISRO and NASA have demonstrated successful collaboration to achieve these goals. QuikSCAT has been extremely stable in its calibration, and the radar instrumentation shows no indication of either calibration drift or deterioration, making this instrument ideal for calibration of these Ku-band scatterometers.

In a change from the last review, this proposal will also use a combination of QuikSCAT and the new NASA ISS-RapidSCAT sensor that will be launched in 2014 to extend the science and application of ocean vector winds. This will be achieved by exploiting a calibrated Rapidscat (using QuikSCAT) and its non-sun synchronous orbit to assess diurnal and semidiurnal wind variation in the tropics, and by adapting QuikSCAT operational near-real time processing to the delivery of Rapidscat OVW data to forecast agencies. It will also use Rapidscat to demonstrate a new method of scatterometer wind vector inter-

calibration for several additional sensors, most specifically the EUMETSAT C-band ASCAT scatterometers. This effort is intended to address a standing scientific and technical issue of reconciling small but climate-relevant differences between winds derived using C- and Ku-band satellite sensors. The Senior Review Panel agrees that this objective has significant merit and that the science and implementation plans to accomplish these objectives are ambitious yet feasible.

In late January, the spin mechanism resumed operations, and 7 days of nominal wind vectors were retrieved and processed. After some experimentation it was determined that successful spin operations could be accomplished, by heating the jammed bearings to 50 °F before starting the spin mechanism. Under these conditions, it appears that 2 weeks of heating might provide 1-2 days of spin operation. However, systems cannot be turned on at the same time as the survival heaters. Thus, the decision has to be made whether to operate QuikSCAT in its original mode, which will allow nominal collection 10% of the time OR continue in its new calibration mode that allows 100% calibration of the OSCAT measurements. The value of each mode cannot be quantitatively assessed and so the mission team has been decided to resume calibration operations exclusively. The Senior Review Panel endorses this decision and recommends that QuikSCAT continue in its calibration mode at the baseline budget.

SORCE

SORCE/TIM provides total and spectral solar irradiance measurements with state-of-the-art accuracy. The scientific focus is on solar physics and the interaction and influence of solar radiation on Earth's physical state. The simultaneity of spectral and total irradiance measurements allows study of a broad range of science questions. The SORCE Mission has provided a decade of solar irradiance observations (TSI and SSI) with high precision and stability and these results have been and will be used by the Earth Science and Solar Irradiance communities. The results from this mission will be important to the development of future climate models that include both TSI and SSI as well as studies of the sources and properties of solar variability.

Recent efforts looking at the discrepancies among different TSI instruments have resolved the discrepancies bringing other TSI records in line with SORCE/TIM. Given the value of these data for the climate science community, and the recent success of the inter-comparison of the multiple TSI data records to bring them in line, the panel recommends that a 'TSI science team" perhaps comprised of experts within the TSI and close climate community be formed that can provide a focal point for oversight, science investigation, and collaboration. Furthermore, discrepancies also exist between the SSI measurements of SORCE and results from other observational and modeling studies. In order to ensure the quality of SORCE SSI results, the panel recommends an independent review of the SSI methods and results.

The spacecraft has battery issues, and the mission team acknowledged that the additional staffing provided in the last Senior Review panel was very helpful in mitigating these issues. However, it must be recognized that the SORCE mission is rated as High Risk for technical failure within the mission extension despite the excellent efforts being made by the mission team to mitigate problems and prolong battery performance. It is quite possible that SORCE will fail to overlap with the future TSI missions planned for late 2013 and 2016. In spite of this risk, the contribution of the measurements to the historical data base of solar flux is invaluable and these measurements should be continued until spacecraft failure in order to help prevent data gaps in this climate-critical data product. Thus, the Senior Review Panel recommends continuation of this mission at the baseline budget.

Terra

Terra is a huge success, and continuation of the 13-year record from its five instruments: ASTER, CERES, MISR, MODIS, MOPITT, providing 79 core products, is critical to a wide array of Earth system science questions. Extending the record will enhance our understanding of long-term atmospheric, terrestrial, and ocean phenomena. It is a workhorse for regional-to-global scale monitoring. Terra data are used in almost every area of earth science, and the science/publication record is outstanding. The demand for Terra data is obvious with nearly 155 M files delivered, and more than 1,100 peer-reviewed publications in 2012 alone bringing the total for the lifetime of the mission to over 7,600.

The overall objectives of the Terra mission include 1) extending the baseline for morning-orbit climate and environmental data records, 2) enabling comparison of measurements acquired so far with likely future recurrences of natural events, e.g., fires, volcanic eruptions, floods, oil spills, changes in ice sheets, and 3) adding value to recently launched missions (e.g., SNPP, LDCM) or those to be launched in the next few years. Each of the five instruments has made valuable contributions to the study of Earth as a system, to discovery of how the Earth is changing, and to exploration of human interactions with these changes.

For the extended mission, the objectives of: ASTER are to extend the record of moderate high-resolution changes in land cover, provide emergency data acquisitions for natural and man-made disasters, and extend the archives for observations of active volcanoes and valley glaciers; CERES are to produce an integrated climate data record for detecting decadal changes in the Earth's radiation budget, improve understanding of cloud-aerosol-radiation interactions, and (with MODIS) bridge the interval between older satellites and SNPP and JPSS; MISR are to update the Plume Height Climatology Product to include extended dust, volcanic, and wildfire smoke plumes and to facilitate the use of the MISR cloud motion vector (CMV); MODIS are to extend the 13-year archive of ocean productivity and sea surface temperature, extend the 13-year archive for land productivity and other land characteristics, such as albedo, leaf area index, land surface temperature, and seasonal variation of vegetation, and extend the archive of tropospheric properties, including cloud and aerosol properties, cloud fraction and atmospheric profiles of temperature and moisture; and MOPITT are to extend the 13-year record of tropospheric CO, show paths of transport for atmospheric pollution, and provide a proxy to aid in constraining the retrieval of tropospheric CO_2.

The continuity of these data products is highly desirable for the scientific community and the broader user community. As such, the Senior Review Panel recommends that the Terra mission should be continued at baseline.

TRMM

The Tropical Rainfall Measurement is an essential mission to address NASA's Strategic Science Questions with regard to the water cycle and climate research, and TRMM products are widely used in weather forecasting, natural hazards, and water and natural resources management and applications. TRMM provides the only consistent measurement of precipitation in the tropics from 4-km resolution to planetary scales, and the TRMM PR and TMI are the standard for remote-sensing of precipitation from space. In addition to the scientific achievements reported in the proposal in Section 2, and which can be tracked in the peer-review literature, there is a large number of users of precipitation products derived from TRMM observations in the operational, public health, agriculture and natural resource management agencies around the world. In addition to precipitation data sets, the LIS (Lightning Imaging Sensor) monitors lightning activity in the tropics, and TMI (TRMM Microwave Imager) measurements are used also to monitor SST (Sea Surface Temperature). Besides 2-D gridded precipitation products, profile data sets such as reflectivity, rainfall and higher level products such as

latent heating have motivated many new scientific insights into the vertical structure of the atmosphere, and tropical climate.

The overall science objective of an extended TRMM mission is to determine the time and space varying characteristics of tropical rainfall, convective systems, and storms and how these characteristics are related to variations in the global water and energy cycles. Extension of TRMM will result in: 1) an improved climatology of precipitation characteristics, especially extremes; 2) diagnosis and testing of inter-decadal and trend-related processes in the water cycle; 3) assessment of the impact of humans on rainfall characteristics and processes; 4) robust determination of convective system, tropical cyclone, and lightning characteristics; 5) advances in hydrological applications over land (basin-scale assessments, water management); 6) improved modeling of the global water/energy cycles for weather/climate predictions; and 7) improved monitoring and forecasting of tropical cyclones, floods and other hazardous weather. TRMM is the precursor to the upcoming GPM mission to be launched in 2014, which will benefit from TRMM sensor technology, ground validation and algorithm legacies, and also from cross-calibration of radar and radiometer instruments. TRMM and GPM are commended for having devised a well-planned transition process that preserves TRMM strengths while building day-1 capacity for GPM algorithms and products. The Panel recommends continuing TRMM at the baseline budget. However, the Senior Review Panel also recommends that the transfer of GV, algorithm development and project management activities be implemented as soon as possible as after GPM launch while preserving core TRMM activities essential to operations and product delivery.

APPENDIX 1. TECHNICAL REVIEW SUBPANEL REPORT

Results from the Technical Review Subpanel
of the Senior Review 2013 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 ESD thus periodically evaluate the allocation of Mission Operations 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 thirteen missions (in alphabetical order) were invited to propose to the 2013 Senior Review: the Active Cavity Radiometer Irradiance Monitor SATellite (ACRIMSAT), Aqua, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), CloudSat, Earth Observing-1 (EO-1), Gravity Recovery And Climate Experiment (GRACE), Jason-1, Jason-2/ Ocean Surface Topography Mission (OSTM), Quick Scatterometer (QuikSCAT), Solar Radiation and Climate Experiment (SORCE), Terra and the Tropical Rainfall Measuring Mission (TRMM). 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. While a mission's contribution to NASA's research science objectives is the primary evaluation criterion for mission extension, the ESD 2013 Senior Review 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 is an independent analysis group with sole responsibility to evaluate the scientific merit of each mission with respect to NASA's Earth science strategic plans and objectives. The Science Panel draws from recognized expert members of the Earth Science research community, and is 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 assesses 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 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.

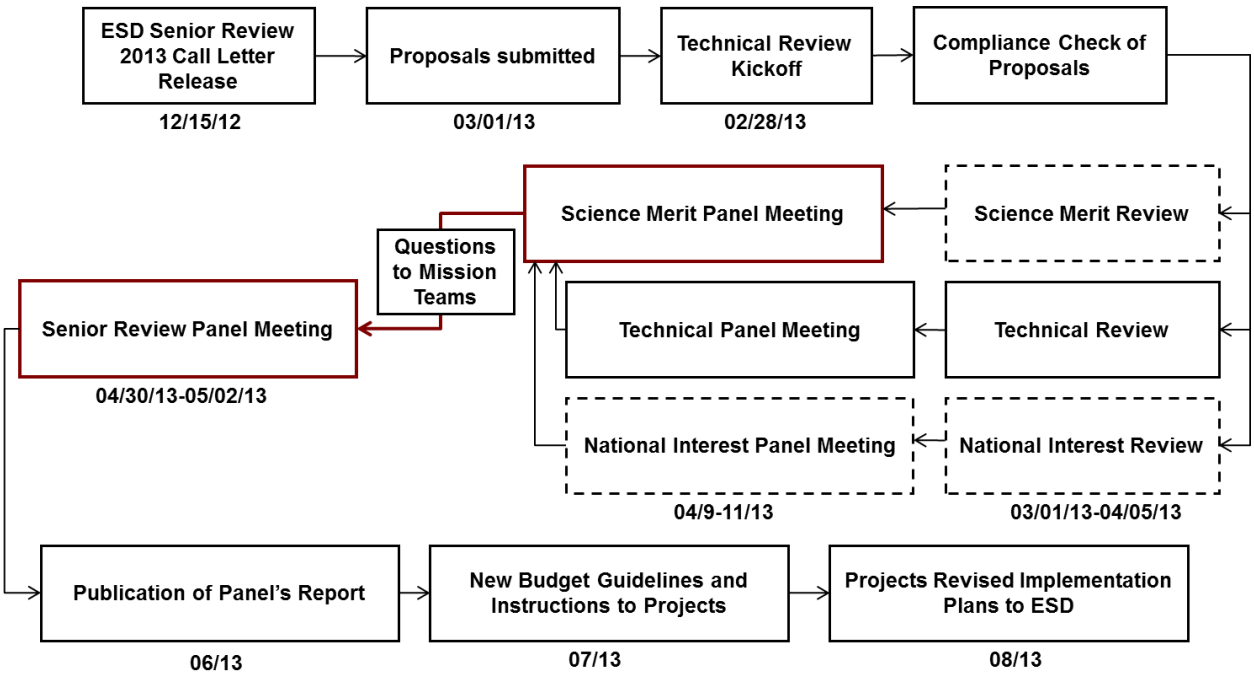


Figure 1. Senior Review Flow

Proposers were instructed in the "Call for Proposals – Senior Review 2013 of the Mission Operations and Data Analysis Program for the Earth Science Operating Missions" to: discuss the overall technical status of the components of the mission, and the team's approach to managing operations to optimize health and vitality of the components including the spacecraft, instruments, and ground systems (e.g., 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 components 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; and 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 review considers 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 review results 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 reviewers that 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 would generate no 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 reviewers who are experts in the areas that they review. These areas included Instruments, Flight Systems, and Mission Design and Operations. The Technical Review Subpanel was 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 generates no finding. For each proposal, these individual findings are gathered into a table that is the basis of a subpanel discussion teleconferences.

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.

The Plenary 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 2013 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 assigned by the Technical Review Subpanel and a rationale paragraph explaining the rating. The form enumerates the Major Strengths, the Major Weaknesses, the Minor Strengths, the Minor Weaknesses, and any questions to be sent to the proposing mission teams. 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 results of the Risk Ratings assigned by the Technical Review Subpanel to 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 is included for each proposal. 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 2013 Senior Review

Mission \ Risk	Low	Medium-Low	Medium	Medium – High	High
GRACE					X
QuikSCAT					X
SORCE					X
TRMM					X
Aura				X	
CloudSat				X	
EO-1				X	
Jason-1				X	
Aqua			X		
CALIPSO			X		
ACRIMSAT		X			
Terra		X			
OSTM	X				

ACRIMSAT

The Active Cavity Radiometer Irradiance Monitor SATellite (ACRIMSAT) proposed mission extension is rated as Medium-Low Risk**.** The Technical Review Panel has identified 2 Major Strengths, no minor strengths, no Major Weaknesses and one minor weakness that influence the risk determination. **All 3 radiometers are performing nominally and are expected to operate very well through the proposed mission extension period. And, the spacecraft bus is in nearly the same condition as when it was launched and should survive through the mission extension period.** However, ACRIMSAT was built using a number of single-string Class D parts that have exceeded their design lifetimes.

Aqua

The Aqua proposed mission extension is rated as Medium Risk**.** The Technical Review Panel has identified 1 Major Strength, 3 minor strengths, 1 Major Weakness and 3 minor weaknesses that influence the risk determination. **The spacecraft bus is in excellent condition and should be fully functional past the mission extension period.** The Atmospheric InfraRed Sounder (AIRS), Clouds and the Earth's Radiant Energy System (CERES), and Moderate Resolution Imaging Spectroradiometer (MODIS) all seem to be degrading gracefully. The AIRS science team has developed techniques to cope with spectral and radiometric shifts and noisy detectors. And, the ground system architecture continues to be robust and has been carefully kept up to date. However, **the reliability of the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) spin motor is uncertain and continued operation has the potential to force the spacecraft into Safe State.** On CERES, there is no data to support the claim that polymerization of molecular contaminant on the ShortWave (SW) channel has leveled off. The MODIS Shortwave and Mid-wave InfraRed (SMIR) and LongWave InfraRed (LWIR) channel Focal Plane Assemblies (FPA) temperatures show oscillations starting in 2011 that are not explained and which could indicate thermal control issues. And, the narrative detailing the performance of the Guidance, Navigation, & Control (GN&C) system is lacking. The risk for the 4-year mission extension is expected to be higher.

Aura

The Aura proposed mission extension is rated as Medium-High Risk**.** The Technical Review Panel has identified 1 Major Strength, 1 minor strength, 2 Major Weaknesses and 5 minor weaknesses that influence the risk determination. **Most spacecraft flight systems are operating nominally with redundancy and are expected to continue to perform very well through the proposed mission extension period.** And, the operational budget status of the four life-limited items on the Ozone Monitoring Instrument (OMI) is good. However, **due to unspecified aging of the Microwave Limb Sounder (MLS) and the lack of redundancy, there is significant uncertainty concerning the remaining observation time. The potential for significantly degraded operation or loss of the Tropospheric Emission Spectrometer (TES) instrument during the proposed two-year mission extension period is high.** The OMI row anomaly, first observed May 2008, continues and the data shown in Figures E-29,30 are not fully explained leading to a concern of further degradation. There are concerns about the impacts of OMI Charged Coupled Device (CCD) temperatures, the impact on science data quality due to the reduction in TES calibration frequency, and the potential for disruption to science data handling due to the recurring anomaly in the Formatter Multiplexer Unit/Solid State Recorder (FMU/SSR). And, staff reductions may leave the Earth Observing System (EOS) operations center inappropriately vulnerable. The risk for the 4-year mission extension is expected to be higher.

CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) proposed mission extension is rated as Medium Risk**.** The Technical Review Panel has identified 1 Major Strength, 2 minor strengths, no Major Weaknesses and 3 minor weaknesses that influence the risk determination. **All flight systems, including Command and Data Handling, Telecommunications, Power, Attitude and Orbit Control, Propulsion, Thermal Control, and Flight Software are fully functional and retain full redundancy.** The Imaging Infrared Radiometer (IIR) and Wide Field Camera (WFC) continue to function well, with no dead or blind pixels. And, CALIPSO operations continue to proceed as planned coordinating between Centre National d'Etudes Spatiales (CNES) and NASA Goddard Space Flight Center (GSFC) Conjunction Assessment Risk Analysis (CARA) for ensuring safety-of-flight with the A-Train. However, the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) Laser 1 is a life-limiting item that is losing pressure at a rate faster than predicted. The portion of the decreasing Laser output caused by laser

diode pump arrays dropouts and the rate of increase of those dropouts were not presented; the proposed workarounds could have deleterious effects. And, the Signal-to-Noise Ratio (SNR) for the 532P channel is expected to fall below requirements before the end of a 4-year mission extension. The risk for the 4-year mission extension is expected to be higher.

CloudSat

The CloudSat proposed mission extension is rated as Medium-High Risk. The Technical Review Panel has identified no Major Strengths, 3 minor strengths, 1 Major Weakness and 1 minor weakness that influence the risk determination. The Cloud Profiling Radar (CPR) sensitivity exceeds predicted end-of-life performance by a significant margin. The spacecraft subsystems, with the exception of the Power Subsystem, are performing nominally and over 90% of critical items have retained their redundancy. And, the Daylight-Only Operation (DO-Op) scenario covers 56% of each orbit while preserving remaining battery integrity during eclipses, demonstrating mission flexibility. However, **the potential impacts of the operational changes required to accommodate the severe reduction in battery capacity create a large uncertainty that the spacecraft will survive the proposed mission extension period.** And, the receive side of one of the transponders is currently latched up and is inoperable, leaving the spacecraft single string using the other transponder. The risk for the 4-year mission extension is expected to be higher.

EO-1

The Earth Observing-1 (EO-1) proposed mission extension is rated as Medium-High Risk**.** The Technical Review Panel has identified no Major Strengths, 1 minor strength, 2 Major Weaknesses and 3 minor weaknesses that influence the risk determination. The EO-1 mission ground system has continually evolved to an efficient and autonomous lights-out operation for maintenance, planning and data dissemination. **However, there is insufficient data presented to assess the true status and risk of the instruments on EO-1 as required by the Call Letter instructions. There is insufficient data presented to assess the true status and risk of the EO-1 bus as required by the Call Letter instructions.** Items 7-10 on the Life Limiting Items List refer to radiation dose tolerances that are sub-minimum for life beyond 2008 and 2011. EO-1 mission life expectancy is power limited and is directly affected by the natural drift of the orbit. And, the operations team has not been performing standard maintenance for an aging satellite. The risk for the 4-year mission extension is expected to be higher.

GRACE

The Gravity Recovery And Climate Experiment (GRACE) proposed mission extension is rated as High Risk**.** The Technical Review Panel has identified no Major Strengths, 3 minor strengths, 2 Major Weaknesses and no minor weaknesses that influence the risk determination. The center of mass trim electronics and the active thermal control system have been failure free and continue to operate reliably on their primary sides with adequate adjustment range. On-board Data Handling and Attitude and Orbit Control subsystems on both satellites are performing nominally, retain full redundancy, and appear able to support operations during the proposed mission extension period. And, the joint NASA/ESA ground system and staffing is very efficient with significant redundancy and robustness to accommodate anomalies and ad hoc mission support. However, **the GRACE mission requires both satellites to be operating to perform the sensitive gravity measurements, but key instrument subsystems now lack redundancy. And, the GRACE vehicle's flight systems are seriously degraded and lack redundancy.**

Jason-1

The Jason-1 proposed mission extension is rated as Medium-High Risk**.** The Technical Review Panel has identified 1 Major Strength, 3 minor strengths, 2 Major Weaknesses and 1 minor weakness that

influence the risk determination. **The key instruments on Jason-1 continue to operate stably and retain redundancy.** The Propulsion System is operating nominally with significant propellant margin. The Power System is operating nominally with 325 W margin in worst case conditions. And, Jason-1 mission operations follow well-defined procedures and backup ground stations provide resiliency to the mission**.** However, **several flight systems have experienced failures and are now using spare or redundant hardware, any failure of which would result in loss of the mission. In March 2012, Jason-1 experienced degradation of its onboard flight software memory, increasing the risk of losing satellite command and control, and imposing a safety-of-flight hazard.** And, the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) ultra-stable oscillator in the primary receiver failed early on, removing redundancy**.** The risk for the 4-year mission extension is expected to be higher.

Jason-2/OSTM

The Ocean Surface Topography Mission (OSTM) proposed mission extension is rated as Low Risk**.** The Technical Review Panel has identified 2 Major Strengths, 2 minor strengths, no Major Weaknesses and no minor weaknesses that influence the risk determination. **OSTM instrument systems continue to perform very well and all retain full redundancy. The OSTM bus has operated exceptionally well providing high confidence that it will remain fully functional during the proposed mission extension period.** Three additional payloads: the Environment Characterization and Modelisation-2 (Carmen-2), the Light Particle Telescope (LPT), and the Time Transfer by Laser Link (T2L2) continue to perform very well with redundancy. And, ground system operations are stable, and teams have well-defined roles.

QuikSCAT

The Quick Scatterometer (QuikSCAT) proposed mission extension is rated as High Risk**.** The Technical Review Panel has identified no Major Strengths, 1 minor strength, 2 Major Weaknesses and 1 minor weakness that influence the risk determination. Most instrument subsystems and their spacecraft interfaces are operating nominally. However, **cell losses have significantly reduced battery capacity, jeopardizing the mission, and requiring that the scatterometer be powered off entirely during eclipse periods. The QuikSCAT bus has lost redundancy in critical subsystems, and the potential of mission-ending failure during the proposed mission extension period is high.** And, additional GPS system failures may force the program to fall back to using ground station tracking data to determine position.

SORCE

The Solar Radiation and Climate Experiment (SORCE) proposed mission extension is rated as High Risk**.** The Technical Review Panel has identified 1 Major Strength, 1 minor strength, 1 Major Weakness and 3 minor weaknesses that influence the risk determination. **The Spectral Irradiance Monitor (SIM) and XUV Photometer System (XPS) instruments continue to perform very well and to retain as-designed redundancy.** The SOLar STellar Irradiance Comparison Experiment (SOLSTICE) and Total Irradiance Monitor (TIM) instruments are performing well despite challenges resulting from powering off during eclipse. However, **SORCE's battery capacity is seriously degraded and any additional battery anomaly would likely end the mission.** If the two-wheel attitude control modes are implemented, pointing stability will be negatively impacted to an uncertain degree for approximately 14% of the year. The attitude control system is now single-string and failure of the remaining star tracker would end the mission. In addition, it is unclear why SORCE mission operations added automation to support a single Tracking and Data Relay Satellite (TDRS) contact per day, but still has 2 crew members manually overseeing the remaining daily contacts.

Terra

The Terra proposed mission extension is rated as Medium Low Risk**.** The Technical Review Panel has identified 2 Major Strengths, 3 minor strengths, no Major Weaknesses and 4 minor weaknesses that influence the risk determination. **The Multi-angle Imaging Spectroradiometer (MISR) instrument is performing very well. The propulsion system, solar arrays, attitude/guidance control and determination and communication subsystems continue to perform very well, maintain their redundancy, and appear to be able to support science operations for a four-year mission extension period.** Overall, a Reliability and Lifetime Study performed in 2010 predicts instrument probabilities ranging from 0.76 - 0.63 for Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) to 0.94 - 0.89 for Moderate Resolution Imaging Spectroradiometer (MODIS) through the two- and four-year extension periods, respectively. The Clouds and the Earth's Radiant Energy System (CERES) instruments are operating well, despite a scene-dependent ShortWave InfraRed (SWIR) error due to UltraViolet (UV)-polymerized contamination. The Measurements Of Pollution In The Troposphere (MOPITT) science team overcame the loss of four of the instrument's 8 channels with a technique that allows vertical resolution that is as good as the pre-failure data. However, although MODIS continues to operate stably, the scan mirror response vs. scan angle continues to be problematic as its effect increases with time. The Direct Access System Modulator (DASM) of the Terra Communications Subsystem has lost redundancy, with the remaining unit a single point failure, the loss of which would curtail direct broadcast to users. The impact of additional battery cell losses on the science mission was not addressed. Overall data storage capacity has been reduced by 15.5% due to 9 of the 29 Printed Wire Assembly (PWA) boards in one of the two Data Memory Units being disabled. The risk for the 4-year mission extension is expected to be higher.

TRMM

The Tropical Rainfall Measuring Mission (TRMM) proposed mission extension is rated as High Risk**.** The Technical Review Panel has identified 2 Major Strengths, 2 minor strengths, 1 Major Weakness and 2 minor weaknesses that influence the risk determination. **The Visible Infrared Radiometer (VIRS), TRMM Microwave Imager (TMI) and Lightening Imaging Sensor (LIS) continue to operate nominally after over 15 years in orbit. All of the spacecraft subsystems are operating nominally or near-nominal and the majority maintain full design redundancy.** There has been little or no perceivable degradation in Precipitation Radar (PR) performance since launch. And, the TRMM ground and mission operations system has continued to modernize and automate support to the vehicle and mission. However, **independent analyses indicate TRMM does not have sufficient propellant to support a two-year mission extension.** The PR experienced failure of the A-side Frequency Converter/ Intermediate Frequency (FCIF) resulting in a loss of redundancy. And, the Clock Card/Frequency Standard and the Power System Integration Box (PSIB) have lost redundancy.

APPENDIX 2. NATIONAL INTEREST PANEL REPORT

Report of the 2013 National Interests Sub-panel of the NASA Senior Review

Chair: Francis Lindsay, NASA Applied Sciences Program

Co-Chair: John Haynes, NASA Applied Sciences Program

The 2013 National Interests Review assessed the contributions of the core data products of the 13[1] 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, 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 US Air Force, the US Navy; the Environmental Protection Agency (EPA); the US Geological Survey (USGS); the Naval Research Laboratory (NRL); Conservation International (CI), the American Society for Photogrammetry and Remote Sensing (ASPRS); the National States Geographic Information Council (NSGIC) and the Urban and Regional Information Systems Association (URISA).

The panel met April 9-11, 2013, in Pentagon City, Virginia.

Pre-panel Activities

Each organization represented on the panel pre-assessed three primary factors and one overall rating for each mission during March 2013. 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.

[1] Note: ACRIMSAT was added for the 2013 Senior Review.

Panel Activities

Following the pre-assessments, the organization representatives met in a formal panel session over three days in April 2013. 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 May 2013.

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 13 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 2013 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, TRMM***
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.	***Aura, CALIPSO, CloudSAT,, GRACE, Jason-1, Jason-2/OSTM, QuikSCAT, 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.	***ACRIMSAT, 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	Overall Score	Utility Rank
Aqua	162	Very High
Terra	153	Very High
TRMM	125	Very High
Aura	109	High
Jason-2/OSTM	106	High
GRACE	91	High
CloudSAT	78	High
CALIPSO	77	High
EO-1	72	Some
Jason-1	71	High
SORCE	61	High
QuickSCAT	59	High
ACRIMSAT	19	Some

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

NASA 2013 Earth Science Senior Review

Overall Utility Rating from National Interests Panel, by Organization & Mission/Sensor

Mission / Sensor	Overall Rating	Civil Agencies						Military / Intelligence Community			State & Locals	Private Sector / NGOs		
		NOAA NWS	NOAA NOS	FAA	USDA	USGS	EPA	NAVY/CNMOC	DOD/NAVY/ NRL	DOD/USAF	NSGIC	Conservation Intl.	URISA	ASPRS
ACRIMSAT	Some Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable
Aqua	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very 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	High Utility
AIRS	Very High Utility	Very High Utility	High Utility	Very High Utility	Not Applicable	Not Applicable	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Not Applicable	Some Utility	Not Applicable
AMSR-E	High Utility	High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	High Utility	Very High Utility	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable
CERES	High Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	High Utility	Not Applicable	Very High Utility	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	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility
Aura	High Utility	High Utility	High Utility	High Utility	Not Applicable	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	High Utility	Not Applicable
HRDLS	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable
MLS	High Utility	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable
OMI	Very High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	Very High Utility	Very High Utility	High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	High Utility	Not Applicable
TES	Some Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable
CALIPSO	High Utility	Some Utility	Some Utility	Very High Utility	Not Applicable	Some Utility	Very High Utility	Not Applicable	Very High Utility	Not Applicable	High Utility	Not Applicable	High Utility	Not Applicable
CloudSat	High Utility	Some Utility	Some Utility	Very High Utility	Not Applicable	Not Applicable	High Utility	Some Utility	High Utility	High Utility	High Utility	Some Utility	Some Utility	Not Applicable
EO-1	Some Utility	Some Utility	Some Utility	Some Utility	Very High Utility	Very High Utility	Very High Utility	Some Utility	Some Utility	Not Applicable	Some Utility	High Utility	Some Utility	High Utility
GRACE	High Utility	High Utility	Very High Utility	Not Applicable	High Utility	Some Utility	High Utility	High Utility	High Utility	High Utility	Very High Utility	Not Applicable	High Utility	High Utility
Jason-1	High Utility	High Utility	Very High Utility	Not Applicable	High Utility	Some Utility	Not Applicable	Very High Utility	Very High Utility	Not Applicable	Some Utility	Some Utility	Some Utility	Not Applicable
Jason-2/OSTM	High Utility	High Utility	Very High Utility	Not Applicable	High Utility	Some Utility	Some Utility	Very High Utility	Very High Utility	Some Utility	Some Utility	Some Utility	High Utility	Not Applicable
QuikSCAT	High Utility	Some Utility	High Utility	Some Utility	Not Applicable	High Utility	Some Utility	High Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable
SORCE	High Utility	High Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	Some Utility	Some Utility	Not Applicable	Some Utility	Not Applicable
Terra	Very High Utility	Very High Utility	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	High Utility	Very High Utility
ASTER	High Utility	Not Applicable	Some Utility	Some Utility	High Utility	Very High Utility	High Utility	Not Applicable	High Utility	Not Applicable	Very High Utility	High Utility	High Utility	High Utility
CERES	Some Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable
MISR	Some Utility	Not Applicable	Some Utility	Some Utility	Not Applicable	Some Utility	High Utility	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable
MODIS	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very 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	High Utility	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable
TRMM	Very High Utility	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	High Utility	High Utility

Color Key	Very High Utility	High Utility	Some Utility	NA

PANEL SUMMARIES OF EACH MISSION

Aqua (Very High Utility)

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

1) AMSR-E: Numerical weather prediction, sea ice, TC location/structure/track; rain estimates for active/global TCs; Considered important to continue for cross-validation with GCOM AMSR2.;

2) AIRS/AMSU: Importance and utility widely noted. Of significant importance to aviation community (SO2, volcanic plumes); volcanic ash detection in Rapid Update Cycle Rapid Refresh Model. Profiles assimilated in NOAA NWP and considered to be their most critical NASA data set;

3) MODIS: MODIS data remains the most widely and broadly used data in NOAA. MODIS images have become one of the primary data sources for their ice analysis. USAF uses MODIS data for WRF model inputs, Snow depth, Land Information System (LIS), precipitation estimates, Cloud Detection Forecast System-II model, Cloud detection, imagery, ice/snow/volcanoes, fires, smoke, Tropical cyclone forecasting NSGIC uses MODIS in similar cloud, fire, dust, cyclone analysis/forecast.

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. Value of other sensors, particularly ASTER, added to utility rating. Uses included:

1) DOD/Navy uses data for fires, volcanic plumes, near coastal; impact ship operations. NOAA/NOS National Ice Center uses ASTER for ice edge detection, tropospheric chemistry,;

2) FAA using MISR to distinguish sulfate/water vapor from ash-dominated plumes which could be used in volcanic air hazard mitigation;

3) CERES value for general climate applications; global weather forecast models, similar to Aura;

4) MODIS: ASPRS uses Terra MODIS for public/environmental health; disease vectors, NDVI, land surface temperature. For EVI or NDVI, blue band at higher resolution would benefit future applications. EPA using MODIS for aerosol, change detection algorithms, hypoxia driven. NOAA/NOS uses data for chlorophyll and suspended matter analysis for monitoring runoff into the Chesapeake Bay. These data are essential for assessing the health and recovery of the Bay and monitoring algal blooms related environmental indicators. NSGIC/Idaho "… use Terra MODIS products for the true and false color imagery and AOD. The imagery is useful to detect transport of smoke and dust."

TRMM (Very High Utility)

TRMM provides key input to global rainfall estimation, as it is used directly within the tropics and indirectly outside of the tropics to calibrate multi-sensor estimates of PPT. TRMM has active and passive microwave plus thermal capabilities, making it the most powerful satellite sensor set for studying

rainfall. Continuation of TRMM data will allow the community to better link the TRMM data set to that of GPM. Uses included:

1) ASPRS: uses TRMM data for public health applications, modeling of disease vectors based on precipitation data.

2) NOAA/NWS notes imagery from TRMM can reveal the location and structure of the TC circulation center when the center is not visible in geostationary imagery due to mid and high-level cloud cover.

3) USGS notes TRMM data are a key component of FEWS Net Data portal.

4) USDA: TRMM precipitation products are used in comparison with other precipitation products from World Meteorological Organization (WMO) and from the US Air Force Weather Agency (AFWA).

Aura (High Utility)

The data are useful for improving understanding for how various molecular species contribute to changes in the atmosphere and to atmospheric forcing. In recognition of this fact and the potential benefit from this research, the panel rated the value of this mission as HIGH with OMI observations remaining the most used. However, the current lack of real time data access and wider swath coverage preclude using this data more widely in operations.
Uses included:

1) USAF using OMI for ozone, total column profile, and used for detection of SO2 for volcanic activity. Supports high-altitude missions and radiation maps.
2) FAA delivers information regarding the presence of SO_2 and airborne volcanic ash. OMI NRT SO2 and Aerosol Index (AI) data have been integrated into the decision support system at the NOAA/NESDIS Washington Volcanic Ash Advisory Center (W-VAAC).
3) USGS using ozone measurements from the OMI are part of a long-term ozone history used to correct for the atmosphere in Landsat, EO-1, MODIS and ASTER surface reflectance retrieval.
4) NSGIC finds the NO_2 products are useful to help quantify and verify emissions inventories and to calculate long-term background NO_2 values for our permit modelers, AQ monitoring.
5) NOAA/NOS Heavy use for sulfur dioxide modeling, decision support tool (volcanic ash advisory product) creation of aerosol scale and sulfur dioxide proxies.

Jason-2/OSTM (High Utility)

This mission has data products central to oceanographic & weather communities, but of less utility for other communities. Tandem mission with Jason-1 to observe the variability of the long-term ocean cycles is seen to be of value. The addition of OSTM has extended the ability to find long time scale cycles that have not been seen by any other method. OSTM and Jason-1 have allowed for the use of cross calibration that enables the overall reduction of variability in either sensor. Uses included:

1) Only Jason-1 and OSTM observations have sufficient accuracy to detect ocean changes at global and basin scales. Increased spatial resolution of sea surface height data is developed when combined with Jason-1 data;

2) OSTM surface wave height (SWH) data are also used by the National Hurricane Center's (NHC) marine forecasters to provide analyses of the wave field associated with tropical cyclones;

3) Wave-height conditions/forecasts; warnings to mariners;

4) USDA's Foreign Agricultural Service (FAS) uses OSTM as part of its Global Reservoir and Lake Monitor system to estimate reservoir and lake surface altimetry globally;

5) AFWA plans to assimilate OSTM data in their Weather Research and Forecasting (WRF) model during 2012-13.

GRACE (High Utility)

The panel indicated that the overall value of this mission was high (67%). The frequency of accessing data ranged from 'routine' (40%) to 'occasional/rare' (30%). The panel indicated that their representative organizations required the data either near real time or within 1-2 days (33%), whereas (30%) used the data for archival purposes.

Uses included:

1) NOAA: The GRACE satellite has been, and remains, one of the most critical satellites to the physical geodesy team at the National Geodetic Survey. Its data is 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.

2) USDA-ARS Genetics and Precision Agriculture Research Unit: The issue of ground water and agricultural production is of immense concern and in some places ground water reserves are being depleted to critical levels. This mission is referenced in several sources as one way to assess terrestrial water variations.

3) USGS/FEWS NET: our current monitoring products reflect anomalies in the weather and vegetation; the incorporation of GRACE-derived information would be reflective of any long term or climate change impacts on terrestrial water components.

4) CNMOC-FNMOC currently ingests GRACE RO data into their weather forecast system.

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.

Uses included:

1) FAA data used 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.

2) NOAA: Earth System Research Laboratory uses CloudSat as one of their 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.

3) NSGIC: Montana Bureau of Mines and Geology uses CloudSat data to model hydrologic systems, determine impact on water resource changes, and determine land use changes.

4) NRL uses CloudSat data for 3D cloud research and verification of operational 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 several others saying it had some utility for their users. Several organizations are using CALIPSO data for operational and verification purposes. Over a third of the agencies do not use CALIPSO data at all. 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.

2) The Idaho Dept. of Environmental Quality uses CALIPSO curtains to explore the vertical distribution of aerosols. The vertical feature mask is useful for identifying aerosol types.

3) The USGS Earth Observation and Science Center utilizes data for monitoring aerosols from volcanic eruptions, and also distributed CALIPSO data through the USGS HDDS system.

4) NRL assimilates data into aerosol models and their 3D cloud analysis scheme, and both NRL and the NWS use it for model validation.

EO-1 (Some Utility)

EO-1s 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 the Landsat/Landsat Data Continuity Mission. The panel split on those who recognize the mission value while an equal group sees only some value. Uses included:

1) NOAA NOS: overall some utility. Hyperion instrument useful for complex shallow area waters.

2) NRL finds value in data for validation purposes.

3) USDA: Very happy with it. Forest service use imagery for burned area emergency response.

4) EPA compares EO-1/Hyperion data with their airborne hyperspectral sensor for validation and calibration and applied research.

Jason-1 (High Utility)

The Panel consensus was to give an overall rating of 'High'. The very high ratings came from the ocean community (NOAA, NRL, NAVY/CNMOC), though interests in water-resource management (especially crop irrigation), and sea-level rise uses for conservation were noted. The loss of Jason-1 would have a negative measurable impact on operational agencies.

Uses included:

1) USDA: Jason-1 and Jason-2 telemetry data are used to provide heights of large 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 NMFS: The Jason altimetry data is used to support the needs from public users (fishermen – commercial & private), national and international government agencies, managers, and researchers in order to identify, track and monitor the development of mesoscale oceanographic eddies throughout the Pacific.

3) NOAA NOS: Jason-1 and other altimetry satellite data are incorporated into oceanic gravity models. These gravity models are one of the most important ways in which near-shore geoid models are kept realistic. Without such altimetry, the available gravity data near shore would dwindle significantly, as would its accuracy.

SORCE (High Utility)

The overall rating was that SORCE was of High Utility. This overall ranking reflects the usefulness SORCE data within agencies applications they use to monitor solar radiation and atmospheric climate change. SORCE data products are utilized for space weather forecasting, and near real time monitoring of solar flare events, and also used as inputs to various agencies climate-modeling applications.
Uses included:

1) NOAA-NOS reported that they use SORCE data to determine how solar irradiance contributes to atmospheric climate change and that the SORCE heritage data will be use to help calibrate the new JPSS total irradiance sensor when launched.

2) NOAA-NWS reported that SORCE irradiance data was critical in climate monitoring and that some application over space weather/proxy for MG2.

3) NRL uses SORCE data on solar irradiance variation is crucial in determining impacts on climate change and that SORCE data has been the most accurate total solar irradiance ever recorded.

4) USAF reported some utility for SORCE irradiance data and that other branches/departments of the Air Force have applications for them.

QuikSCAT (High Utility)

Due to its use as an accurate cross calibration source of other sensors measuring/monitoring tropical cyclone activity, and the importance of TC forecasting to the national interest, QuikSCAT is considered to have relatively high rating to the National Interests Panel. Additionally, of the National Interests Panel agencies that rated the QuikSCAT mission for utility, 5 rated it as having “High Utility” to the mission of their organization.
Uses included:

1) NAVY/CNMOC: We are just beginning to receive OceanSat-2 OSCAT data. As this sensor integrates into daily operations the cross-calibration from QuikSCAT’s backscatter signal makes this sensor’s utility very high for TC forecasting, aviation weather and navigation safety/ship routing.

2) FAA: Data from the satellite can be used for calibrations of other satellite systems for long term improvements in general forecasting.

3) NOAA: Use for calibration with OSCAT.

ACRIMSAT (Some Utility)

Panel members provided overall ratings of either “Some Utility” or “Not Applicable”. The overall rating of “Some Utility” reflects fact that most of the organizations represented on the panel do not make direct use of the TSI data but it was acknowledged that the data is essential for long-term climate change research.

Uses included:

1) NRL: Similar use and value as SORCE, but ACRIMSAT is far less accurate and produces more noise, making it hard to develop reliable models. Using both devices fro the same end – data input for climate change.

2) NOAA NCBO: Using in some capacity.

APPENDIX 3. DETAILED SCIENCE PANEL MISSION REVIEWS

ACRIMSAT

Positive endorsement: ACRIMSAT/ACRIM3 provides total solar irradiance measurements that are used for studies of solar physics and the interaction and influence of solar radiation on Earth's physical configuration. This mission is the third in a series (ACRIM1 on SMM; ACRIM2 on UARS), and represents the last in this series. The instrument and spacecraft are in good health, with the main concerns centered on correct assessment of instrument degradation and spacecraft battery maintenance.

Recommendation: Continuation of projects as currently baselined.

ACRIMSAT observations should be continued to avoid the possibility of future data gaps in the TSI data record. Currently operating missions for TSI include TIM on SORCE, VIRGO on SOHO, and PREMOS and SOVAP on PICARD. The SORCE spacecraft has experienced battery failures and it may not continue to operate until either the TIM witness instrument, TCTE, to be flown on STPSat-3, or a new TIM to be flown on JPSS, are launched. As for the non-U.S. missions, VIRGO/SOHO was launched in 1995 and PICARD is scheduled for termination in the near future.

The 2009 Senior Review Panel recommended the ACRIM team resolve the existing 0.35% discrepancy between ACRIMSAT/ACRIM3 and SORCE/TIM. As part of the GLORY/TIM mission, LASP developed the TRF facility. The recent measurements of the ACRIM3 Engineering Model (EM) at LASP TRF, and characterization of its components at LASP, NIST, and NRL has resulted in an estimated correction of about -0.5% that has been applied to the ACRIMSAT ACRIM3 TSI record. The agreement between ACRIMSAT/ACRIM3 and SORCE/TIM is now within the estimated uncertainties. The ACRIM team is to be congratulated for successful reconciliation of this discrepancy in the TSI record.

The Senior Review Panel strongly endorses the plans to repeat these calibrations and characterizations with ACRIM radiometers in 2013. The Senior Review Panel is concerned that there are no functioning versions of ACRIM1 or ACRIM2 to be tested. Instead, hybrids will be constructed, using ACRIM3 cavities and electronics, and reconstruction of ACRIM1 and ACRIM2 foreoptics (apertures and baffles). The Senior Review Panel is concerned as to how representative these tests will be, but understand this will be "best available."

The ACRIMSAT mission proposal did not discuss End of Mission implementation plans. The Senior Review Panel welcomed the news that this is in progress. The effort should include full documentation of all data reduction algorithms, delivery of software, data, and all other necessary components to allow for a robust archival of this critical time series.

The Senior Review Panel finds that ACRIMSAT should be terminated upon satisfactory validation of follow-on U.S. TSI mission, whether that is TCTE on STPSat-3 or TIM in the JPSS program. "Satisfactory validation" should be a TSI community assessment.

There is work to be done in the TSI community given the recent corrections for scattering, diffraction, and cavity reflectance determined using TRF. First, the community will adopt a new value for TSI at solar minimum. Second, the community will develop methods to create a critically compiled and validated time series. The ACRIM team is strongly encouraged to participate directly in these efforts. To date, the PI has not participated directly in these efforts. This situation is a disappointment to the Senior Review Panel, and the recommendation is made that the PI, D. Willson, attend the ISSI, or similar,

workshops. Given the value of these data for the climate science community, and the recent success of the inter-comparison of the multiple TSI data records to bring them in line, the panel recommends that a 'TSI science team" perhaps comprised of experts within the TSI and close climate community be formed that can have the responsibility for archival, delivery, and critical compilation of the entire data sets, including the results of all the laboratory calibrations and characterizations.

Scientific Merits: Very Good

Until the on-orbit uncertainty in the TSI determination for a mission is established to be adequate for long term climate studies, that is, less than 0.01 %, it is necessary to maintain a continuous TSI record using well characterized and stable sensors. The proposal argues that ACRIMSAT is the best choice to maintain data continuity given that SORCE/TIM has battery problems, PICARD will be terminated in early 2013, and TCTE, scheduled for launch in late 2013, may have degraded measurements as a result of its spacecraft and orbit constraints. The ACRIM team proposes to:

- continue TSI measurements;

- provide comparison measurements for TSI measured by other current and future instruments;

- incorporate planned 2013 LASP/TRF calibration results into ACRIM1, 2, and 3 on orbit results;

-compare pre-flight LASP/TRF calibrations to in-flight instrument performance where possible; and

- continue several scientific studies that utilize TSI internally and in collaboration with other groups.

Strengths:

ACRIMSAT is likely to continue to be fully functional. Scientific collaborations have been established with planetary science researchers. The recently determined corrections factors improve the quality and value of the ACRIM3 TSI time series. Continued TSI measurements from ACRIMSAT will help maintain a continuous TSI time series. Additional tests at LASP/TRF should help improve the accuracy of the results of the earlier ACRIM1 and ACRIM2 TSI time series. Full resolution of the ACRIM gap issue from these new results is a subject of research. This type of collaboration with other TSI monitoring groups will improve understanding of the quality of LASP/TRF calibration and the ability to transfer it to other instruments. Additional science activities include the examination of the role of planetary motions on the solar cycle as well as observations of transits of Venus.

Weaknesses:

In the proposal, there is focus on the formation of the TSI historical composite and much less emphasis on scientific results from the community of ACRIM TSI users. This may be a reflection of the PI-nature of the mission, without an independent science team, resulting in discussions related to instrument science. The TSI historical composite is problematic because of the ACRIM data gap and issues related to the TSI sensor's characterizations, especially for on-orbit degradation. Because the sensors used to bridge the data gap had no means to assess on-orbit degradation, this topic may remain unresolved. Compared to the discussion on the historical record and the stability of the TSI at solar minimum, the lack of discussion on the more recent results giving lower values of TSI for the current maximum is puzzling. There is also a lack of quantitative information in the proposal and presentation, e.g. the inability of the PI to state instrument specifications such as SNR. The similarities and differences in the TSI record between the different instruments could have been presented much more clearly. The uncertainty estimates were poorly described. Improvements in data processing were discussed but sources of periodic TSI oscillations at solar minimum are poorly addressed or explained. The source and

value of the TSI difference at minima (1985 & 1996) is still not clear. Hopefully the LASP/TRF tests of ACRIM1 and ACRIM2 will shed some light on this issue.

Value of data record and overall data continuity:

There is value in continuing the TSI data record using sensors like ACRIM that have means to assess in flight degradation. It would make sense to continue ACRIMSAT until TCTE on the Air Force's STPSat-3 is launched and its TSI data product is validated.

TSI time series is extremely important to models of long term climate change. The corrections realized during the recent efforts improved the value of the ACRIM3 TSI time series to the community. Similarly improved results with the earlier data sets would be especially beneficial to the community.

Core mission data product quality and maturity: Good

The ACRIMSAT core mission data products are the TSI values and their uncertainties. This product is developed and refined, however the uncertainties on the Web Page appear to be statistical only, where they should include uncertainty components related to the full processing and establish traceability of the values to the SI. The SI traceability should now be possible given the work at LASP/TRF. Recently a correction for temperature sensitivity was reactivated in the data reduction algorithm, removing periodic TSI variations on annual timescales. The characterization and calibration of the ground-based ACRIM 3 at the LASP/TRF facility indicated this sensor was biased high by 0.5 %, and this information was used to correct the ACRIM 3 data, resolving the discrepancy noted in the previous SRP between ACRIM 3 and SORCE/TIM. At the TSI workshop at NIST in 2005 and published in Table 2 of Butler et al. (2008),[2] it was noted that, in the case of sensors with multiple cavities (for degradation studies), there can be large differences unrelated to degradation in the TSI results depending on which cavity is used. The range (maximum to minimum) of the TSI values among the three redundant cavities was 0.4 % (ACRIM2) and 0.12 % (ACRIM1); ACRIM 3 was 0.21 %. This would appear to introduce ambiguity into the application of a correction factors from a ground based unit that the SRP did not feel were fully addressed. This needs to be included to derive a better estimate of the absolute value and uncertainty of the current time series.

The guideline for data product quality and maturity is based on well-defined data product uncertainties for a range of conditions and validation using independent measurements. The independent measurements provided by SORCE/TIM, designed with the objective of 0.01 % absolute uncertainty, motivated the NIST TSI Workshop in 2005 where representatives from four different sensor teams presented their uncertainty budgets, and this led to the adoption of the recommendation to perform ground based, system level calibrations and characterizations by LASP/TRF, which has demonstrated that scattering was causing a bias in the ACRIM 3 results. As proposed, this effort should be repeated for ACRIM 2 and ACRIM 1 ground based units. The proposed definition of the core data products needs to include the absolute uncertainty according to SI traceability. There are potential collaborations among the TSI teams as demonstrated through the recent ground-based comparisons.

[2] J. Res. NIST, **113**, 187 – 203.

Relevance to NASA Science Goals: Very Good

Accurate knowledge of TSI contributes to NASA's science goals because the sun is the source of almost all the energy that drives the Earth's climate. As was seen in the "ACRIM Gap" during the early 1990s, lacking a continuous TSI record has been the source of significant scientific effort and controversy, with fundamental disagreements on the long-term behavior of the Sun. Steps to ensure the overlap between current and subsequent instruments is important especially with the concerns about the SORCE lifetime. The benefit is that ACRIM 3 is now corrected for biases and making routine measurements with high probability of continued operation, and with project continuation ACRIM 2 and ACRIM 1 will also have correction factors. The weakness is the uncertainty associated with operating an instrument beyond its design lifetime. Close-out and finalization of the data set at this point in time would introduce risk to the TSI time series because of the uncertainty that SORCE/TIM will continue to function, and it is not possible to predict future failure modes for either mission.

Strengths:-

The production, analysis, and interpretation of the ACRIM3 TSI data set directly supports ESD missions, analysis, and modeling studies that utilize TSI observation. Understanding the sources of TSI variability is important to being able to fill data gaps and predict or estimate future TSI based on limited image data (Ca II K or sunspots, etc.).

Weaknesses:-

Some of the science topics do not appear to directly support Earth Science Goals (CMSS impact of TSI) but this is a minor part of the proposed study. As with SORCE, ESD should provide an opportunity for other member of the community to compete for Data Analysis Funding that utilizes or examines the ACRIMSAT/ACRIM3 data set. This last point is not a weakness in the proposed study.

Technical Panel:

The mission is rated medium-low risk, and the costs seem reasonable; please refer to these reports.

National Interests Panel:

The national needs was rated "Some," again please refer to this report directly.

Other Comments:

Although the ACRIM group is small the proposal could have provided additional descriptive text. For example, Section 1.2 (The Scientific Merit) could have contained additional discussion about the details of the Science Objectives, History, and Recent Accomplishments rather than a simple listing.

Aqua

Recommendation: Continuation of projects as currently baselined

Aqua is an extremely successful mission. The panel recommends continuation of the mission as currently baselined. This mission is producing a very large number of critical products addressing NASA's Earth Science mission objectives both from the perspective of creating climate data records necessary to evaluate climate change and from the perspective of products needed to better understand fundamental Earth science processes. The impressive list of core science products is very mature and stable. The reasons for extending the Aqua mission are to allow current scientific and applied benefits to continue, increase the value of the Aqua data to climate studies through increasing the length of the Aqua data sets, allow continued data overlap with NPP and GCOM-W1, and potential future data overlap with OCO-2 (NPP, GCOM-W1 and OCO-2 carry instruments intended to extend many of the Aqua data records), and continue to provide valuable auxiliary data for other A-Train satellite missions. Of the several instruments on Aqua, MODIS and AIRS are making extremely unique and popular measurements for science and operational applications. The continuity of these data products is highly desirable for the scientific community and the broader user community. As long as one of these two instruments is in good health (currently both are), the panel feels that the Aqua mission should be extended.

Aqua makes a wide array of measurements that have made significant contributions to quantifying the state of the Earth system and predicting future climate change. The contributions of the Aqua mission and the importance of Aqua data products can be readily illustrated by the following publication and data usage statistics: In each of the past two years, there have been over 1,000 Aqua science publications and over 20,000 citations to papers incorporating Aqua data. Annually, over 1,600 terabytes of Aqua data have been distributed to over 39,000 users. Complementing the importance of the Aqua mission to the science community is its comparable importance for a large variety of practical applications. Aqua data have been extensively used by many governmental agencies (e.g., NOAA, USDA, EPA, FAA, DoD, U.S. Forest Service, U. S. Coast Guard, etc.) for a large variety of practical/operational applications. The National Interests Panel rated Aqua products "very-high utility", and ranked the Aqua mission #1 among the 13 missions under this Senior Review. Additionally, Aqua is a member of the A-Train constellation of satellites; it provides valuable data for other A-Train missions for parameter retrievals and data synergy.

The Aqua satellite was launched in May 2002, and completed its prime mission in September 2008. Although it is now 5 years into its extended mission, the spacecraft and most of its Earth-observing instruments are still healthy and operating. There are six Earth-observing instruments on Aqua providing unprecedented information about the Earth system. Currently, three of six instruments – AIRS, CERES and MODIS – are in excellent health. AMSU is in good health with 12 of the 15 channels operating normally. The HSB ceased operations early in the mission. However, there was enough overlap with AIRS/AMSU that HSB failure had no impact on core data. The most significant change in instrumentation since the past Senior Review is the cessation of science data collection from AMSR-E, which suffered a major anomaly and ended its science data collection in October 2011. Since December 2012, AMSR-E is operating again with a low rate of antenna rotation (2 rpm), allowing the instrument to provide important data for cross-calibration with the AMSR-2 instrument on JAXA's GCOM-W1 satellite launched in May 2012 (GCOM-W1 is also in the A-train constellation). The spacecraft bus is in excellent health, and the satellite has adequate fuel to operate through 2022.

Scientific merits: Excellent

The Aqua science efforts have a strong focus on NASA's strategic goal to "Advance Earth System Science to meet the challenges of climate and environmental change" and on answering the fundamental question of "How is the Earth changing and what are the consequences for life on Earth?" The science objectives of the Aqua mission are as follows: (1) to advance the understanding of the factors that control the global water and energy cycles; (2) to assess natural and anthropogenic climate forcings (especially by greenhouse gases and aerosols), climate variations, and feedbacks; (3) to examine the processes involved in atmosphere surface interactions; (4) to address issues related to diurnal cycles in cloud properties and to indirect effects of aerosols on clouds; (5) to produce an integrated climate data record for detecting decadal changes in the Earth's radiation budget from the surface to the top of the atmosphere; (6) to improve the understanding of soil wetness retrieval methodologies in preparation for future soil moisture satellite missions; (7) to contribute to improved operational weather prediction and other practical uses of Earth science data; (8) to increase understanding of the carbon cycle by monitoring atmospheric CO_2 with AIRS, along with terrestrial and marine ecosystems with MODIS; and (9) to facilitate a wide range of future Earth science advances through: extending the records of the climate variables generated as core data products from the Aqua mission, contributing Aqua data and expertise to process studies involving the A-Train and/or field programs, contributing Aqua data and expertise in examining natural and human-influenced phenomena such as the solar cycle, major atmospheric oscillations, volcanic eruptions, and accelerated ice sheet changes, and bridging the gap between heritage sensors and future satellite missions.

Strengths:

The Aqua mission has been extremely successful in addressing its scientific objectives as listed above. Aqua data are widely used for scientific research and the publications and data distribution have been consistently increasing since the start of the mission. The Aqua mission's scientific contributions are broadly distributed in many disciplines of Earth sciences. In the following, these contributions are grouped according to the following six NASA's SMD focus areas: atmospheric composition, weather, carbon cycle and ecosystems, water and energy cycle, climate variability and change, and Earth surface and interior. Research highlights *during the past two years* in these areas are listed below:

Atmospheric Composition: Among the noted strengths of the full Aqua data set is the considerable information provided about atmospheric constituents, in particular the information provided by AIRS/AMSU and MODIS regarding aerosols and the following trace gases: water vapor (H2O), CO_2, CO, CH_4, O_3, and SO_2. In the past two years, analysis of AIRS CO_2 data revealed the connections of AIRS tropospheric CO_2 with the Tropical Biennial Oscillation and with the changing of Walker Circulations; in situ and aircraft-based studies confirmed the Southern Hemisphere midlatitude AIRS CO_2 belt first found by AIRS/AMSU data; implemented and tested MODIS Collection 6 aerosol optical depth (AOD) product that incorporated many new features over Collection 5: (1) an increase in the valid solar zenith angle to 84°, allowing coverage to high latitudes, (2) inclusion of wind speed dependence to retrieve aerosol properties over ocean, (3) merging of "dark target" and "deep blue" aerosol retrieval methods to extend the global availability of AOD over deserts and land regions, and (4) introduction of higher-spatial resolution 3-km AOD product of interest to air quality and urban communities.

Weather: Aqua data from AIRS/AMSU, AMSR-E, and MODIS have proven valuable both to weather forecasting and to enhanced weather understanding. ECMWF's study showed that the impact on weather forecasts of assimilating AIRS and IASI data to be roughly comparable and second only to the collective impact of assimilating four AMSU units. In several studies of the past two years, Aqua data have been used to understand the interactions of moisture and dust with hurricane development; to

study deep convections and Arctic inversions; to test model forecast of cloud parameters; to characterize Madden-Julian Oscillation; to study gravity waves and their effects on regional and global circulations; to derive a global climatology of large hail events; and to study diurnal characteristics of rain.

Carbon Cycle and Ecosystems: Major contributions to examining the carbon cycle and ecosystems are being facilitated by the use of Aqua data. AIRS data have been used to estimate surface carbon fluxes. For building long-term time series of ocean color data for climate change studies, Aqua MODIS data are being used to extend the continuous record of ocean color measurements that began in late 1997 with data from SeaWiFS, which operated until December 2010. Aqua MODIS has been considered highly accurate and the standard for comparison for other ocean color sensors. Publications showed that Aqua MODIS ocean color and sea surface temperature measurements continue to provide the foundation for research and modeling of phytoplankton, the carbon cycle, and ecosystem dynamics in the world's oceans; MODIS is the only sensor currently in orbit with the capability to measure natural fluorescence of chlorophyll, which is providing critical new insights on the physiological response of phytoplankton to environmental conditions. The next sensor that measures natural fluorescence will not be available until Sentinel. So keeping Aqua MODIS around is important for data continuity. Additionally it is desired to have MODIS overlap with Sentinel.

Water and Energy Cycle: When AMSR-E was still fully operational, Aqua data were providing information about almost all major aspects of the water cycle, including water vapor, precipitation, cloud liquid water, snow cover, and sea ice. Aqua data are providing considerable information about the energy cycle, with CERES data products in particular providing information about the radiation budget at the top of the atmosphere, within the atmosphere, and at the Earth's surface. Numerous studies have been conducted in the category during the past two years (at least partially) using Aqua data, including estimation of surface evaporation and precipitation lead to closure of the atmospheric hydrological cycle both regionally and globally, characterization of cloud properties and its radiative effects, studies on snowpack, surface hydrology and sea ice coverage, using observations from CERES and *in situ* measurements of ocean heat content change to calculate a 0.5 Wm^{-2} imbalance in net radiation at TOA during the past decade, and a revision of our understanding of the Earth's surface energy budget through synergistic use of observations from CERES, MODIS, CALIPSO and CloudSat.

Climate Variability and Change: While Aqua has not been on orbit long enough to generate climatological long-term datasets by itself, the Aqua data are extending earlier datasets and are providing details on atmospheric state, clouds and radiation variations that are helping to improve both the understanding of and the ability to model climate variability and change. Among many of studies conducted in the past two years, the following are some of the examples: Small variations in temperature over the Niño 3.4 region detected by AIRS data are attributed to changes in solar output during the declining phase of solar activity; Studies using AIRS data showed that tropical upper tropospheric water vapor distributions are different depending on whether the QBO and the ENSO are in phase or out of phase, thereby suggesting a connection between stratospheric dynamics and tropospheric variability; AIRS data have been used to help develop and evaluate model parameterizations and model results, and it is found that climate models systematically underestimate thermodynamic variance at small scales; AMSR-E along with other satellite data sets established a global drying trend in soil moisture since 1988; Among the largest natural variations in the climate system, the El Niño and La Niña, are clearly seen in global area average all-weather SST and total integrated water vapor data from AMSR-E, with cool ocean surface conditions and a less humid maritime atmosphere typically associated with La Niña, and warmer, more humid conditions with El Niño; Compared to analysis using CERES data, all climate models participating in CMIP5 project overestimate the magnitude

of both the shortwave and longwave radiative effects of clouds. The models produce overly bright but too few low-level clouds, and they overestimate mid-level and high-level clouds. Using a decade of CERES observations, it is found that while the Northern Hemisphere reflects more solar radiation than the Southern Hemisphere under cloud-free conditions owing to the asymmetric distribution of continents and aerosols between the hemispheres, the Earth exhibits near-perfect symmetry in planetary albedo between the hemispheres for all-sky conditions; Analyzing AIRS and CERES observations together with climate model simulation results has revealed a coherent pattern between mid-tropospheric relative humidity (RH) and albedo variations. The result underscores the utility of RH in diagnosing clouds, which are the main reason for albedo variability and uncertainty in model-predicted climate sensitivity.

Earth Surface and Interior: Aqua data reveal information about the Earth's interior through the information provided about volcanic emissions by AIRS/AMSU and MODIS infrared data and about ongoing volcanic activity by MODIS thermal data. Aqua data additionally reveal considerable information about the Earth's surface, including land surface temperature (LST), SSTs, sea ice and land ice coverage, and vegetation.

Weaknesses:

None.

Value of data record and overall data continuity:

Aqua data have been extremely valuable both to progressing scientific research and to meeting national needs for operational services. The extension of the Aqua mission will allow current scientific and applied benefits to continue. Aqua measurements provide many core data products needed for climate research, such as atmospheric state and composition, cloud properties, radiative fluxes, surface properties, and snow and ice coverage, etc. Extending Aqua data length of these variables has great value to climate studies. An extended mission will allow continued data overlap with NPP and GCOM-W1, and potential future data overlap with OCO-2. NPP, GCOM-W1 and OCO-2 carry instruments intended to extend many of the Aqua data records. To study climate trends when using data from multiple satellites, cross calibration by overlapping observations of consecutive sensors is extremely important. Additionally, the Aqua Mission has been providing valuable data to other A-Train missions for product retrievals and data synergy. The extension of the Aqua Mission will continue to provide valuable auxiliary data for other A-Train satellite missions.

Core mission data product quality and maturity: Excellent

There are four science teams for the Aqua mission: AIRS/AMSU/HSB Science Team, AMSR-E Science Team, CERES Science Team and MODIS Science Team. Data products are produced and validated separately by each individual science team. Overall these products are well validated and have reached high maturity. Specific information for data product quality and maturity from each of the four teams is given below:

AIRS/AMSU/HSB Data Products: The Level 1 (quality controlled radiances) algorithm maturity is very high. Level 1B products have been validated and exceed stability and accuracy requirements. Level 2 product maturity and validation status varies depending on the product: atmospheric temperature and moisture products at maturity level of "Validated Stage 3" (highest level, accuracy has been assessed and the uncertainties in the product well established via independent measurements in a systematic and statistically robust way representing global conditions), atmospheric minor constituents products mostly (O3, CO, CH4, mid-tropospheric CO2) at "Validated Stage 2" (accuracy has been assessed over a

widely distributed set of locations and time periods via several ground-truth and validation efforts), and cloud and surface products mostly at "Validated Stage 3". Level 3 products are composed of Level 2 products that have been spatially and temporally binned and quality-control filtered to provide compact statistical summaries. The Level 3 algorithm maturity varies, depending on product, from mature to provisional.

AMSR-E Data Products: AMSR-E is a JAXA-provided sensor with its instrument operations under the control and funding of JAXA. Science data products include columnar cloud water over ocean, columnar water vapor over ocean, SST, sea surface wind speed, rainfall, sea ice concentration, sea ice drift, snow water equivalent and snow depth, and soil moisture. All products are in mature stage. Since AMSR-E now only operates with 2 rpm antenna rotation, its data for this Senior Review period will be mainly used for cross-calibration with the AMSR-2 of GCOM-W1.

CERES Data Products: CERES is a PI-instrument with its instrument operations and data retrievals all funded by this Senior Review. The Aqua and Terra missions share the same CERES science team. There are 10 CERES data products; all have been substantially validated and are in mature stage. The current version of the CERES data is Edition 3, with the two exceptions of CRS (clouds and radiative swath) and FSW (monthly gridded radiative fluxes and clouds), which are Edition 2.

MODIS Data Products: The Aqua and Terra missions share the same MODIS science team. There are 23 core products from MODIS (and a number of other products); all the core products have been substantially validated over a widely distributed set of locations, conditions, and time periods via several ground truth and validation efforts. Level 1 (sensor radiance, calibration and geolocation) products are in Validated Stage 3. MODIS atmospheric products (aerosol, temperature, moisture, clouds) are in Validated Stage 2; MODIS land surface products (temperature, emissivity, reflectance, land cover, vegetation index, etc.) are mostly in Validated stage 2 except for evapotranspiration and implementation of atmospheric correction, which are in provisional/beta stage; MODIS cryosphere products are Stage 2 for snow cover and sea ice extent, and Stage 1 for snow albedo and ice surface temperature; MODIS ocean products (temperature, color, chlorophyll, etc.): major products such as SST, ocean color and sub-surface chlorophyll-α, diffuse attenuation at 490 nm, aerosol optical thickness (for ocean color atmospheric correction), and aerosol Angstrom exponent are in either Validated Stage 3 or 2, while MODIS particulate organic carbon and inorganic carbon are in Validate Stage 1, fluorescence line height, and instantaneous/daily photosynthetically available radiation are in provisional stage (sufficient for use by the general research community).

Relevance to NASA Science Goals: Excellent

The Aqua measurements are helping scientists to quantify the state of the Earth system, validate climate models, and address such key questions as: How is the net radiation at the top of the atmosphere changing? What are the roles of greenhouse gases, aerosols, clouds, and sea ice in the climate system and climate change? Is the water cycle accelerating? All of these are central issues in addressing the following 'fundamental question' identified in the NASA Science Mission Directorate's *Science Plan* (NASA 2010): "How is the Earth changing and what are the consequences for life on Earth?"

Technical Panel:

Currently, three of six Aqua instruments – AIRS, CERES and MODIS – are in excellent health. AMSU is in good health with 12 of the 15 channels operating normally. AMSR-E is operating under the mode only for providing cross calibration data for AMSR-2. At least one year overlap of AMSR-E and AMSR-2 for

cross calibration is highly desirable. A close coordination between (JAXA) AMSR-2 and (NASA) AMSR-E teams is needed. The spacecraft bus is in excellent health, and the satellite has adequate fuel to operate through 2022.

The Technical Review Panel evaluated the Aqua mission as "Medium Risk". The Science Panel reviewers concur with the Technical Panel report.

National Interests Panel:

The Aqua mission is addressing numerous important national objectives and science applications, with considerable practical benefits to the nation and to society, in the areas of weather forecasting, air quality, natural disaster (such as volcanoes, fires, floods, tropical cyclones/hurricanes/typhoons) monitoring and evaluation, and support of major human activities (agriculture, aviation, coastal management, energy management, military operations, oil slick monitoring and shipping). Direct broadcast capability facilitates many real-time or near real-time applications. MODIS products are heavily used by numerous agencies, including: NOAA, USDA, EPA, FAA, DoD, U.S. Forest Service, U. S. Coast Guard. In the area of weather forecasting, AIRS radiance data are assimilated routinely at virtually all operational weather prediction centers around the world; A study by The European Center for Medium-Range Weather Forecasts (ECMWF) showed the impact on weather forecasts of assimilating AIRS and IASI data to be roughly comparable and second only to the collective impact of assimilating four AMSU units.

The National Interests Panel rated Aqua products "very-high utility", and ranked the Aqua mission the #1 among the 13 missions under this Senior Review. The Science Panel reviewers concur with the National Interest Panel report.

Other Comments:

The proposal is generally well written. A minor critique is that the science highlight section could have been better organized to focus on the most important science accomplishments.

Aqua products, with MODIS products in particular, are used extensively in many different fields by users with different levels of experience in handling satellite data. As such, the demand is very high for a well-organized repository of documentation on the availability, applicability, limitation and uncertainty of these data products. While the panel recognizes that the Aqua mission is making efforts in meeting this demand by updating websites, the panel *strongly* recommends that the Aqua mission appoints a designated person (within the baselined budget) to work on this issue.

Aura

Recommendation: Continuation of mission as currently baselined

This is an excellent mission and proposal. The Aura mission is aimed at atmospheric composition measurements related to the stratospheric ozone layer, tropospheric chemistry and climate change. These topics are central to core NASA research objectives. The scientific output from Aura is substantial, with over 450 publications since the 2011 Senior Review. The Aura MLS, OMI and TES instruments are showing signs of aging, but are still producing high-quality science data, and there is a good chance of extending measurements beyond the current proposal cycle. The data are highly utilized in the research and operational communities. There is excellent science justification for continuing the mission.

Scientific merits: Excellent

The scientific output from Aura has been impressive, with over 1100 journal publications and 450 since the last review. There is a large and active scientific community utilizing the Aura data. With regards to developing and utilizing data products related to tropospheric chemistry and climate, Aura has continued to make important strides since the 2011 Senior Review.

<u>New activities and results from the 2011 proposal:</u>

Several new products resulting from combination of Aura and A-Train sensors including: 1) Retrievals of near-surface ozone from combined OMI+TES; 2) Tropospheric CO profiles from combined MLS+TES retrievals; 3) OMI/MODIS cloud parameter dataset; and 4) Improved OMI UV aerosol product (using CALIOP and MODIS).

Additional species include: 1) New TES products: tropospheric methanol and formic acid (markers for biologic activity), PAN (organic reactive nitrogen) and OCS; and 2) New validated MLS retrievals of methyl chloride.

Improved products include: 1) TES V005 retrievals with improved vertical resolution; 2) OMI general reprocessing (reduced biases and 'striping'); 3) Improved OMI NO_2 and SO_2 retrievals (consistent KNMI and NASA results); 4) MLS BrO, HO2 and HOCl improved; 5) Improved MLS near-real time products (ozone, H2O, CO, HNO3 and SO2); and 6) MLS V4 retrievals: improvements near thick clouds.

<u>Primary science objectives for this proposal include:</u>

1) Extending the record of key tropospheric and stratospheric constituent observations. Understanding atmospheric variability and changes in response to emissions and climate is greatly enhanced by long and continuous satellite records, and the Aura measurements (almost nine years long) become increasingly valuable as the data record increases. Because of the loss of the European Envisat satellite, many of the Aura capabilities are unique for the present and near future;
2) Contribution to airborne missions. Aura will provide unique satellite measurements in support of several ongoing and planned aircraft campaigns (DISCOVER-AQ, ATTREX, SEAC4RS);
3) Contributions to operational and hazard products;
4) Diagnosing and evaluating air quality and chemistry-climate models. Aura provides key observational data for ongoing ACCMIP, CMIP5 and CCMI chemistry-climate model evaluations; and
5) Several new data products and improved retrievals will become available as evaluation of Aura measurements continues to mature.

Strengths:

1) The mission has been highly successful and scientifically fruitful, providing a novel record of tropospheric and stratospheric composition for almost nine years;
2) Data retrievals continue to improve in terms of quality, vertical resolution and additional species;
3) Aura team has made strong efforts to generate synergistic products by combining different Aura and A-Train measurements;
4) Aura spacecraft appears to be healthy with high probability of lasting through the proposal period. The MLS, OMI and TES instruments are still producing high quality science data, with a reasonably high probability of lasting through this funding cycle;
5) Near-real time (NRT) usage of Aura data has increased dramatically. OMI NRT measurements are used in aviation safety, UV index forecasting and air quality applications. Many of the Aura products are used within the European MACC-II project for assimilation, validation and forecasting; and
6) Strong likelihood of continued synergies between Aura and other instruments, including: MLS + CALIOP and CloudSat, OMI + MODIS, TES + OCO-2 (2014), plus SAGE III (2014) and TROPOMI (2015).

Weaknesses:

1) The TES Interferometer Control System (ICS) stalled in December 2011 (to April 2012). Operations resumed after this time, but the TES team has devised a new observational strategy to optimize remaining instrument lifetime and minimize likelihood of another ICS stall. The global survey mode for TES is no longer feasible and future TES observations will focus on targeted observations including: a) validation of new products, b) megacity emissions and pollution, c) campaign support and d) the time record of pollution over Asia. These focus areas are evaluated as being a good use of the reduced TES capabilities;
2) External blockage on the OMI instrument has produced 'row anomaly' since 2009, affecting 30-55% of the OMI swath. Global coverage is still available over 2 days. No correction has been applied to the affected measurements, but they are monitored and clearly documented in the data files. There is increased pixel degradation from radiation damage, with some time-dependent biases in gases with small radiance signals (such as HCHO). The remaining OMI measurements (excluding the row anomaly) still provide high resolution global coverage in 2 days; and
3) Upper stratospheric – mesospheric OH measurements from MLS are currently limited due to lifetime of the 2.5 THz laser; data are being taken during August of each year to monitor trends and solar cycle variability. Also, MLS upper stratosphere HCl measurements have been deactivated to conserve remaining lifetime (estimated only a handful of days).

Value of data record and overall data continuity:

The Aura data record is unique for many species. Long continuous records are especially valuable for quantifying and understanding atmospheric response to changing emissions and climate, and evaluating complex chemistry-climate models. Aura data are even more valuable given the loss of the European Envisat satellite in 2012. Continuing the Aura measurements should be a top priority.

Because of continuing improvements and novel additions in Aura data products, continuation of annual Aura Science Team meetings should be a priority to enhance and support the broad user community.

Core mission data product quality and maturity: Excellent.

Strengths:

1) The Aura team has done an excellent job of continually improving data products and making mature data available to the user community in a timely fashion;
2) The team has placed an appropriate emphasis on the validation of data products; and
3) The team has gone beyond the original plans and produced numerous additional data products. Good progress has been made in combining measurements from different instruments, aiming to increase the vertical resolution and near-surface sensitivity. These include near-surface ozone from TES+OMI and CO profiles from combined MLS+TES data.

Weaknesses:

1) The global survey mode of TES is no longer available, in order to optimize instrument lifetime.

Relevance to NASA Science Goals: Excellent

Aura is unique in terms of providing comprehensive atmospheric composition measurements, and contributes to all facets of characterizing, understanding and predicting Earth System changes. The Aura measurements underpin research in five of the six NASA SMD focus areas: atmospheric composition, weather, carbon cycle, water and energy cycles, and climate variability and change.

Technical Panel:

The Aura mission is evaluated as Medium-High risk. Most spacecraft flight systems are operating nominally with redundancy, and are expected to continue to perform very well through the proposed mission extension period. The primary issues with the individual instruments were brought up directly in the questions to the Aura team, and were adequately addressed in their presentation. Critical components for most of the MLS instrument are expected to have a remaining lifetime of 5-10 years. The potential for significantly degraded operation or loss of the Tropospheric Emission Spectrometer (TES) instrument during the proposed two-year mission extension period is high. The operational budget status of the four life-limited items on the OMI instrument is good**.** In addition, the OMI instrument benefits greatly from support from KNMI (Netherlands) and FMI (Finland) and the mission has made excellent use of NASA ROSES proposal calls to augment funding.

National Interests Panel:

Aura was given an overall mission rating of High Utility by the National Interests Panel. See the panel report for detailed discussions.

Other Comments:

The Aura team is complemented for a well written and compelling proposal.

CALIPSO

Recommendation: Continuation of project as currently baselined

The CALIPSO spacecraft flies in formation with 5 other satellites in the larger A-Train constellation, 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); and

(3) A single visible wavelength imager (the Wide Field-of-View Camera, WFC).

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; and

(4) Assessments of cloud-radiation feedback mechanisms.

The review panel strongly recommends that the mission should be continued as baselined. CALIPSO provides a unique set of data products that are not currently available from any other platform. In addition, synergistic use of CALIPSO, CloudSat, MODIS, and CERES observations has led to the development of robust combined aerosol, cloud, and radiative heating rate products. Continuation of the mission will allow extension of the data record of these products as well as enable critical overlap with soon-to-be launched cloud/aerosol (e.g., EarthCARE) and stratosphere (e.g., SAGE III) missions. Data products are mature, well validated, and widely used by the scientific community. The science team has been responsive to the recommendations of the 2011 panel, having:

(1) resolved discrepancies between CALIPSO and MODIS cloud optical depth;

(2) produced a global gridded aerosol vertical profile product; and

(3) begun production of a near real time L1.5 attenuated lidar backscatter product.

The technical review panel rated the mission extension as Medium risk of failure in the next two years, with increased risk after. The Proteus spacecraft is functioning well and all subsystems are functioning. The two passive instruments (IIR and WFC) are performing well, but there is a slow leak in the pressure canister of the laser subsystem. This leak was anticipated pre-launch. The laser should last until sometime in 2017, but the technical team notes that diode bar array lasers can be unpredictable and may exhibit sudden transitions to more rapid pressure decreases.

Scientific merits: Excellent

<u>Strengths:</u>

In the past two years, the CALIPSO mission has produced an impressive number of fundamental scientific advances. These include new estimates of the surface longwave energy balance that have led to a significant revision of long-standing surface energy budget numbers. In addition, CALIPSO data has

led to improvements in the understanding of cloud-aerosol direct and indirect interactions. Combined CloudSat and CALIPSO data is being used to explore the interaction between clouds and atmospheric dynamics through via the production of a more accurate atmospheric heating profile dataset. Near real time CALIPSO data is being assimilated into an increasing number of operational numerical weather prediction systems.

Weaknesses:

None

Value of data record and overall data continuity:

Since June 2006, CALIPSO has provided unique observations of the three dimensional distribution of aerosols and optically thin clouds. Extension of this dataset is important for improved understanding of aerosol radiative forcing and cloud-aerosol interactions both regionally and globally. Extension of the CALIPSO data record is critical for continued production of a growing number of scientifically important multisensor A-Train datasets. Extending the CALIPSO mission bridges the gap to three different follow-on missions: Cloud Aerosol Transport System lidar, the Atmospheric Dynamics Mission, and EarthCARE, as well as with OCO-2. CALIPSO is the only current mission capable of monitoring the stratospheric aerosol layer, and continuation will provide critical overlap with the upcoming SAGE III mission (2015).

Core mission data product quality and maturity: Excellent.

CALIPSO data products are mature and stable. Version 3 represented a significant improvement in accuracy over version 2 data. Version 4 is scheduled for release starting in June 2013. Quality of the data products since the release of version 3 has been consistently high. Since the 2011 review, a new Level 3 gridded 3D global monthly aerosol product has been released to the community. This dataset is the first of its kind. The science team now also provides an "Expedited Level 1.5" data product to operational centers with sufficiently low latency to allow for assimilation of CALIPSO data into numerical forecast systems.

Data from CALIPSO has been very successfully combined with other A-Train measurements, specifically CloudSat and MODIS, to provide global three-dimensional radiative heating estimates and three-dimensional profiles of liquid and ice water content.

The CALIPSO team has conducted extensive validation activities since the 2011 review. These include 112 under-flights with the LaRC HSRL, multiple field campaigns, and comparison of cirrus cloud properties with airborne and ground-based lidars. A previously reported factor of two disagreement between CALIPSO and MODIS optical depth has been resolved.

There are stripes in the IIR data over homogeneous scenes. This is a long-standing issue that is being addressed by CNES. The science team reports that development of a solution is possible, but contingent on available funding from CNES following the recommendations of the French REDEM review panel.

Relevance to NASA Science Goals: Excellent

Strengths:

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 2011, the CALIPSO mission has made the following contributions:

Atmospheric Composition:

- CALIPSO monitors changes to the global 3D distribution of aerosol, identifies aerosol types relevant to climate change, and observes aerosols in previously unobserved regions. CALIPSO is also the most successful tool available for observing global distributions of volcanic aerosol
- CALIPSO provides insight into the effect of aerosol on the Earth's energy budget. In addition, the combination of CALIPSO, OMI, and MODIS is being used to examine aerosol optical properties above clouds.
- CALIPSO measurements are being used to assess the effects of aerosol emissions on local ecosystems, air quality and weather patterns.

Climate Variability and Change:

- Cloud vertical profiles from CALIPSO and CloudSat, in combination with a three-dimensional estimate of radiative heating, provide the first reliable estimate of the coupling of clouds, radiation, and atmospheric dynamics.
- CALIPSO profiles are proving to be critical in the evaluation of climate models and their cloud and aerosol parameterizations.

Water and Energy Cycle:

- In combination with CloudSat, MODIS, and CERES, CALIPSO is providing improved estimates of the surface radiation budget.
- CALIPSO's observations of aerosol profiles between and above clouds provide an assessment of the effect of aerosols on cloud brightness, water content, and precipitation.

Weather:

- As weather forecast models begin to produce predictions of air quality, CALIPSO data are being used for model evaluation and increasingly also being assimilated to improve forecast initial conditions.
- CALIPSO data are also being used to evaluate (and by extension improve) the parameterization of clouds in weather prediction models as well as the height assignment of assimilated cloud-track winds.

Weaknesses:

None

Technical Panel:

The technical review panel rated the mission extension as Medium risk of failure in the next two years, with increased risk after. The Proteus spacecraft is functioning well and all subsystems are functioning. The two passive instruments (IIR and WFC) are performing well, but there is a slow leak in the pressure canister of the laser subsystem. This leak was anticipated pre-launch. The laser should last until some time in 2017, but the technical team notes that diode bar array lasers can be unpredictable and may exhibit sudden transitions to more rapid pressure decreases. The science panel concurs with the assessment of the technical panel evaluation.

National Interests Panel:

CALIPSO received a high overall rating from the agencies that make use of the data, but scored relatively low compared with other missions (8th of 13) primarily due to the fact that over 1/3 of the agencies polled make no use of CALIPSO data. Several agencies note that, even though an expedited dataset is now routinely produced, data latency is still an issue. This was primarily an issue for operational decision-makers (e.g., FAA), many of whom require data delivery within an hour of observation. Many also note that it would be helpful if the data were provided in different formats (e.g., geotiff). The panel suggests development of reference datasets ("golden granules") and associated data use tutorials to encourage broader use of CALIPSO in the science and applications community. The science panel concurs with the assessment of the National Interest panel evaluation.

Other Comments:

This was a very comprehensive and well organized proposal. The few areas that required clarification were addressed to our satisfaction during the in-person discussion with the science team. The science team is to be commended in particular for addressing all of the concerns raised by the 2011 senior review panel.

The 2013 review panel recommends the following actions for the coming two years:

(1) It is anticipated that the new level 3 global gridded aerosol profile dataset will be widely used by the community. It will be important to conduct an ongoing assessment of the uncertainties in this dataset and to monitor its utility for regional climate and process studies and model evaluation;

(2) It is expected that synergy with other A-Train sensors and the production of joint products will continue. Specifically, we look for continued research progress based on the C3M, DARDAR, and combined CloudSat-CALIPSO products in the CloudSat data stream;

(3) The laser canister pressure leak and possibility of diode-bar based degradation of the laser signal will require close monitoring. Performance of the CALIOP laser at low pressure levels is currently unknown and will become an issue in the next four years (perhaps two if the pace of degradation increases). The technical panel is skeptical that workarounds to increase laser signal to noise will be successful, and feels that reactivation of the primary laser system (deactivated in 2009) will likely also prove to be unsuccessful;

(4) The panel recommends increased outreach to agencies (identified by the National Interests Panel) that do not currently make use of CALIPSO data, but for whom the data would likely prove to be of high utility. The selection of "golden granules" with associated user tutorials is anticipated to be useful in this regard;

(5) The science team has conducted a significant number of validation exercises including more than 100 underflights with high spectral resolution lidar. Even so, the science and operational user community continues to encounter difficulty understanding when the data is scientifically reliable. Development of additional user tutorials, centered around the aforementioned "golden granules" is strongly recommended; and

(6) Consistent with the recommendations made in (4) and (5) above, we recommend development of a keyword searchable database of publications, documents, and current user groups for the purpose of assisting new users in the appropriate use of the various data products.

CloudSat

Recommendation: Continuation of projects as currently baselined.

CloudSat carries a single instrument - a w-band (94 GHz or 3 mm) cloud profiling radar (CPR) that is sensitive to both cloud and precipitation-size particles. It provides the science community with *the first global survey of the vertical precipitation structure of clouds*. The vertical dimension of cloud is particularly novel information, considering that decades of satellite observations in the past since 1960s have only looked at clouds horizontally. This novel observation from CloudSat has spurred a range of new research including critical evaluation of global model representation of clouds and new insights into cloud and precipitation processes. CloudSat is also a member of the A-Train constellation. Synergistic use of CloudSat and other A-Train measurements (e.g., CALIPSO, MODIS, AMSR-E) have enabled new science in the area of aerosol-cloud-precipitation interactions.

Continuing the CloudSat mission carries a number of benefits: 1) allowing for new science in the context of weather and climate variability and also enabling new products, 2) uninterrupted applications to aviation and weather forecasting, 3) improved understanding of seasonal and interannual variations in cloud behavior, 4) enhanced data for evaluating model behavior, and 5) providing calibration for future missions such as EarthCARE (2016) and GPM (2014). There is also strong synergy with the future OCO-2 mission as the oxygen A-band from OCO-2 provides complementary information on clouds.

In summary, the panel recommends that CloudSat mission be continued as currently baselined.

Scientific merits: Excellent

The CloudSat mission is motivated by the need to better represent cloud processes in global predictive models. The science objectives include:

1) Evaluating GCM cloud parameterizations;
2) Understanding the relationship between the vertical profiles of cloud water content and the radiative heating, as well as the large-scale atmospheric circulation;
3) Evaluating cloud properties retrieved from other satellite systems, especially passive systems from Aqua, and quantifying relationships with satellite precipitation measurements; and
4) Improving our understanding of the indirect effect of aerosols on clouds.

For the proposed extended mission (beyond 2013), all four areas will be continued and enhanced.

Accomplishments of the past two years include:

Influencing IPCC assessment: Numerous recent publications have made use of CloudSat data to assess cloud feedback and aerosol indirect effects in IPCC model simulations. One of the most profound revisions of the current IPCC assessment is the revised estimate of aerosol indirect radiative forcing;

Characterizing the moist processes of cloud systems and storms: Understanding the underlying physical processes is a necessary step to improving representation of clouds in models. To this end, researchers have used CloudSat data, in conjunction with other A-Train measurements, to study tropical deep convective processes, extra-tropical frontal cloud processes, and low cloud microphysics;

Evaluating moist physical processes in models: Over the past two years, research has been focused on evaluating warm rain processes (e.g., onset of precipitation), MJO convection and entrainment processes, and storm track dynamics;

Evaluating cloud climatologies: continued evaluation of cloud climatologies from passive sensors have been conducted and limitations of passive cloud products were documented; and

Establishing connection between cloudiness and large-scale circulation: this connection is the most elemental building block of cloud-climate feedback. Recent developments include studies of associations between stratospheric circulation/ENSO and changes in clouds.

Strengths:

The overall strength of CloudSat mission lies in its novel approach to observing clouds. As the first w-band or millimeter wavelength (3 mm) radar in space, it provided the science community with the first global survey of the vertical structure of cloud systems and measurements of the profiles of cloud water content. This adds critical information to our understanding of the vertical dimension of clouds.

Weaknesses:

There is no obvious weakness. The only thing to say in the hindsight is: we wish NASA had included the Doppler capability and allowed CloudSat to scan across track. But it's comforting to see the future follow-on mission – EarthCARE – will add the Doppler capability.

Value of data record and overall data continuity:

The value of the CloudSat data record is very high, as demonstrated by more than 19,000,000 files being downloaded by users in 59 countries. CloudSat team puts a lot of emphasis on multi-sensor data products, taking advantage of nearly simultaneous measurements from the A-Train constellation (Aqua, CloudSat, CALIPSO, Aura, GCOM-W1, and the future OCO-2). A number of products exploited the synergy between radar and lidar observations, and between passive and active systems.

One panel member added that CloudSat is the only instrument that can provide information on moderate to light snowfall in mid- and high-latitudes. Even with the future GPM mission (which is sensitive to relatively heavy snow), we will still rely on CloudSat and follow-on mission (such as EarthCARE) to provide measurements of moderate to light snowfall.

Due to a battery anomaly in April 2011, CloudSat is now operating in a new mode, called the Daylight-Only Operation (DO-Op) that relies on the solar panel to power the satellite. Only the sun-lit portion (~ 56%) of the whole orbit has data. Because of this, the satellite can no longer observe clouds in the polar night. However, the overall CloudSat data quality is not compromised and the mission objective can still be met, namely, surveying the vertical structure of clouds.

The technical panel raised a few questions concerning the new DO-Op mode:

1) Clarify claim that the additional battery failure would NOT be mission ending,

2) Provide an assessment of risks associated with some of the steps taken to reduce power consumption, such as turning electronics off and on.

Regarding the first question, CloudSat team responded as follows. There are three possible scenarios for battery failure: battery wear-out, cell short (both soft and hard), and diffusion limited current. Analysis shows that due to the shallow Depth of Discharge (DOD), the likelihood of failure due to wear-out in the next two years is extremely low. Although the likelihood of a short is higher, the low load in DO-Op makes it possible for the battery to tolerate an additional soft short. A hard short has the advantage that a backup battery would be brought online. As to diffusion limited current, DO-Op has margin to it and

monthly health testing indicates that there is low likelihood that worsening of the diffusion limit will result in a mission-ending failure in the next 2 years. For the second question, the CloudSat team identified three key areas where risks have been increased in DO-Op: wear-out of relays due to On/Off cycling of electronics, failure of electronics due to increased thermal stress as a result of On/Off cycling, and failure of wheels due to increased speed resulting in more rapid wear-out. Analysis again shows that these risks are low in the next two years. *The panel recommendation is: continue to monitor the health of DO-Op closely, although it has been running fine over the past 18 months*.

Core mission data product quality and maturity: **Excellent**

The accuracy of core mission data products has been constantly assessed and the uncertainties in the products are well established via various validation approaches including comparison with similar products derived from different observations and direct ground-truth measurements (e.g., field campaigns). The retrieval algorithms used by CloudSat, which are based on the Bayesian Theory, also have uncertainty estimation built in.

In addition to core mission products, advanced products that exploit synergy with other A-Train measurements and/or use new algorithms have also been developed and released, in response to the Senior Review in 2011. For example, the new 2C-ICE product uses both CloudSat and CALIPSO data to retrieve ice particle size and ice water content.

The panel asked a question in the context of Data Analysis (DA): how does the CloudSat group plan to interface new products from the Science Team to the users? The PI answered by saying that these new products come in *ad hoc* ways (e.g., through ROSES selection), but whenever it becomes available, it will be absorbed. A success story is Dr. Guosheng Liu's snow retrieval algorithm: it was developed through ROSES selection, but the algorithm was incorporated by the in-house snow product, which was released to the public.

Relevance to NASA Science Goals: Excellent

CloudSat mission contributes to four of the six NASA SMD focus areas:

1. Atmospheric composition: understanding the effects of convection on constituent transport;
2. Weather: CloudSat was used to correct precipitation biases in weather models; also used to study tropical and extra-tropical convective storms;
3. Water and energy cycle: CloudSat observation of clouds and precipitation is essential for studying the cycling of water in the atmosphere and the effects of clouds on Earth's energy balance; and
4. Climate variability and changes: climate variability is ultimately established by variability in the energy and water cycle. CloudSat provides a way to observe these changes and to quantify systematic errors in cloud/precipitation predictions in models.

For a ~$100M cloud-focused ESSP (Earth Systems Science Pathfinder) mission, this is rather impressive.

Technical Panel:

Per communication with C. Yuhas, the previous so-called "approved" budget for CloudSat was made based on the assumption that it will shut down soon (the same assumption was made for several other satellites). Under the current condition of CloudSat (DO-Op mode with mission life expectancy through

and beyond FY17), this assumption is no longer valid. Given tremendous contributions CloudSat has made and will continue to make to the science community and the expected calibration value for several future missions (e.g., EarthCARE and GPM), it is important to keep CloudSat operating until at least 2017 or beyond. The proposed "sustainable" budget looks reasonable to the panel.

National Interests Panel:

CloudSat was given an overall mission rating of High Utility by the National Interests Panel. See the panel report for detailed discussions.

EO-1

Recommendation: Continuation of projects as currently baselined for FY 14-15. Close out in FY16-17.

Summary of findings:

The NASA 2013 Senior Review Science Panel recommends that the EO-1 mission be continued as currently baselined. The 12.5 year old EO-1 mission continues to make numerous valuable contributions to the Earth Science community. It serves as a model for advanced technology capabilities, including spacecraft agility, on-board intelligent processing, reliable support technologies, and unique passive optical imagery. The mission also delivers and tests new technologies and strategies for satellite acquisition, algorithms for terrestrial environmental monitoring, calibration and validation, data synergy, and continuing technology advancements for data volume throughput, autonomous operations, and on-board processing. The two instruments onboard EO-1, the Advanced Land Imager (ALI) and Hyperion, are high spatial resolution sensors capable of imaging any spot on earth up to 5 times every 16 days (plus 5 nighttime images over the same period).

The EO-1 mission is central to NASA's strategic Earth Science plan: to advance Earth system science related to climate and environmental change, and to characterize, understand, and predict how the earth is changing, with consequences for life on Earth. Though originally designed as a technology demonstration project (ALI to inform Landsat 8 and Hyperion as the first grating-based, hyperspectral, civilian sensor in orbit), the mission continues to serve that purpose but has also made significant progress as a contributor to science and applied science investigations as well as national and international disaster monitoring efforts.

Despite the small team size (<10 part time) in the Mission Science Office (MSO) and Missions Operations (MO), the EO-1 mission supports an impressive array of activities. Science support activities include:

- Development of Level 2 science/technology products and prototype products for HyspIRI;
- Cal/Val activities – including lunar/terrestrial calibration;
- Technical interface for science community, including NASA HyspIRI mission concept team;
- Providing imagery and expertise to support ~14 HyspIRI ROSES AO projects; and
- Support for Landsat and LDCM.

Operations support activities include:

- Developing advanced software to automate scene tasking and prioritization;
- Providing an interface with national and international disaster relief organizations;
- Developing/upgrading SensorWeb technologies that link ground-based and satellite observations; and
- Developing Intelligent Payload Module (IPM) for on-board autonomous capabilities for HyspIRI and other missions.

Over the past 2 years, significant progress has been made on concerns expressed by the 2011 ESD Senior Review, which had rated EO-1 with the lowest scores of all missions under review. This progress has strengthened the relevance of EO-1 to NASA's science goals. In particular, the EO-1 Mission Science Office (MSO), in partnership with the USGS EROS has made data processing improvements and

continues to advocate for science-quality products. The panel also notes significant improvements to data tasking and acquisition and the mission is highly commended for these changes. The EO-1 website provides mission information, a reference list, user support tools, and links to data. In addition, through its web-based task management system (GeoBPMS), the user community can submit task requests, which could likely serve as a model for future sampling missions.

Other significant accomplishments of the EO-1 mission over the last two years include:

- Improved data processing;
- Improved Level 1T geometrically terrain corrected product;
- Increased data downloads: 16% increase in data downloads from USGS; 59% increase in use by government agencies; 72% increase in requests to USGS for emergency response/disaster support;
- Completed collections for 2010 Global Land Survey;
- Augmented lunar calibration procedures to improve calibration method for future earth observing missions;
- Continued in-house science investigations to estimate carbon parameters such as GPP from Hyperion data;
- Strengthened collaborations with the HyspIRI Decadal Survey Mission;
- Increased outreach and capacity building in support of the disaster community through SensorWeb;
- Established cloud-based archive with integrated Web Coverage Processing Service to allow users to apply co-registration, atmospheric correction, and user specified methods;
- Established Intelligent Payload Module for onboard processing capabilities; and
- Special Issue of IEEE JSTARS devoted to EO-1.

The Senior Review Science Panel concurs with the EO-1 mission team with regards to decommission plans. The EO-1 Mean Local Time (MLT) will degrade to earlier than 9:30 am by December 2013 but this does not entirely preclude the acquisition of useful imagery. Battery life is anticipated through 2015-2020. In preparation of the End of Mission Plan, the EO-1 mission has set September 30th, 2015 as the nominal decommissioning date. As such, the Senior Review Science Panel recommendation is to "terminate and close-out" the mission in the out years (FY16-17).

Scientific merits: Very Good

The EO-1 mission serves a global user community and constituency. One of the original, and most important of the scientific contributions of EO-1 is to inform other NASA missions: ALI was critical as a prototype for Landsat 8 and Hyperion provides "orbital heritage" for the Hyperspectral Infrared Imager (HyspIRI), proposed for launch in ~2022. With the recent launch of Landsat 8, ALI will continue to play a critical role in the initial calibration/validation of Landsat 8 products. In addition to this critical role, EO-1 continues to improve its usefulness for science and application investigations. The contribution of EO-1 to national and international disaster monitoring efforts is exemplary. The pointing capability, autonomous scheduling, and on-board processing have enabled the EO-1 mission to become the cornerstone of several disaster monitoring efforts, in particular SensorWeb.

The EO-1 mission also continues to expand its usefulness for a broad suite of earth science investigations which the panel feels were very well documented by this proposal. The four-fold increase in signal-to-noise ratio of ALI versus Landsat ETM+, along with the extra SWIR channels makes ALI very useful for remote sensing of active fires and lava flows. Hyperion data have been instrumental for time series calibration/validation sites, including Committee on Earth Observation Satellites (CEOS) calibration sites, eddy flux towers (FLUXNET), and International Long Term Ecological Research (LTER) sites. Earth science applications stemming from EO-1 data are broadly in the fields of geology, forestry, agriculture, hydrosphere, land use, vulcanization, and fire management. More specifically, EO-1 data have been utilized in a wide variety of studies investigating species discrimination and invasive species, shallow water bodies and coastal ecosystems, desertification, soil properties, ice and snow, coral reefs and water quality, disturbance recovery, archaeology, vegetation phenology, climate change, forest growth and carbon dynamics, agricultural monitoring, pollution effects on forests, and habitat fragmentation. Hyperion data and spectroscopy techniques are instrumental for species mapping, derivation of vegetation indices, mapping of forest nitrogen content, primary production, LAI, vegetation canopy closure, vegetation fractional cover and light use efficiency, canopy greenness, wetness, and pigment content, and comparison of vegetation bio-physical parameters derived by VIIRS, MODIS, AVHRR.

Strengths:

The science merit strengths of the EO-1 mission broadly include the contributions to successor missions, science, and applications. In addition, the EO-1 mission continues to partner with NOAA to develop an advanced version of the lunar-based calibration model. The 2011 Senior Review panel noted the lack of publications stemming from EO-1 data. This panel notes the significant progress made on that front, especially with regards to the forthcoming special issue of IEEE JSTARS devoted to EO-1 science.

Weaknesses:

The perceived weaknesses of the scientific merit of the EO-1 mission are few. The panel noted concerns about the diminishing quality and consistency of time series observations based on the degrading orbit and the associated increases in solar zenith angle.

Value of data record and overall data continuity:

EO-1 data have been instrumental for ensuring data continuity for the Global Land Surveys of 2005 and 2010, by gap filling for Landsat data, and providing a unique data record of islands around the world. Hyperion data have been instrumental for time series calibration/validation sites.

Core mission data product quality and maturity: Good

The stability of ALI and Hyperion data after 12.5 years of operation continues to be quite good (within 5% for ALI and 1.5% for Hyperion). Level 1 products are of very high quality and utility to the broad user community. Radiometrically (L1R) and terrain/geo-corrected (L1Gst) imagery from both ALI and Hyperion are provided upon request to users. The complete ALI and Hyperion data archives have recently been upgraded to L1T processing level which is a geolocated product co-registered to the Global Orthorectified Landsat Data (GOLD).

Level 2 data products are only produced “in-house” for MSO studies and select science users. Atmospheric correction for both ALI and Hyperion are still in the research phase and do not appear to be fully operational. However, atmospheric correction tools for Hyperion data are available to users on demand for correction of data to reflectance. Hyperion level 2 science products like reflectance are made available to users on demand. Other Hyperion level 2 products, like vegetation indices, land cover

classifiers, and science bio-physical products are still being tested but are provided to users on demand. For ALI, level 2 products, including reflectance, vegetation indices, land cover classifiers, and bio-physical products are currently provided on user demand and distributed free of charge via FTP. According to the proposal, vegetation bio-physical variables will become available in 2013 for users to generate on a routine basis.

As the 2011 Senior Review Panel noted, and this panel also notes, one perceived weakness of the EO-1 mission is the continued lack of level 2 product maturity and availability. The panel recognizes the fact that the EO-1 mission has a small team and lacks a dedicated Science Team, and, therefore, is commended for the breadth of their activities, but a focus on level 2 data product maturity is warranted and recommended by this panel.

Relevance to NASA Science Goals: Very Good

The mission originally served an important role of informing Landsat 8 development. Since the successful launch of Landsat 8, the EO-1 mission will be critical for initial calibration/validation of Landsat 8 acquisitions with ALI. Similarly, Hyperion data are critical for informing the future HyspIRI mission. In addition to these central roles, the EO-1 mission continues to be a critical asset to NASA's strategic Earth Science goals as well as NASA's Applied Sciences program. With 12.5 years of data acquisition, the mission supports many important long-term science investigations, including Hyperion time series for global change studies. On the Applied Science and Technology front, applications like SensorWeb are central to national and international disaster monitoring efforts. Furthermore, the EO-1 mission continues to pilot the "do it yourself" data processing (atmospheric corrections, co-registration, user-defined processing algorithms) in the cloud environment as a prototype for future missions. This new approach will allow for improved access to "big data" and allow users to create high-level information rather than just download raw data.

Strengths: The strengths of the EO-1 mission with regard to relevance to NASA Science Goals are varied. First and foremost, the mission served a critical role as a prototype for other missions, and it continues to be extremely important in this role. The panel in particular noted the strength of the unique fine scale hyperspectral measurements provided by EO-1.

Weaknesses: There were few perceived weaknesses of EO-1 with respect to NASA Science Goals. The panel noted that despite the broad scope of earth science applications related to NASA science goals, these are by design limited to smaller area investigations.

Technical Panel:

The overall evaluation from the Technical Review Panel is "Medium High Risk". Please see the Technical Review Panel summary evaluation for details.

National Interests Panel:

The overall evaluation from the National Interests Panel is "Some" utility. Please see the National Interests Panel summary evaluation for details. It was noted by the Senior Science Panel, however, that EO-1 is a critical national and international asset for disaster monitoring because of its pointing option, autonomous scheduling, and on-board processing. The EO-1 project has become the international

leader in SensorWeb demonstration projects and is associated with a large number of disaster working groups.

Other Comments:

Overall, the panel agreed that this was an excellent proposal that highlighted the many strengths of the EO-1 mission. The panel particularly liked the focus on the prior two years of accomplishments since the 2011 Senior Review and commends the EO-1 mission on these accomplishments and progress.

GRACE

Recommendation: Continue Project as Baselined

The GRACE mission has delivered unique datasets of the global gravity field and the large-scale temporal changes in mass distribution within the Earth system since it was commissioned in 2002. The GRACE data have provided novel insights on critical planetary processes such as ice sheet mass balance, the flux of meltwater into the global oceans, mass exchanges within the oceans and seasonal and interannual variability in groundwater storage at the regional scale, which have been used to detect and map major water use patterns. Furthermore, GRACE data have been used in operational settings including the radio occultation data that is assimilated into atmospheric models and the GRACE accelerometer provides some of the best *in situ* data on satellite drag and atmospheric neutral density at high altitudes. The mission has provided critical contributions to the development of a global gravity field complementing terrestrial gravity, CHAMP and GOCE. The health of the mission continues to be an issue as there are few components left with any redundancy. The team continues to work the power issue to extend the mission life at the expense of the annual cycle and event detection. The time varying missions is so unique that the mission should be continued as long as possible. Currently data are collected for ~120 days out of every 162 days. If the third battery on GR-1 fails data will only be acquired for ~50 days out of 162 days but the time varying mission should be continued. GRACE might become a single satellite gravity mission with a high resolution radio occultation experiment in the next 2 years. The single gravity mission status would occur with the loss of the k-band ranging system, the instrument processing unit on either vehicle (IPU) or the transmitter (RF XMTR) or the Ultra Stable Oscillator/Microwave Assembly (USO/MWA) on GRACE 1. This configuration will not meet the Level 1 science goals and unless there is a strong call from the radio occultation users or the gravity community the mission should be terminated.

Scientific Merits: Excellent

Strengths:

The publication record using GRACE data has exceeded 1190 peer reviewed articles with over 200 articles and book chapters in each of the last 2 years. The data has underpinned a number of the important insights into the changes in the earth system specifically in ice sheet mass balance, quantifying the changes in glaciers and ice caps globally and enabling the separation of the changes in ocean mass from the changes in ocean volume due to thermal expansion. Increasingly the GRACE data are being used to both study how the global oceans are redistributing mass from the Southern Oceans to the Arctic and the Mediterranean and as a data set that can be assimilated into numeric ocean models. The almost decade-long gravity record from GRACE has provided insights into the global hydrologic cycle capturing emerging trends in water storage some of which are from climate variability and some of which are from human activities. On the solid earth side GRACE has improved models of glacial isostatic adjustment and resolved mass changes from the very large earthquakes, e.g., in Japan and Sumatra. The GRACE satellite GPS receiver is used to measure globally vertical profiles of the atmosphere, bending angles, refractivity and dry temperature based on the radio occultation of the GPS signal. These measurements serve as the calibration for radio occultation measurements on other systems. These data provide atmospheric temperatures for assimilation into weather models. GRACE temporal gravity field observations further contributed to enabling the separation of mass change and elevation change (obtained from SAR and altimetry) for several Earth systems, e.g. ice sheets, ocean,

surface water versus ground water. There is currently no other mission that would allow these insights into these processes on a regional to global scale.

Weaknesses:

None

Value of data record and overall data continuity:

The strength of the GRACE mission is its global resolution of time varying processes as mass shifts on planetary scales. The value of the data record increases with the increasing length of the record. The instrument performance is degraded for wavelengths less than 500km as a result of relaxing the thermal control to reduce the battery load. There has been no thermal control since April 2011. The lack of thermal control has resulted in increased measurement noise and a systematic error. After tuning the processing strategy, there is no visible evidence of data quality degradation at spatial scales of 500 km or larger. For spatial-scales smaller than 500 km, some of the Level-2 data products are noisier after April 2011, but the annual and decadal variations are still captured. Processes with small spatial scales and large signal amplitudes such as outlet glaciers on ice-sheets, major deltas, and great earthquakes will still be resolved in the GRACE data. Processes at small spatial scales and with small signal amplitudes such as several river basins (e.g. Danube, Euphrates, Okavango, Colorado) may not be resolved with the increased noise levels.

Power limitations due to battery issues have introduced the 40 day data holes out of every 180 days. This data outage occurs during the deep shadow season and leads to a loss of information. In 2011, Level-2 data were not delivered for the months of January, June and December. In 2012, data for all months except May and October have been delivered. The estimates of the secular change in the polar ice mass variations are not affected. The goal should be to extend the mission to provide mission continuity with the GRACE Follow-On mission if possible. The team is working to preserve the time series with the recognition that the annual cycle variability and the study of transient events will be impacted by this strategy. The primary goal is to ensure overlap with GRACE-Follow-on and document the long-term change. The time varying gravity measurements are so unique that the mission should be continued as long as possible. Currently data are collected for ~120 days out of every 162 days. If the third battery on GR-1 fails data will only be acquired for ~50 days out of 162 days but the time varying mission should be continued. However, it is unclear how the gravity field recovery will be degraded if the ACC/ICU on either satellite were to fail, therefore we cannot make any recommendation on the response to this failure.

Core mission data product quality and maturity: Very Good

The core mission data product quality and maturity is ranked very good primarily due to the absence of a product that can be used by the non-specialist used community. There are two widely used GRACE data products, i) the monthly and ii) the mean gravity field – a level 2 product delivered as spherical harmonic coefficients. The Level 1 products include the ranges between the satellites, the geocentric position of the satellites, and the attitude and accelerometer outputs from the vehicles. These products are produced by a globally dispersed team beginning with the German DLR mission operation center, which works with JPL to produce the level 1 products and the teams at GFZ (Potsdam), UT and JPL who produce the level 2 products and validate the level 1 products. The products appear to be mature recently were reprocessed (RL-02 Level-2 January 2003-December 2012). Informal feedback suggests that the new release shows an improvement by a factor of 2-3. The number of unique users downloading GRACE data is over 22,000, up from ~18,000 in 2011. Quicklook gravity products have

been developed to look at floods and similar rapid response events.

More widespread use of GRACE data continues to be hindered by the data format. The last senior review panel suggested that mascons become an alternative data format for delivering the GRACE results. This has not been completed although the JPL validation effort has focused on developing a mascon solution for the Release 05 series in 2014. This product should be integrated with other NASA tools for looking at Earth satellite data. The Senior Review Panel recognized that the community using the GRACE products is still rather narrow and specialized. While the CSR team is very responsive to individual requests for detailed data, it is important that towards the end of the mission lifetime the data become more widely available. In addition to the mascons maps, the team should make the monthly solutions available globally so they can be used by a wider community. The spherical harmonics form of the Level 1 and 2 data are not easy to use for many potential users. Currently the GRACE product delivered by CSR is not easily accessible and still contains significant striping. The team should be tasked with making the GRACE data accessible to the broader community. Ideally the GRACE monthly products with options to filter different spectral bands would be accessible in the standard NASA tools such as Worldview. These efforts shall be initiated well before the close out of the mission.

In summary to enhance the use of GRACE data by a wide community, the team should:

(1) Deliver the mascon product sooner than 2014 – this has been pending since the last senior review;

(2) Develop a series of global grids reflecting standard selection of harmonics for the month products that could be available to the broader community; and

(3) Recommend and document the used standards, filtering methods and maps of products in a format which follows geospatial standards which allow easy inclusion in mapping/visualization systems

Relevance to NASA Science Goals: Excellent

The GRACE mission estimates mass variability on the Earth's major systems including the oceans, land, cryosphere and oceans. These key estimates contribute to the goal to characterize and understand "*How is the global Earth System changing?"* The mission specifically addresses three ESD focus areas including: Climate Variability and Change; Water and Energy Cycle and Earth's Surface and Interior. For Climate Variability GRACE supports applications in ice sheet mass balance, sea-level rise, dynamic topography and the transport of heat and mass in the upper ocean and ocean processes. In the water and energy cycle segment GRACE addresses global water balance and provides inputs for evapo-transpiration for weather models. In the Earth Surface and Interior GRACE has captured major mass moving events and facilitated the development of an improved national reference system. In support of the Weather focus area GRACE radio occultations provide input into atmospheric and ionospheric conditions.

<u>Weaknesses:</u>

No weaknesses with respect to the relevance to NASA's goals.

Technical Panel:

The technical panel outlined that the GRACE mission requires both satellites to be operating to perform the time-varying gravity measurements, but key instrument subsystems now lack redundancy, which leads to a ranking of the mission as high risk.

National Interests Panel:

GRACE is used for a wide array of applications from ingestion into weather models, to developing drought monitoring tools to providing long-wavelength control of high-resolution geoid models and in situ data on high altitude satellite drag and atmospheric neutral density. GRACE data would have even broader use if the GRACE data were more accessible. The National Interests panel ranked GRACE high utility and captured many of these uses. The National Interests Panel also highlighted how GRACE data would be more widely used if it were more accessible.

Other Comments:

The team should develop an end of life plan for the mission including specifically addressing the question of if it is worthwhile continuing a single satellite gravity mission as the vehicles descend. This should include an assessment of whether a CHAMP-type single satellite gravity mission would have a justifiable contribution to the development of a more accurate global geopotential field. The uses of the radio occultation and the accelerometer drag should also be considered.

Jason-1

Recommendation: ***Continuation of projects as currently baselined;***

The panel recommends that the Jason-1 mission to be continued as baselined at least until the upcoming Jason-3 mission has been launched and calibrated. While the primary calibration is expected to be achieved by OSTM flying in a tandem configuration with Jason-3, there is concern that Jason-1 be maintained as a backup *in case of unanticipated failure of OSTM prior to Jason-3 calibration.* There is some value in using Jason-1 to detect and correct large errors in sea-surface heights from Jason-3 in the absence of OSTM. This potential calibration value as well as the impact of Jason-1 to the wider scientific community through its contribution toward increased resolution for oceanic mesoscale monitoring should be re-evaluated by the next Senior Review panel.

Jason-1 is a critical mission to establish a near global continuous record of sea surface height (SSH) observations and spatio-temporal changes which was started in 1992 by Topex/Poseidon and is currently continued by Jason-2/OSTM. Due to several safe holds early in 2012 and the potential risk of a collision with OSTM or its successor Jason-3 (to be launched 2015), Jason-1 was successfully moved to a lower geodetic orbit (recommended by the Joint CNES-NASA steering committee and the Senior Review Report 2011). The new geodetic orbit extends the repeat period from 9.9 days to 406 days and leads to significantly greater observation density at the cost of temporal resolution. As a consequence, Jason-1's contributions to extend the sea-level change time series along the established track have switched to providing SSH observations along a new track pattern. Despite the change, Jason-1 continues to provide valuable observations for mesoscale oceanography, which requires 2-3 operational altimeters. The SSH product from the geodetic mission shows only minor degradation in sea surface anomaly variance and is still assimilated into operational models by several agencies.

The main advantage of the new orbit is the high spatial coverage that significantly improves our knowledge of the marine geoid, marine gravity, bathymetry and sea surface topography. The improvements are targeted in both spatial resolution and accuracy. This will lead to improvements in bottom mixing models and sea surface topography data by combining gravimetric data and altimetric sea surface height. In addition, the improved marine /gravity observations are expected to outperform all existing altimetry observations since 1986. While these new products are to be developed by the OSTST (Ocean Surface Topography Science Team), we recommend that these products be adopted by the mission team for distribution and user support.

In addition, Jason-1 may become a critical mission if OSTM experiences difficulties or the recently launched missions Altika and HY-2A cannot be calibrated soon. We also note that these new missions do not provide the precision achieved using Jason-1 and OSTM, which represent the standard for ocean radar altimetry.

In summary, Jason-1 continues to provide high-quality sea-surface height information which remains highly relevant for operational oceanography and now also geodesy and geodynamics. The Jason-1 team has successfully implemented the recommendations made in the 2011 NASA Senior Review Report by moving it to the geodetic orbit and maintaining the health of the mission. A continuation of the mission as currently baselined for FY14-15 is recommended.

Scientific merits: ***Excellent***

Strengths:

The Jason-1 SSH observations in the new geodetic orbit are of considerable value in spite of the minor quality degradation that will be reduced with an increasing number of observations. Large scale oceanographic circulation and decadal variability such as ENSO and the North Atlantic Oscillation are observed. Monitoring of major current systems including the Kuroshio, Brazil and Malvinas currents relies on Jason-1 observations. Together with OSTM, Jason-1 products allow for targeting oceanic mesoscale processes, which could not be resolved by OSTM alone. Furthermore, Jason-1 data were critical for forecasting the Deep-Water Horizon oil spill trajectory. The main scientific advance has been the improvements of the global marine geoid, marine gravity, and bathymetry fields by incorporating Jason-1 data since May 2012 to the existing ERS-1 GM and Geosat GM data. A tremendous number (90,000) of newly charted seamounts are expected as is a geoid accuracy increase by a factor of 2-4 (depending on one 406-day or two 406-day cycles). The reason for these advances is due to the low inclination of the Jason-1 orbit compared to ERS-1 and Geosat. This improves the sensitivity to the East-West component of the gravity field, especially in equatorial regions. Initial results provided by two independent research groups indicate that one cycle of Jason-1 GM marine gravity observations outperforms all previous altimetry derived marine gravity from ERS-1 GM and Geosat GM. The Jason-1 mission has seamlessly transferred from an oceanographic mission to an oceanographic-geodetic mission and continues to contribute to these scientific areas. The mission is expected to increase the community's research output and publication numbers by providing these new GM observations.

The products are frequently used by the science user community with increased numbers of unique users after the transition to the Geodetic Mission. The publication record is very strong and a new wave of scientific achievements must be expected from the GM products.

Weaknesses:

While the mission can provide observations over rivers and lakes as well as providing assistance to tsunami debris modeling, these applications are neither mission critical nor well established beyond occasional examples. The change from a 9.9-day to a 406-day repeat cycle, is likely to further reduce the relevance of Jason-1 observations for lakes and rivers applications. This is a minor weakness.

Value of data record and overall data continuity:

Jason-1 data is continuously provided with high quality and with very minor down time. Its most important contribution is that it allows for the continuation of the sea surface height time series started by 1992 by Topex/Poseidon. The previous sea-level data gap between Geosat and Topex/Poseidon (1989-1992) was shown to be detrimental to the estimation of decadal sea-level change. While the project scientist indicated that even a 1-2 year observing data gap could be overcome with alternate data products, the panel has doubts that this holds for the acceleration of sea-level change, ocean currents, climate events such as ENSO or melt-water pulses at shorter and irregular time scales. Hence, Jason-1 is one of the few missions that can prevent a potential future gap in these fundamental climate records.

Core mission data product quality and maturity: Excellent

The GDR data products are well calibrated and represent the highest accuracy levels compared to other radar altimeters. The product quality has not changed significantly despite recent technical challenges. The provision of highest quality products (SSH with RMS of 2.5 cm) for over 12 years is commendable.

The algorithms are well established and only minor adjustments are required for the new orbit geometry (e.g. initially replacing the mean sea-surface height by a geoid model as a reference for sea-level anomalies). The new products gravity, geoid and bathymetry are a contribution of the OST Science Team. The products are generated with equally well established algorithms building on the heritage of the geodetic missions of ERS-1 and Geosat. However, the products should be adopted by the mission team and distributed through the mission dissemination channels. Synergies with OSTM are obvious and are exploited with respect to data assimilation into models. The panel also noted that the user community often relies on community-provided data access tools (e.g. RADS) for data download and processing. This is considered important and should be supported by the Jason-1 mission operations. The quality of data production is high and maintaining and the core mission products are rated as excellent.

Relevance to NASA Science Goals: Excellent

Strengths:

Jason-1 observations contribute to answering the four main NASA science questions. Below, a few examples outline how this is achieved. The relevance to the NASA science goal is considered as excellent.

How is the Earth system changing? The project directly contributes to improved understanding of sea-level change, ENSO, ocean currents, circulation patterns, heat, and ocean-bottom mixing.

What are the sources of change? The project contributes to this question through assimilation of Jason-1 products into current and circulation models in combination with other NASA products. Furthermore, Jason-1 observations lead to improved sea-surface topography estimates from a combination of the new geoid data (in combination with GRACE) and SSH will shed light on the oceanographic versus geodetic sources of sea-surface topography.

How will the Earth system change in the future? Jason-1 data directly contribute to better constrained predictions of sea-level change as well as operational forecasting of wind and wave climate.

How can Earth system science improve mitigation and adaptation to global change? Accurate observations of sea-surface heights, ocean tides, wind and wave patterns lead to local predictions of sea-level change (including crustal motion) and potential mitigation means. Jason-1 observations contribute to accurate representation of mesoscale processes as direct indicators of climate change and the impact on fisheries.

We note that OSTM is currently the only alternative for acquiring these measurements.

Weaknesses:

NASA Science goals can potentially be answered by using OSTM measurements. However, not all of the processes can be targeted by OSTM alone including specification of the geoid, bathymetry observations, and mesoscale oceanography. Using OSTM alone would lead to a degradation of the accuracy and spatial resolution of altimetry products.

Technical Panel:

The Technical panel identified several technical risks, which could eventually lead to mission termination. However, the advantages associated with continuing the geodetic mission for geoid/gravity, and wind and wave data retrieval even after the loss of precise orbit determination from

GPS and DORIS, and the loss of the C-band altimeter, are considered important enough to continue the mission despite the technical risks. The Senior Review Panel concurs with the findings of the Technical Panel.

National Interests Panel:

The Jason-1 mission was given an overall utility rating of "High" by the National Interests Panel. Several federal agencies assimilate Jason-1 products and indicated that a termination of Jason-1 observations would be detrimental to the accuracy and relevance of their products. The Senior Review panel concurs with the findings of the National Interests Panel.

Other Comments:

The single-string risk for Jason-1 seems high, however, even with the loss of several instruments, the Ku-band altimeter alone would be able to provide valuable observations of the sea-surface slope and this is the quantity needed to derive geoid/gravity/bathymetry. For this application, even the loss of the precise orbit determination system is acceptable. Consequently, a continuation of the mission with reduced functionality is still highly valuable to determine the marine gravity field at short spatial scales. Every completed orbit will improve the gravity field retrieval.

While the mission team used the argument of the benefits of the GM and its new products in the proposal, the Senior Review Panel also noted their statement that product generation and dissemination (gravity/geoid/bathymetry) is the responsibility of the OSTST. We recommend that the mission team should adopt the new products and integrate these products in dissemination and support.

The Senior Review Panel strongly supports the Jason-1 mission to be continued as baselined for the proposed extended mission. Jason-1 should be considered a backup to OSTM for Jason-3 calibration in case of unanticipated failure of the OSTM mission. The next Senior Review Panel should then evaluate the continued value of Jason-1 based on the following questions: 1) Would additional GM cycles beyond 2015 significantly improve the quality and resolution of the marine gravity field; and 2) Is the improvement in resolution of oceanic mesoscale observations by continuing Jason-1 in addition to OSTM and Jason-3 of critical importance to the user community. The close-out of the mission is a potential recommendation if the findings indicate no significant relevance of Jason-1 beyond 2015.

OSTM

Recommendation: ***Continuation of projects as currently baselined.***

Note: *Presently, NASA is only supporting a small number (three) of the sub-systems for the OSTM mission. The satellite is operated primarily by NOAA, partnering with NASA, Eumetsat (European Meteorology) and CNES (French Space Agency). The requested NASA budget for OSTM is $1.2M out of the total $130M for all missions.*

The overall Mission is judged to be "Excellent", as defined by the "Review Plan", i.e.

- The data sets are widely used, multidisciplinary and recognized as the standard ('reference') for the Earth Science community;
- Continuation of the data sets at the same high level of quality is highly likely, data gaps are negligible, and the mission is fully responsive to the priorities of the ESC science objectives; and
- There are no major weaknesses in the program, with numerous, significant strengths.
- [In addition, the cost is minimal]

The OSTM/Jason-2 altimeter is the third "precision" altimeter to occupy the 10-day repeat (TOPEX/Poseidon, T/P) "reference" orbit, while measuring changes in the ocean's sea surface height (SSH) to instantaneous accuracies of several centimeters. In this orbit, OSTM serves as THE reference satellite for the other altimeters in orbit at the same time (these are now Cryosat-2 and Altika), improving the accuracy of their products by comparing heights during orbit "crossovers." In 2015, Jason-2 will be joined in the reference orbit by its replacement, Jason-3, which will fly in tandem with OSTM (along the same orbit separated by 1 minute) for six months to provide the coincident measurements needed to assure complete consistency in their time series of SSH measurements. *Thus, data from OSTM serve as the reference for the present constellation of altimeters and also for the next precision altimeter (Jason-3).*

After its replacement by Jason-3, it will move to an interleaved orbit to contribute to an even higher spatial resolution of the SSH fields. The time series from the reference altimeters provides the present estimate of global sea level change, a primary oceanographic climate data record. Not only does it monitor the change in the mean sea level of the global ocean with accuracies of better than 1 mm/year, it also describes the spatial variability of the changes in sea level. Together with the system of subsurface floats (the ARGO system), it provides a record of changes in the 3-D structure of density, temperature and salinity in the ocean. Further combinations with observations by the gravity missions (GRACE and GOCE) monitor the exchange of mass of water between continents, oceans and glaciers on seasonal to inter-annual time scales. By using its precise orbit to remove offsets between all of the altimeters in the constellation, the reference altimeter allows the combined SSH fields to resolve mesoscale features (eddies with scales of 50 km and longer). Still further combinations of the circulation fields with biological data from satellite ocean color sensors and in-water instruments are used to investigate biophysical interactions. All of these data can be assimilated into ocean circulation models to form the most complete description of ocean dynamics and (eventually) marine ecosystem dynamics. Ancillary measurements of significant wave heights and winds are routinely included in

operational wind and wave forecasts, while estimates of upper ocean heat content are used to predict changes in hurricane intensity. In these and other applications, the data are widely put to use in interdisciplinary and multidisciplinary enterprises, constituting numerous major strengths. The science goals directly address the NASA ESC science objectives, as expressed in the two questions: "How is the global Earth system changing?" and "What are the sources of change in the Earth system and their magnitudes and trends?" Through assimilation of the altimeter data into ocean circulation and climate models, the altimeter data sets are helping to answer the third question, "How will the Earth system change in the future?"

Scientific Merit: ***Excellent***

The proposal states that the "overarching goal" of the OSTM mission is to "continue and extend the T/P and Jason-1 time series to study the changing ocean on ever-longer time scales."

Strengths:

OSTM forms a crucial link between future and past altimeter data sets for climate studies. One climate goal is to monitor the continuing rate of global sea level rise (SLR), along with the spatial patterns of SLR. Several studies combine data from the altimeters, scatterometers, radio occultation (GRACE), and the global system of profiling "ARGO" floats to address this goal. The altimeter shows SLR in the western tropical Pacific, where the ARGO subsurface data find a layer of warm surface water, created by changes in the currents (revealed by the altimeter) due to increased strength of the trade winds and larger-scale Walker circulation (seen in the scatterometer data). The increase in global SLR during the 1997-98 El Nino and the subsequent drop during the La Nina are compensated by decreases and increases in the terrestrial water storage, as estimated by changes in the GRACE gravity fields. Similarly, an apparent leveling off of the global SLR during 2010 and the first half of 2011 is caused by a temporary increase of the terrestrial storage of water over Australia, northern South America and SE Asia.

Other examples of changes in ocean circulation noted by the proposal include: (1) North-south fluctuations of Southern Ocean fronts and cross-front eddy fluxes; (2) An increase in the Atlantic Ocean Meridional Circulation (from altimeter and in-water data), counter to previous hypotheses about climate change; (3) Extensions of the altimeter 20-year period to a 110-year period using tide gauge data, showing changing patterns of ENSO events; (4) The changing global distribution of eddy locations and their water properties, along with interactions of the eddy SST fields and the overlying winds; and (5) Consistent patterns of altimeter SSHA fields and sea-surface salinity (SSS) in equatorial current systems. The SSS fields are from the NASA Aquarius mission (the newest ocean sensor).

The increased understanding of oceanographic processes, such as described above, allows us to test, improve and gain confidence in models of ocean circulation, which are incorporated into the climate models that predict short and long-term variability in oceanic and terrestrial climate conditions. Regional analyses of altimeter data, often involving emerging coastal applications, are being compared to downscaled (nested) versions of the coupled climate models, leading to improvements in the regional scale climate predictions. Through these studies, altimeters are playing an important role in improving our ability to predict future changes in the Earth system, on both regional and global scales.

Weaknesses:

There were no major or minor weaknesses in the proposal.

Value of Data Record and Overall Data Continuity:

One measure of the value of the data is the productivity of the mission, as indicated by the number of peer-reviewed papers that use the altimeter data or acknowledge support by the altimeter project. JPL maintains a literature data base for all altimeter missions (T/P, Jason-1 and OSTM) with 3574 published papers in 23 years - an average of about 155 per year. In the five most recent years (the OSTM Mission years, 2008-2012), there were approximately 650-1000 papers (depending on the data base queried), averaging about 130-200 per year. Thus, the altimeter data set has continuously formed the basis of a multitude of successful scientific analyses over the past twenty years. The titles of those papers show that the science being conducted with OSTM data cover not only sea level variability and ocean circulation on scales ranging from coastal eddies to basin-scale circulation, but also studies of sea-floor topography, significant wave height, hurricane forecasts, atmospheric water vapor and space weather. Outreach and education are also represented. Once again we see that "*the data sets are widely used, multidisciplinary and recognized as the standard for the Earth Science community*."

Furthermore, the value of the data is demonstrated by the importance of the problems addressed by those projects. The questions related to the ocean circulation's role in climate variability (on multiple spatial and temporal scales) and the impact of sea level rise in coastal regions are critical to the future well-being of human populations in many regions of the globe.

The "*data continuity*" issue is exactly one of the reasons to continue the OSTM time series for the next 3-4 years, until it can be used to calibrate the next precision altimeter (Jason-3). Although a gap of 1-2 years between OSTM and Jason-3 would not make it impossible to continue the record of sea level rise using Jason-3 after the gap, it would require a much longer period to recalibrate and match the Jason-3 data to the previous record (using tide gauges and fixed platform cal/val sites). For example, the comparison of TOPEX and Jason-1 data during the 6-month tandem phase allowed the identification of differences in the corrections due significant wave heights, which would have taken much longer to discover and correct. A gap of 1-2 years will also make it more difficult to assess accelerations in the sea level rise rates and to separate human from natural causes of sea level rise. Thus, we recommend continuing the mission through the at least the first 6 months after the launch of Jason-3, preferably through both FY14-15 and FY16-17 periods, with baseline funding.

Core Mission Data Product Maturity: Excellent

The OSTM project warrants an evaluation as *"Excellent",* defined as, "*Core mission data product accuracy has been assessed and the uncertainties in the product well established via independent measurements in a systematic and statistically robust way, representing a broad array of conditions. The quality of data production is high and maintaining".*

During the history of satellite radar altimetry, the evaluation of the error budget in the final dynamic topography calculation has been the central organizing concept of the data quality control and analysis. There has always been an emphasis on the "*uncertainties in the product*". A focus on the components of the error budget was used to organize the efforts of the Science Definition and Science Working Teams during 1988-1992, prior to the launch of T/P. It has continued to be the focus of the OSTST during the 20 years since that launch, using precise and very stable measurements at several platforms maintained by the T/P and Jason-1 Missions, in combination with a global tide gauge network and measurements made by individual members of the OSTST. Because of these efforts, the working RMS total error has been reduced to ~3 cm, compared with the original 13 cm.

During the past several years, unexplained biases that have existed between the different precision altimeters over the 20 years have finally been understood and all of the historical altimeters now agree to RMS 1 cm (Figure 3 of the proposal). Two other spurious trends have been identified and corrected recently (Figures 3-5 of the proposal). Thus, the *quality of data production* is not just *high and maintaining,* it is *improving.*

NASA is not responsible for the original Core Mission Data Products for OSTM, which are produced by NOAA and CNES. NASA/JPL is responsible for three sub-systems, the GPS, AMR and LRA (Laser Retroflection Array) deployments, along with the command and control, health and safety monitoring, instrument test-bed operations, anomaly analysis and recovery for these components. NASA/JPL is also responsible for cal/val activities for these systems. This includes the improved Autonomous Radiometer Calibration System (ARCS), developed at JPL, the GPS precision orbit determination and analysis, and laser ranging support.

JPL is also responsible for two "complementary" data products: (1) a near-real-time SSHA, using Precision Orbit Determination orbits derived from the GPS sensor that are more accurate than the near-real-time orbits calculated using the DORIS positioning system; and (2) AMR-ESP, an improved atmospheric water vapor path delay product, originally calculated within 25 km of land for coastal uses, along with radiometer-derived land, rain and ice flags.

Although these data products are officially "complementary" or "supplemental", the AMR-ESP has now been incorporated into the newest version of the official Geophysical Data Record (GDR-D), used in all altimeter products. This product and the Automatic Radiometer Calibration System (ARCS) have improved the accuracy and stability of the OSTM wet tropospheric path delay, a critical component of the altimeter error budget. Similarly, the use of the GPS-based orbit affects the operational SSHA products, which are used in the operational ocean circulation models in the US Navy and NOAA, as well for forecasting hurricane intensity. Thus the small amount of funding allocated to NASA for the OSTM budget is easily justified by the value of the data products it is providing.

Education and Public Outreach: The budget provided for the E/PO effort is small ($41K, 3-4% of the OSTM total). However, the JPL Outreach Office does an excellent job in providing knowledge of space, satellites and the Earth systems to the public. If NASA wants to improve mitigation and adaptation to global change (see below), it should increase support for the JPL E/PO office for that specific focus. Unfortunately, the recently proposed elimination of E/PO throughout NASA will make this impossible.

Comments:

"Redundant or complementary products not noted in the individual mission proposals." Jason-1 data are complementary to OSTM rather than redundant, now that it is in a geodetic orbit that will improve the marine geoid. The improved geoid will eventually allow the combined data sets over the complete history of altimetry to be used in non-repeating tracks and without removing the mean currents. Other satellite altimeters that are presently (or soon to be) flying, such as Altika, Cryosat-2, Sentinel, do not have the same precision as OSTM, since they often use a single frequency (less accurate ionospheric corrections), with or without radiometers for direct removal of water vapor path delays, etc. They are complementary to the need for the Reference Mission, in that OSTM improves their accuracy and removes offsets between altimeter data sets, allowing their data to be combined with OSTM data to improve the spatial and temporal resolution of the SSH fields. Other satellite data for SST, winds, chlorophyll concentrations, salinity and gravity are complementary, allowing a more complete analysis of upper-ocean forcing and response. In-water measurements are also complementary, since the

altimeter cannot see beneath the surface. Finally, data-assimilating models are complementary, providing a temporally varying 3-D representation of the complete system.

"Definitions of core data products for each mission, including any recommended changes." The present definitions for altimetry have been developed during more than two decades and are adequate.

"Justification of the level of science support required to maintain the quality of these core data products." The funding requested here is very small and maintains the AMR, GPS and laser reflector array. The LRA is static and requires little effort. The AMR is essential and not very expensive. The GPS is inexpensive and improves the accuracy of the near-real-time altimeter data, which are assimilated into the operational ocean circulation models of the US Navy and NOAA. We recommend continuing this level of support for the next 4 years.

The panel noted the important synergies with Jason-1, Cryosat-2, the gravity missions (GRACE, GOCE), wind (QuikSCAT), SST and chlorophyll concentrations (Aqua) and salinity (Aquarius).

Relevance to NASA Science Goals: Excellent

OSTM measurements are helping to answer the following NASA three science goals/questions: How is the global Earth system changing? What are the sources of change in the Earth system and their magnitudes and trends? and How will the Earth system change in the future?

Strengths:

The growing length of the altimeter data set is already addressing the first question on the interannual to decadal time scales, with statistical connections to longer (past) time scales. Continuing the OSTM data record through the first year of the Jason-3 altimeter (2015) will assure the continuity needed to extend the data set to 25 or more years. Moreover, the recent analysis of SSH in combination with complementary satellite (GRACE, scatterometer, SST and ocean color) and in water (ARGO float) data are identifying the sources of the changes in SSH and ocean circulation on scales from months to decades. The SSH observations are integrated into ocean circulation and coupled climate models, which are used to explore the causes of the monthly-decadal changes within a more dynamical framework. Moreover, the assimilation of the SSH data improves the predictive properties of those models. This includes relatively new forecasts of ocean circulation and water properties, along with short-term atmospheric forecasts of hurricane intensity and climate models which predict changes in the future environmental conditions. The fourth NASA question addresses mitigation of, and adaptation to global change. Attempts to mitigate the effects of near-term weather events (hurricane intensity) and long-term changes in sea levels, ocean currents and climate will depend on the confidence that we have in our understanding of the processes and in our predictions. Mitigation and adaptation requires effort and expense, which will only occur through a willingness to act on the part of the population. This willingness requires trust in the scientific process and conclusions. This is the realm where education and outreach play a key role. Thus the answer to this fourth question depends on the strength of the science involved in the first three questions and on our ability to communicate the conclusions of those scientific analyses to policy makers and the public. This raises the question of whether the support for Education and Public Outreach is sufficient to communicate the need for mitigation and adaptation.

Weaknesses:

None.

Technical Panel:

The Risk is Low and the Cost is very small. Even after the recent "safe holds", approximately 99.0% of the possible data have been collected over the past 5 years. The Mission team made it clear that the safe hold events are typical of the other (TOPEX and Jason-1) satellites and presently have not eliminated any redundancy in the OSTM instruments or electronics. The benefit to cost ratio for the small NASA funding is huge, reaping the rewards of NASA's substantial investment in T/P and Jason-1 altimeters. The AMR is critical for the accurate measurement of the wet tropospheric path delay; improvements in this product during the past two years have advanced the use of the global OSTM data set in coastal and ice-edge regions. The GPS measurements improve the accuracy of the near-real-time OGDR, which is assimilated into the operational ocean circulation models (US Navy, NOAA, and various universities) and forecasts of hurricane intensity and wave fields. The panel concurs with the findings of the technical panel.

National Interests Panel:

NOAA and the Navy use these data for ocean sea level, wave and current forecasts (including hazardous spill and marine debris trajectories), while it is also used in hurricane intensity forecasts. Along the U.S. coasts, it is assimilated into coastal ocean circulation models run primarily by universities and made available to users through the U.S. Integrated Ocean Observing System. Gridded fields from the French (AVISO) are used by many users at all levels. Those using the coastal fields include a growing population of recreational and commercial boating and fishing interests.

Final Comments

The only "weakness" noted in the OSTM program is the concern caused by the pair of "safe holds" during March and April, 2013. Although still under investigation, the cause of these events is thought to be an error in the computer memory caused by radiation (South Atlantic Anomaly) and is not considered to constitute a serious threat to the mission. The TOPEX and Jason-1 systems recovered routinely from many such events and continued without problems. The original instruments are still being used, cross-strapped to the platform B electronics, with no apparent change in characteristics. A bad memory location has been identified on the platform A side of electronics and a fix is being engineered to bypass that location. There is presently no loss of redundancy for any of the components, leaving the mission hardware and software in excellent health. Even with these events, 99.0% of the possible data has been collected and there is every reason to expect the data to continue to be collected at the same high level of quality, with minimal data gaps.

QuikSCAT

Executive Summary: This mission proposes the continued use of QuikSCAT to calibrate Ku-band ocean backscatter from the Indian Space Research Organisation (ISRO) scatterometer (OSCAT) as well as the new NASA ISS-RapidSCAT sensor that will be launched in 2014. They will also continue to use and improve adapted QuikSCAT algorithms to produce climate quality OSCAT ocean vector winds and ice products that continue the high quality QuikSCAT time series. This approach is viewed as the optimal way to continue the science- and climate-quality data record, since the ISRO mission is directed at near real time operational applications. Without appropriate calibration and data processing, these data will not be useful for climate and cryosphere research. ISRO and NASA have demonstrated successful collaboration to achieve these goals. QuikSCAT has been extremely stable in its calibration, and the radar instrumentation shows no indication of either calibration drift or deterioration, making this instrument ideal for calibration of these Ku-band scatterometers. In a change from the last review, this proposal will also use a combination of QuikSCAT and Rapidscat to extend the science and application of ocean vector winds by exploiting a calibrated Rapidscat and its non-sun synchronous orbit to assess diurnal and semidiurnal wind variation in the tropics, and by adapting QuikSCAT operational near-real time processing to the delivery of Rapidscat OVW data to forecast agencies. It will also use Rapidscat to demonstrate a new method of scatterometer wind vector intercalibration for several additional sensors, most specifically the EUMETSAT C-band ASCAT scatterometers. This effort is intended to address a standing scientific and technical issue of reconciling small but climate-relevant differences between winds derived using C- and Ku-band satellite sensors and we agree that this objective has significant merit. The science and implementation plans to accomplish these objectives are ambitious yet feasible.

The sustaining budget guidelines are recommended and would include mission operations and science and data analysis activities for FY14 and 15. The science panel unanimously supports the sustained funding, as a strong case has been made for the science. The National Interest Panel found high support for the mission. The key weakness remains the technical status of the satellite: the technical panel rates the risk of failure as high based on medium risk across several potential failure points. This rating was also given in the 2011 review process. The QuikSCAT radar is currently functioning very well, with considerable redundancy. Given the strong support for the mission science and national interests, and the high quality and stability of the QuikSCAT data, the Senior Review Panel recommends continuing the QuikSCAT calibration mission at the baseline funding level out to FY17, subject to review by the 2015 Senior Review Panel.

Recommendation: Continuation of projects as currently baselined

The sustaining budget plan is recommended to continue to derive research and climate quality ocean wind vector data in FY14 and 15. The proposed activities are also needed to produce data of desired quality for a wide range of operational activities as indicated by the National Interests Panel. Continued operation into 2015 is highly desirable in support of the proposed ISS-Rapidscat calibration and science data production, and to monitor calibration drift in the OceanSat-2 (OSCAT). Operations and data analysis support for the QuikSCAT team in FY16-17 may be necessary for data continuity, and will be of great advantage for science (including climate and cryosphere) and operational applications.

Scientific Merit: Excellent

Strengths:

The science supported by the long-term QuikSCAT wind and sea ice data sets is strong and clearly presented, particularly the case to use this mission to maintain and extend science and climate-quality ocean wind vector and sea ice data using the ultra-stable QuikSCAT radar in tandem with other sensors in the international constellation. Program performance in the past two years is commendable, with finalization and delivery of the 1999-2009 QuikSCAT version 3 wind data set for the community, and clear success in the proposed satellite wind and sea ice cross-calibration objectives. The version 3 QuikSCAT global wind product for climatological applications represents a marked improvement and should contribute to additional science capabilities, particularly for deriving more accurate vector wind and wind stress derivative (e.g., curl and divergence) fields. The panel finds an increase in scientific merit for the QuikSCAT extended mission in comparison to the last senior review where the rating was already excellent. This is because of: 1) the demonstrated success in combining ISRO OSCAT with the non-scanning QuikSCAT mission data to bring more than four additional years (2009-to-present) of climate-quality global ocean vector wind and sea ice data online; and 2) the proposed steps to apply the same tools and experience to the newly approved two-year ISS-Rapidscat mission and produce specific new science, operationally-desired weather forecasting data, and further extension of OVW climate data records. We view the QuikSCAT/Rapidscat activities as consistent and leveraged use of the extended mission core assets and expertise towards NASA Earth Science program goals. This science plan implicitly strengthens NASA ties to the broader international research community including the Indian Space Research Organisation.

Extending this highest quality long-term OVW record as long as possible with the hardware at hand (in this case QuikSCAT + OSCAT + OSCAT2 (~2015) + Rapidscat) is a unique mission contribution to precise climate change trend determination in ocean winds that NASA should continue to support. It is clear that the collaboration between ISRO and NASA has been successful and has allowed the extension of these data from 2009-2013 and eventually through 2017 (OSCAT-3 expected to launch in 2015). Ongoing collaboration with non-NASA groups (e.g., Remote Sensing Systems and Brigham Young University) continues to lead to improvements in the NASA products and in producing additional high quality products at a reduced cost to NASA. These additional products have a wide range of users.

Weaknesses:

A perceived minor weakness is the limited new science achieved to date working directly with the non-scanning QuikSCAT data sets collected since 2009. It is understood that the main focus for collecting these data is to provide a known reference for ocean Ku-band backscatter, and hence ocean wind vector product continuity using OSCAT and soon Rapidscat. However, we wonder if there is relevant science to be gained directly from the L1B-NS (non-scanning) data that might be considered within mission or science team activities. If so, this could further strengthen a recommendation to extend the mission.

A second minor weakness is the newly encountered requirement to power down the instrument for 60-80 days each year during eclipse. While the team does have an adequate plan to achieve mission objectives, any radar instability in OSCAT occurring in this Nov-Jan. time window will be unobserved.

Value of data record and overall data continuity:

The technical issues related to maintaining continuity of the data record are clear for ocean vector winds, ice and backscatter products derived from the radar. Several new studies have shown that the long-term stability of the scatterometer data record serves as a valuable and unique reference to unify wind speed data from numerous passive ocean microwave sensors. This project team's successful

combination of OSCAT and QuikSCAT data to provide the science and applications communities an additional four years of scanning scatterometer data has also been highly successful. Use of the mission's scatterometer-derived sea ice and iceberg products continues to grow and is a primary source of data for cryospheric process research. In some ways, these uses of QuikSCAT to obtain mission-to-mission intercalibration are far better than expected in the original planning for the mission. This is critical to obtaining multi-decadal climate quality data records. The consistency with GCOS principles is also well stated.

Core mission data product maturity: Excellent

Satellite ocean vector wind products have the advantage of access to accurate validation data sources via ground truth from ocean buoy and ship observations in addition to maritime weather forecasting models. There is ample evidence in the proposal and from both mission science team calibration and validation activities that QuikSCAT, and now OSCAT via the QuikSCAT/OSCAT cross calibration, provide wind speed and direction data at the 12.5 km resolution that represent the state of the art. The new version 3 product is an improvement on what already is the standard, and only enhances the mission's core and continuing contribution, that being an independent and stable long-term ocean wind climate record. Documentation of this recent work is complete and commendable. While not yet fully executed, it is anticipated that there will be little if any product degradation between the QuikSCAT standard (1999-2009) and the OSCAT 12.5 km (2009-forward) data. Similar findings hold for the mission sea ice products. The project has continued to maintain data production and validation and has extended this using the OSCAT sensor as proposed in the last review process with all OSCAT data openly available to users at PODAAC and BYU. The science team support to maintain the algorithms, data production, and delivery to PODAAC is viewed as a reasonable and efficient use of personnel and mission expertise. The proposed tasks will also benefit from continued successful international collaboration with India, and with national agencies through the well-established work with NOAA near real time data production efforts. Thus for the rating of core ocean vector wind and sea ice data product maturity, it is clear that the QuikSCAT mission products should continue to meet the standard of excellence within the NASA mission review process.

Relevance to NASA: Excellent

Strengths:

The redirected QuikSCAT mission continues to address the following Earth Science program objectives within NASA's 2010 Science Mission Directorate Science Plan:

Quantify the changing distributions of extreme weather events and enable improved weather prediction:

- The intercalibration, stability monitoring, reprocessing and distribution of OSCAT data supported by QuikSCAT measurements and science algorithm is a vital mission contribution to this goal; and
- The new version 3 processing shows measurable improvement in wind data accuracy in extreme events with rain, of value to past and future data.

Quantify the key reservoirs and fluxes in the global water cycle and improve models of water cycle change and fresh water availability:

- Surface ocean wind speed is one critical component to determining the evaporation over the global ocean;

- Near-surface wind field convergence, now more accurately observed using version 3 products, is closely coupled to precipitation and is a growing science focus in NASA ocean and atmosphere programs; and
- The continuous long-term sea ice record supported under this mission, including mapping of icebergs, is of clear importance in the era of rapid change at high latitudes.

Understand the roles of oceans, atmosphere, and ice in the climate system and improve predictive capability for future evolution:

- Vector winds are key to a host of coupled air/sea interaction processes under active investigation by the science community, including links to the upper troposphere (through wind and SST coupling) and to the deep ocean via Sverdrup flow
- Proposed satellite determination of diurnal and semi-diurnal vector wind field dynamics in the tropics should yield additional new science benefit
- The continuous multi-year sea ice record also provides vital boundary condition information for climate prediction modeling

Enable the broad use of Earth system science observations and results in mitigating and adapting to a changing environment:

- The proposed mission support for near real time data products from OSCAT and Rapidscat to national agencies via NOAA should serve to provide timely and unique maritime weather data for extreme storm forecast and monitoring purposes.

Weaknesses:

None

Technical Panel:

We concur with the findings from the technical panel. Clearly this is an old satellite with a several possible failure modes that lead to the high risk assessment.

National Interests Panel:

We concur with the panel and also reference the strong letter of endorsement from NOAA NESDIS for project support in near real time data production at NOAA.

Other Comments:

This was a well-written proposal and represents important mission work needed to continue a vital data record for ocean- atmosphere research despite QuikSCAT's age and scanning mechanism failure. Given the eminent demise of the instrument we encourage the QuikSCAT science/data analysis team to develop alternative funding plans to support continued work with these alternative ongoing and future scatterometer data sets. Such work is highly valued and represents a unique expertise within the NASA program.

SORCE

Recommendation: Continuation of project as currently current baselined.

Executive Summary:

SORCE/TIM provides total and spectral solar irradiance measurements with state-of-the-art accuracy. The scientific focus is on solar physics and the interaction and influence of solar radiation on Earth's physical state. The simultaneity of spectral and total irradiance measurements allows study of a broad range of science questions. While the data products from SORCE are of very high quality discrepancies exist between the SSI measurements of SORCE and results from other observational and modeling studies. In order to ensure the quality of SORCE SSI results, the panel recommends an independent review of the SSI methods and results. Furthermore, while the spacecraft has battery issues, the mission team acknowledged that the additional staffing provided in the last Senior Review panel was very helpful in mitigating these issues. This Senior Review Panel recognizes the efforts being made by the mission team to prolong battery performance.

The SORCE Mission has provided a decade of solar irradiance observations (TSI and SSI) with high precision and stability and these results have been and will be used by the Earth Science and Solar Irradiance communities. The results from this mission will be important to the development of future climate models that include both TSI and SSI as well as studies of the sources and properties of solar variability. These results contribute to the historical data base of solar flux and should be continued until spacecraft failure in order to prevent data gaps in this climate-critical data product.

Initially, the TSI time series produced by SORCE/TIM showed the TSI level to be approximately 4 W/m^2 lower than reported by earlier TSI instruments such as ACRIM3 and VIRGO. As advocated by previous Senior Review Panels, laboratory measurements have now been performed at the LASP TRF facility with flight and engineering instruments. This has established corrections to the TSI time series that bring other TSI instruments, including ACRIM3, into agreement with SORCE/TIM. Future efforts by the community aim to agree on a revised value of TSI at solar minimum as well as to converge on methods to construct the composite time series. Given the value of these data for the climate science community, and the recent success of the inter-comparison of the multiple TSI data records to bring them in line, the panel recommends that a 'TSI science team" perhaps comprised of experts within the TSI and close climate community be formed that can provide a focal point for oversight, science investigation, and collaboration.

The SSI time series produced by SORCE/SIM, SOLSTICE and XPS are estimated to have absolute accuracy of 2% for SIM, up to 6% for SOLSTICE, and up to 24% for XPS. However, the early results from SIM and SOLSTICE during the declining phase of SC 23 contradict model results in the UV/visible/IR as well as earlier observations in the UV, which are outside the stability estimates of the SSI measurements (see Haigh, et al, 2010). Several peer-reviewed publications postulate that the source of these discrepancies is uncorrected instrumental degradation of the SIM and SOLSTICE instruments, especially during the early part of the mission. Thus, this Senior Review Panel recommends that an independent SSI Calibration Working Group be established to examine the SORCE SSI calibration issues.

Several spacecraft system failures have occurred; one of four reaction wheels, one of two star trackers, and some battery cells. Of these, the concerns with battery life are most significant and continue to be addressed by the SORCE Team. Regardless of the possibility of battery failure, it is *recommended* that the SORCE Mission be extended to continue these important (TSI & SSI) and unique (SSI) observations

and to pursue overlap with the upcoming TCTE TSI mission and, if possible, with the upcoming TSIS Mission. The impact of instrument health to the current products is thoroughly described, and mitigation plans have been developed, tested, and implemented to the degree possible.

Scientific merits: Excellent

Briefly, the three science objectives which are the focus of the SORCE Mission are:

(1) Make high accuracy, high precision measurements of TSI;

(2) Make daily validated SSI measurements from 120 to 2000 nm; and

(3) Improve our understanding of the how and why of solar variability.

Objectives (1) and (2) will play an important role in ocean-atmosphere-chemistry climate models, which are being developed and which require SSI as well as TSI inputs.

Until the on-orbit uncertainty in the TSI determination for a mission is established to be adequate for long term climate studies, that is, less than 0.01 %, it is necessary to maintain a continuous TSI record using well characterized and stable sensors in order to understand solar variability and its impact on Earth's climate. The TIM uncertainty, though better than other TSI instruments, is about a factor of three too large to afford independent, non-overlapping sensors, and therefore should be continued. Likewise, the spectral irradiance data set on SORCE is unique in coverage and capabilities, with NOAA's SBUV and NASA's Aura OMI providing only partial coverage of this time series.

Strengths:

The SORCE science team is very strong and interacts significantly with the science community. The results, significance, and application of the measurements are well described and relevant to solar physics and Earth science. Pre-flight characterizations were extensive, and the pre-flight calibrations were made traceable to the SI in collaboration with NIST. The methods to track on-orbit degradation are sound. The degradation for SORCE/TIM is extremely small, 0.02 % in 8 years, which facilitates relating the results to other TSI sensors. Many significant scientific accomplishments are noted in the proposal for all four instruments.

The recent tests with several TSI monitoring (ACRIM & PREMOS) at the TRF calibration facility at LASP have validated the TIM approach to measuring TSI and helped establish that values of about 0.03% to 0.05% for the radiometric, system level, uncertainties that are possible to achieve pre-flight. It is most likely that the TSI community will adopt a TSI value at solar minimum that is in agreement, within the uncertainties, with the SORCE/TIM value. Support by the SORCE Team in the evaluation of several TSI monitors has effectively removed the previously large discrepancy between the several current monitors. This is a substantial achievement in metrology and TSI measurement science and answers the recommendations of previous Senior Review panels.

The SSI instruments continue to make high quality solar irradiance measurements over an extremely large wavelength range (~ 115 to 2000 nm). These data are being used by models of the Ocean-Atmosphere System and will be extremely important to continued development of these models. Studies of solar variability also utilize these results.

Data product availability continues to be maintained and to evolve with the development of the LISIRD and LaTiS systems which improve public access to available data sets.

The Mg II index, which is an important and useful proxy of solar activity, continues to be available from SOLSTICE. Issues with the index are being addressed as part of a series of workshops.

Weaknesses:

The SSI calibration (degradation) appears to need to be validated given the differences between SORCE and other instruments and models.

The Mg II index needs to be re-examined and difference between this index from various sources needs to be addressed.

Value of data record and overall data continuity:

The TSI time series is accurate and extremely valuable to the Earth Science and Solar Irradiance communities. Regardless of the SSI calibration issues, this data set is an important component for modeling studies. SSI calibration does need to be addressed but once this is validated this will be an extremely important input to these modeling studies.

There is great benefit to having the both the spectral and total measurements. It is critical to maintain data continuity of these records for as long as possible.

Core mission data product quality and maturity: Good

Data processing and generation of the TSI and SSI data products is mature. Corrections required by recent battery failures have been effectively implemented. Production of data products is automated and quickly available to the public. Problems with validation of the SSI calibration (degradation) affect this score but this can be resolved by a recommended validation activity.

TIM/TSI: Excellent – The TIM TSI time series is uncertain to 0.035%, reporting a value of ~ 1360 W/m^2 near solar minimum. Although SORCE/TIM flew without the system level calibration that is now possible with TRF, a careful and thorough component-level characterization was performed prior to launch. Laboratory tests with the TRF calibration facility at LASP include a cryogenic radiometer and well controlled laser light source. These have been used to compare and absolutely calibrate several TSI instruments, both flight and engineering models, starting with GLORY/TIM. Work with the TRF calibration facility has helped develop corrections and calibrations for PREMOS and ACRIM instruments. Thorough uncertainty analysis has been performed and the uncertainties are well documented.

XPS/SSI: Excellent – This EUV irradiance has been properly corrected and provides an important contribution to the EUV irradiance data based available to the upper-atmospheric community. After discussion with the SORCE team revealed that the XPS could be shut off for a cost savings of ~ ½ FTE (~ $100K), the Senior Review Panel recommends this be done.

SIM & SOLSTICE/ SSI: Fair – Although the precision of this data set appears very high the results from these instruments differ significantly compared to results from other space-based instruments that are well calibrated on the ground and in orbit (both absolutely and relatively). The two main conclusions relevant here are: (1) the SORCE measurement of solar irradiance variability in the 200 – 400 nm region from early in the SORCE mission is greater by factors of up to 20 in the UV than has been seen previously by other space-based instruments; and (2) the variability in the visible and NIR appears to be out-of-phase with the solar cycle, contrary to model results.

Most importantly for item (1) is the availability of the UV results from the UARS/SUSIM instrument which overlapped with SIM and SOLSTICE during the first several years of the SORCE Mission. UARS/SUSIM was composed of numerous channels (some of which were exposed very infrequently), with and without filters, and carried onboard D2 calibration lamps. No attempt appears to have been

included by the SORCE Team in this proposal to utilize this data set in the validation of the SIM and SOLSTICE degradation corrections at UV wavelengths.

The SORCE Team has implemented a series of SSI calibration workshops to examine issues such as the irradiance differences observed by SORCE compared to other instruments and models. These workshops have provided a forum for discussion but have not yet lead to significant action. In order to address this important calibration issue *it is recommended that NASA ESD established and fund an independent SSI Working Group specifically to address the discrepancies described above and to validate the SORCE/SIM & SOLSTICE degradation correction and other aspects of the SORCE SSI calibration as needed.* This group should be made up of experts in both laboratory and space-based calibration as well as members of the SORCE Team including the instrument leads for SOLSTICE, SORCE/SIM, and TSIS/SIM.

The Working Group should initially convene at LASP so that direct access to the original SORCE data is assured. Comparison with the SUSIM data sets should be one goal of the Working Group but if other data sets (e.g. SBUV) are required then these should be considered as well. One additional goal should be to understand the impact of the results on the upcoming TSIS/SIM operations planning. The Working Group should report back to ESD with preliminary results within one year and with a Final Report within two years outlining any needed changes to the SORCE SSI calibration procedures including recommendations for TSIS/SIM operations.

Relevance to NASA Science Goals: Excellent

The proposed SORCE science program outline the contributions of this Mission to the ESD research objectives and focus areas as stated in the SMD Science Plan. These are listed in the Strengths below.

SORCE is relevant to SMD questions through direct observation of the sun, through the use of SORCE data to develop better predictive models of solar variability, and through research with global climate models. The strengths include the ability to study total and spectral solar irradiance from the same platform using well characterized and robust sensors.

Strengths:

From the SMD, 2010 Science Plan:

(1) How and why are Earth's climate and the environment changing?

(2) How and why does the Sun vary and affect Earth and the rest of the solar system?

From the 2010 Science Plan:

(3) What are the sources of change in the Earth system and their magnitudes and trends?

(4) How will the Earth system change in the future?

Weaknesses:

The weakness is the uncertainty in mission life due to hardware issues, in particular the battery performance.

Technical Panel:

The panel concurs with the results of the Technical Review Panel. See the report of this panel for further information.

National Interests Panel:

The panel concurs with the results of the National Interests Panel. See the report of this panel for further information.

Other Comments:

The proposal is exceptionally complete and thorough. The team has done a superb job in program management, science, community outreach, and pushing this field to a new level. The project is well organized and gives students an exciting opportunity for training. The discussion of end of mission activities was welcomed.

Terra

Recommendation: Continuation of projects as currently baselined

The Science Panel endorses the continuation of the Terra mission because it will extend the records for numerous data products used to monitor and understand changes in climate and the effects of those changes on land, ocean, and atmosphere over the next few years. The Terra mission has already accumulated 13 years of data from five instruments, each of which provides valuable data for scientific questions pertaining to the Earth and its changes, including 79 core products as well as support for monitoring and relief efforts for natural and man-made disasters. The continuation of the Terra mission would extend the baseline of these measurements and, for some instruments, provide continuity linking past and future missions.

Scientific merits: Excellent

The overall objectives of the Terra mission include 1) extending the baseline for morning-orbit climate and environmental data records, 2) enabling comparison of measurements acquired so far with likely future recurrences of natural events, e.g., fires, volcanic eruptions, floods, oil spills, changes in ice sheets, and 3) adding value to recently launched missions (e.g., SNPP, LDCM) or those to be launched in the next few years. Each of the five instruments has made valuable contributions to the study of Earth as a system, to discovery of how the Earth is changing, and to exploration of human interactions with these changes.

- The objectives of **ASTER** are to extend the record of moderate high-resolution changes in land cover, provide emergency data acquisitions for natural and man-made disasters, and extend the archives for observations of active volcanoes and valley glaciers.
- The objectives of **CERES** are to produce an integrated climate data record for detecting decadal changes in the Earth's radiation budget, improve understanding of cloud-aerosol-radiation interactions, and (with MODIS) bridge the interval between older satellites and SNPP and JPSS.
- The objectives of **MISR** are to update the Plume Height Climatology Product to include extended dust, volcanic, and wildfire smoke plumes and to facilitate the use of the MISR cloud motion vector (CMV).
- The objectives of **MODIS** are to extend the 13-year archive of ocean productivity and sea surface temperature, extend the 13-year archive for land productivity and other land characteristics, such as albedo, leaf area index, land surface temperature, and seasonal variation of vegetation, and extend the archive of tropospheric properties, including cloud and aerosol properties, cloud fraction and atmospheric profiles of temperature and moisture.
- The objectives of **MOPITT** are to extend the 13-year record of tropospheric CO, show paths of transport for atmospheric pollution, and provide a proxy to aid in constraining the retrieval of tropospheric CO_2.

In the last two years:

- The joint U.S./Japan **ASTER** project released Version 2 of the Global Digital Elevation Model (October 2011).

- Observations from **CERES** and in-situ measurements of change in ocean heat content indicated a 0.5 Wm^{-2} imbalance in net radiation at the top of the atmosphere during the past decade. CERES observations were compared with other instruments, used to calibrate other instruments, and used to develop and produce new data products.
- Recent project accomplishments from **MISR** include the release of a Level 2 Cloud Product, generation of MISR winds in near-real time, algorithm refinements to the Level 2 aerosol retrieval, expansion of the Plume Height Climatology Product, and the release of Level 3 Cloud Motion Vector.
- In the last 2 years there have been several major improvements to the calibration of Terra **MODIS**, especially its ocean color spectral bands and vegetation indices.
- A new **MOPITT** product (version 5) is the first satellite-based product to exploit TIR and NIR radiances for CO, resulting in much greater sensitivity to surface CO concentrations. Results were validated with measurements from NOAA's tall-tower network over the U.S.

Strengths:

The products from Terra are invaluable to a large number of scientific investigations related to the Earth system and global change. From the perspective of the Science Panel, the data from MODIS, alone, justifies that the mission be continued.

Weaknesses:

None

Value of data record and overall data continuity

The value of the data record to science is demonstrated by the fact that nearly 116 million Terra data files were delivered in 2011 and 155 million files in 2012. In addition, more than 47 million near real-time files were delivered to NOAA, DoD, USDA, FAS and other operational users. More than 1,100 peer-reviewed publications using Terra data appeared in 2012, bringing the total for the lifetime of the Mission to more than 7600, so far.

Core mission data product quality and maturity: Excellent.

Strengths:

The accuracy of core mission data products has been assessed and the uncertainties in the products well established via independent measurements in systematic and statistically robust ways representing a broad array of conditions. The quality of data production continues to be high. At the same time, new versions and new levels of products continue to be developed (and validated) by some of the instrument teams and/or PIs.

Weaknesses:

It is not clear what the impact of the relaxation of the Mean Local Time (MLT) to 10:15 versus 10:30 will be on data continuity. This is the second such relaxation, and the total record will now include a 30 minute difference between start and end.

It is also not clear how the incipient degradation of some MODIS bands will affect the integrity of the land and ocean color data products. Quantification of long-term trends is particularly sensitive to such degradation.

Relevance to NASA Science Goals: Excellent

Strengths:

The mission objective for continuation of Terra is to provide answers to the overarching question from NASA's Science Mission Directorate: "How is the Earth changing and what are the consequences for life on Earth?" Individual instruments observe the Earth's atmosphere, oceans, lands, and cryosphere and continue to contribute as follows:

- The ASTER instrument team is processing about 20 urgent requests per month to provide observations for relief efforts following major disasters.
- CERES provides an on-going, operational calculation of the Earth Radiation Balance.
- MISR provides continual observations of cloud motion and winds in near real time.
- MODIS has improved its calibration of ocean color and bands critical for aerosol and cloud products and for vegetation indices.
- MOPITT provides daily CO observations, employing TIR and NIR radiances which yield greater sensitivity than other satellites.

Weaknesses:

None

Technical Panel:

The Panel supports the findings of the subpanel reviews, attached as appendices.

National Interests Panel:

The Panel supports the findings of the subpanel review, attached. Terra contributes substantially to scientific monitoring and understanding of the causes and impacts of climate change. It also plays a role in monitoring disasters and relief efforts, some of them national.

Other Comments:

This is a well-written, comprehensive proposal. It does a better job than the Aqua proposal in highlighting the issue of data continuity and long-term data records. It also does a better job of discussing the unique combination of spatial resolutions, multi-angles, and temporal sampling relative to the Aqua proposal. Both missions are strong missions and deserve to be continued, and it is interesting to see how the two complementary missions pitch themselves.

We recommend that there be working groups of PIs convened to provide in-depth reviews of algorithms for successive instruments; e.g., for comparing the algorithms for MODIS terrestrial products with those developed or expected for VIIRS. Whether NOAA will continue with the products of MODIS is unclear, but the topic is of great interest to the scientific community, and every effort should be made to ensure the continuity of data products.

TRMM

The Tropical Rainfall Measurement is an essential mission to address NASA's Strategic Science Questions with regard to the Water Cycle and Climate research, including Hydrology, Ecology, Carbon Cycle, Geomorphology, Meteorology and Climate, and TRMM products are widely used in Weather Forecasting, and Natural Hazards and Water and Natural Resources management and applications. TRMM provides the only consistent measurement of precipitation in the tropics from 4km resolution to planetary scales, and the TRMM PR and TMI are the standard for remote-sensing of precipitation from space. In addition to the scientific achievements reported in the proposal in Section 2, and which can be tracked in the peer-review literature, there is a large number of users of precipitation products derived from TRMM observations in the operational, public health, agriculture and natural resource management agencies around the world. In addition to precipitation data sets, the LIS (Lightning Imaging Sensor) monitors lightning activity in the tropics, and TMI (TRMM Microwave Imager) measurements are used also to monitor SST (Sea Surface Temperature). Besides 2-D gridded precipitation products, profile data sets such as reflectivity, rainfall and higher level products such as latent heating have motivated many new scientific insights into the vertical structure of the atmosphere, and tropical climate.

TRMM has now passed the 15-year benchmark, which is a remarkable accomplishment considering that the initial life of the mission was to be three years. Because of this long record, and the broad constituency of data users for myriad applications, the continuity of the TRMM mission alone is justified in order to preserve the continuity and robustness of the longest global scale precipitation data set and meet operational demands. In addition, the record is currently enabling studies of global scale processes from annual to 3-5 years variability such as the Asian and Nth and South American Monsoons and ENSO. TRMM is the precursor to the upcoming GPM mission to be launched in 2014, which will benefit from TRMM sensor technology, ground validation and algorithm legacies, and also from cross-calibration of radar and radiometer instruments. TRMM and GPM are commended for having devised a well-planned transition process that preserves TRMM strengths while building day-1 capacity for GPM algorithms and products.

The big challenge faced by TRMM is the uncertainty associated with the end of fuel date. GPM is planned to be launched by February 2014. Assuming the worst case scenario for fuel consumption, there should be 2+ years between end-of-fuel and the end-of-life date, during which TMI data will always be available, including about 1 year during which the PR will also be available as the satellite drifts to the 350km elevation range. Assuming the moderate case scenario, there will be an initial six-month period during which both PR and TMI data will be collected through October 2014, followed by the same 2+ years of TMI first followed by TMI and PR data collection. Thus in both cases, within +/- six months the mission will be collecting data through 2016 and into 2017. During this period, the TMI data may also be used as experimental GMI-like observations in the GPM constellation to examine the value of low –inclination radiometer observations. GMI was part of the initial plans for the GPM constellation but was eventually decommissioned, thus this is a unique opportunity to evaluate the value of the original measurement concept. There will also be opportunity for designed in-flight experiments with the PR that can inform the GPM DPR algorithms.

Overall Recommendation: Continuation of projects as currently baselined

Specific Recommendations

Recommendation #1 - The panel encourages that the transfer of GV, algorithm development and project management activities be implemented as soon as possible as after GPM launch while preserving core TRMM activities essential to operations and product delivery.

Recommendation #2 - The panel recommends funding at baseline level through 2017, followed by termination and close-out unless there is evidence of delay of the expected end-of-fuel date. It is recognized that the TRMM team will be in condition to make a more robust estimate of end-of-life date within six months, after the anticipated end of the present peak in solar activity. Accordingly, the TRMM mission should make public updated estimates of end-of-fuel and end-of-life dates on the TRMM website periodically along with an explanation of mission status. Because of minimum budget resources required for TRMM after GPM launch, and the uncertainty in estimating fuel availability, the panel recommends an adaptive strategy to close-out in order to take advantage of data collection for as long as possible.

The TRMM budget appears to be minimal for the maintenance tasks required to keep the craft safely operating. Most science-related developments have been transferred to the Precipitation Measurements Mission (GPM) budget to support algorithm development for the forthcoming GPM mission. It is clear that the algorithm development for GPM is vital to final success of this TRMM follow-on mission. The potential extension of the current TRMM greater than 15-y dataset through calibration with GPM toward a much longer effective observing period so that key climate questions such as decadal variability can be addressed cannot be denied.

TRMM has met and exceeded its original goal of advancing our understanding of the distribution of tropical rainfall and its relation to the global water and energy cycles. The TRMM suite of measurements has provided an unprecedented 15-y database of precipitation measurements including detains of the vertical structure of that precipitation in the tropical and extratropical regions of the world. The precipitation radar (PR) is the only space-borne rain radar (until the GPM launch in 2014) and provides the 3-D structure of rain as well as quantitative information over both land and ocean of rainfall amounts. The TRMM microwave imager (TMI) provides information of hydrometeor structure, and SSTs. The lightning imaging sensor (LIS) detects all lightning within its field of view. An additional strength of the TRMM satellite is the co-location of a visible and infrared scanner (VIRS), which provides a cloud context for the PR, TMI, and LIS, as well as providing a link to the GOES satellites so that retrievals from both systems can be easily compared. Some of the products that are either directly from TRMM, or that TRMM plays an integral part of, include visible and infrared radiances, 3-h almost global (50°N to 50°S) rain-rate retrievals, 3-D structure of rain, hydrometeors and heating profiles, lightning flash climatology and actual lightning flashes. The TRMM project has also supported the development and continued production of ground validation observations from surface radar and rain gauges from 4 sites located in the tropics.

TRMM has evolved from an experimental mission focusing on tropical rainfall climatology into the primary satellite in a system of research and operational satellites used for analyzing precipitation characteristics on time scales from 3-hr to inter-annually and beyond. One science objective of the extended mission is to determine the time and space varying characteristics of tropical rainfall, convective systems, and storms and how these characteristics are related to variations in the global water and energy cycles, which is fundamental to NASA's Earth Science strategy and provides answers of key science questions for both the Water and Energy Cycle and Weather focus areas. Examples of operational uses include the use of near-real time images for tropical cyclone intensity estimates and vertical structure, and integration of TRMM SSTs into standard SST products. TRMM TMI near-real time

images are used by forecast centers around the world.

A compelling reason to continue this mission is that there is currently no platform that can provide the coverage and detail of rainfall observations that TRMM provides. In addition, on account of superior instrument performance and mission operations, and either the lack or the progressive loss of ground-based observing networks, TRMM-based observations and rainfall products are now the "de factum" rainfall climatology of the tropics. Until the launch of GPM in 2013, there is no alternative. Continued operation until the GPM launch is necessary to ensure a continuing dataset for climate studies. The additional years of data will allow studies of decadal-scale variability of rainfall, and provide a more robust diurnal cycle. Some overlap between the missions would be useful to calibrate and validate the GPM algorithms after GPM launch and allow an ongoing dataset of tropical and extra-tropical rainfall measurements that began in 1997. As pointed out in the proposal, there is the potential that between GPM launch and TRMM passivation phase, the TRMM satellite can function as low inclination replacement to the GMI initially planned as part of the GPM constellation with duration not unlike the typical 3-year mission life.

The proposal indicates that currently there are no major issues with platform instruments or subsystem-specific issues except for the lack of redundancy of the Frequency Converter and SCDC in the PR (table E-12). Although the TRMM technology has largely exceed the most optimistic expectations, there is inherent risk in that instruments and platform are aging and therefore reliability is expected to become an issue eventually.

Nevertheless, the key factor in determining mission effective longevity is the available fuel load, which will determine the calendar for the end-of-life plan. The estimates vary widely depending on predictions of solar activity and platform performance, with the average estimates pointing to October –December 2014 as the anticipated end-of-fuel milestone. The satellite orbit is then expected to slowly begin descent reaching the passivation altitude of roughly 330 km about 29 months later, during which the TMI, VIRS and LIS instruments would be operating.

The basic mission extension will continue production of TRMM standard and real-time products. Version 7 algorithm datasets, the last TRMM algorithm revision before GPM launch, are already available. Thus, a multi-year extension of TRMM has a very high payoff for science and applications at a relatively low cost to NASA. The science budget at GSFC includes support for the TRMM and GPM project offices, for GPM algorithm development to be ready at launch, and for GV activities. A plan to transfer resources and assets to GPM is in place, which is commended.

Scientific merits: Excellent

Strengths:

TRMM's enormous success is related to its two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of *complementary observing instruments* and (2) its *orbit characteristics*. TRMM provides a complementary suite of active and passive sensors flown on a single platform, providing the most complete view of precipitation. Due to its complement of instruments, TRMM has been called the "flying rain gauge", i.e., the space standard for precipitation observation. The TRMM observing system employs the only precipitation radar in space, the PR, which provides the most direct method of observation of precipitation and its vertical distribution (i.e., enabling a three-dimensional view of precipitation). Efforts to resolve disagreements between precipitation estimates from the PR and the passive microwave radiometer, TMI, have reached the point where TRMM is used as a global rainfall reference standard. *Without the PR in space, there will be no similar opportunity for*

calibration with an active sensor until GPM is launched in 2014, and the cross-calibration of the PR and the DPR are highly desirable.

Since its inception, the TRMM science goal has been to advance knowledge of the global energy and water cycles by observing time and space distributions of tropical rainfall, and convective systems, and their associated hydrometeor structure and latent heating distributions. TRMM currently provides a 15-y rainfall dataset that covers the tropics and much of the extratropics. This dataset is at a stage where the regional impacts of climate change on precipitation patterns – arguably the most important climate variable for societal mitigation – can be assessed. Additional years of data will allow these impacts to be assessed on decadal scales.

The proposal provides an extensive summary of the multiple contributions of TRMM to advance NASA's science objectives and questions that are directly impacted by TRMM measurements.

These include:

1) Climate-related research: TRMM has provided multiple rainfall datasets extending back 13 years for the study of climate-related water cycle questions. These products include a 3-h 13-yr multi-satellite sensor product extending from 50°N and S, of which TRMM PR and TMI are the core components. These products have allowed robust climatologies of tropical rainfall to be developed on seasonal and monthly timescales, and even allowed the diurnal cycle climatology to be studied. LIS has allowed the first detailed global lightning climatology to be developed. In addition, detailed regional climatologies of lightning have been produced using LIS data. Lightning chemistry has also been studied. TRMM data has yielded new insights into the dynamics of tropical waves and oscillations and into hypotheses on the dynamics of convective-climate feedback. The TRMM rainfall and storm height data along with SSTs were used for these studies. TRMM rainfall and LIS data has yielded information on the human impacts on the climate system though the study of the relationship between aerosols, land use change, rainfall, and lightning. SSTs from TRMM help improve SST analyses used for climate studies as well as every day events.

2) Convective systems and tropical cyclones: Characteristics of convective systems have been studied using the PR, LIS, VIRS, and TMI. These systems have also been used to study the detailed structure of tropical cyclones, and allowed valuable insight into inner-core processes that were previously not well observed.

3) Measurement advances: Comparison between PR and TMI rain rates has lead to improvements in retrievals for passive microwave sensors. In addition, the rain rate estimates from TRMM have been used to calibrate rain rates from other satellites resulting in analyses of rain rates at higher spatial (0.25°) and temporal (3-h) resolution than would be available from one satellite alone.

4) Data Assimilation: The TRMM rain rates are being used to develop new assimilation techniques for rainfall, SSTs, and soil moisture to improve analyses and forecasts of atmospheric models.

5) Hydrologic Applications and Forecasts: TRMM –based multi-satellite analyses are being used by the hydrologic community as inputs to hydrologic models to study variations on surface runoff and improve forecasts of river flow, floods, and other natural hazards mainly landslides. TRMM rainfall products also provide valuable information to establish antecedent moisture conditions that can be used to plan agricultural activities.

6) Algorithm and model development: LIS data has been used to help develop the GLM for the GOES-R satellite. TRMM rainfall data are used to evaluate the performance of numerical models from cloud-resolving models to global models and GCMs.

7) TRMM also provides support to numerous operational centers globally for various activities including the monitoring of tropical cyclones, rainfall, particularly extreme events with a potential for producing floods, numerical weather prediction, and air-traffic control. This highlights the continued need for the real-time observations that TRMM continuously provides.

Weaknesses:

Although the proposal provides a comparison between the CPR and the PR, it is not clear whether there has been a systematic substantial effort, or indeed if it is even realistic due to the differences in spatial and temporal resolution, to use CPR to calibrate the PR algorithm for low rainrates and snow. One minor weakness is that although the current rainfall climatology is very good, it still needs a longer time series to begin to answer questions relating to decadal variability and climate change. A longer mission that overlaps with GPM helps solve this issue.

There is a strong need to provide synthesis of uncertainty from peer-reviewed literature and from GV activities. Even if it is difficult to establish an overall uncertainty measure for all products, there should be great benefit from establish a place-based/regime based document of known uncertainties.

For example, a survey of quantitative uncertainty studies perhaps expressed as geo-referenced gridded/matrix product could be completed, and a routine updating protocol implemented. It is recognized that the US TRMM Office may be constrained by international agreements for the PR products, but given the wide use and critical utility of the data for national interests, it is important to establish a framework that may also be transferred to GPM day-1.

Value of data record and overall data continuity:

The proposal highlights the National Academies (NA) assessment of the scientific accomplishments of TRMM and the benefits of extending the TRMM mission (NRC report, 2006). A key conclusion from the Executive Summary of the NA report was: "*Considering the past and expected scientific and operational contributions presented in this report, important benefits would be obtained if TRMM were extended until it runs out of fuel.*"

From that report: *"From the perspective of anticipated research contributions, TRMM is worth continuing for six primary reasons:*

1. TRMM provides a unique complement of measurements. Specifically, the precipitation radar, the passive microwave imager, and the visible and infrared instruments provide a powerful overlap of precipitation, cloud, and water vapor measurements and the lightning imaging sensor helps isolate intense convective cells. In addition, the TMI permits sea surface temperature measurement through clouds at high spatial resolution. Continuation of the mission is vital to the future development of spaceborne precipitation radar technology, especially in the evaluation of radar technology life cycle.

2. Mission extension creates the opportunity for cross-calibration, validation, and synergy with sensors on future missions, such as CloudSat and the A-Train satellite series, National Polarorbiting Operational Environmental Satellite System's Conical Scanning Microwave Imager/Sounder, and Global Precipitation Measurement core satellite and other constellation satellites.

3. TRMM's unique low-inclination, lowaltitude, precessing orbit enhances science by providing unique spatial and temporal information that fills the gaps in data from other current and upcoming polar-orbiting satellite sensors.

4. TRMM data will enhance field experiments and programs (e.g., TCSP, AMMA, GEWEX, THORPEX, TEXMEX-II), tropical cyclone research (including tropical cyclone forecasting), and development of cloud-resolving models.

5. A longer record is required to collect enough examples to cover the parameter space of synoptic variability more fully. For example, over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits. The narrow swath of the PR and the rare occurrence and great variability of tropical cyclone structure, intensity, and precipitation amount strongly argues for mission extension to increase sample sizes for statistical analyses.

6. Longer TRMM data records will better characterize tropical seasonal-interannual climate variability in general and the El Niño-Southern Oscillation (ENSO) cycle in particular. ENSO is the dominant mode of global interannual climate variability. TRMM provides quantitative ENSOrelated tropical rainfall anomalies that are needed to improve our understanding of both the local and remote effects of this phenomenon, and ultimately to make better predictions of its socioeconomic effects in both the tropics and extratropics."

These points are as valid today as they were seven years ago. The TRMM records are now 15 years long. The value of such an extended dataset is being demonstrated in the use of this dataset to robustly characterize annual, seasonal, monthly, and diurnal variability in rainfall across much of the globe. With another 2-3 years, (the projected lifetime of TRMM), including a year (possibly) of overlap with GPM for calibration, the dataset can be extended (via GPM) to the point where it may be possible to characterize ENSO cycles beginning to approach decadal times-scales.

Core mission data product maturity: Excellent

The core mission data (rainfall) are the standard used to assess other remote-sensed rainfall measurements and are the heart of the current 3-h merged satellite rainfall product. These measurements are not redundant.

TRMM operations, ground validation sites, and algorithms are being used as the basis for algorithm development for the future GPM mission.

The transition to PPS was smooth and without breaks. The products, user-oriented software, ease of access and friendliness of the entire system are exemplary. Access to standard TRMM data is facilitated by a well-functioning website and data extraction tools and can be used in remote sensing classes and for other educational applications more generally with success. The literature shows that users of TRMM data span a wide range of disciplines and socio-economic activities from geology to water resource management to farming.

Relevance to NASA Science Goals: Excellent

<u>Strengths:</u>

The overall science objective of an extended TRMM mission is *to determine the time and space varying characteristics of tropical rainfall, hydrometeor structure and associated latent heating for convective systems and storms, and how these characteristics are related to variations in the global water and energy cycles*. This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions, primarily for the Weather and the Water and Energy Cycle focus areas, i.e., *"How are global precipitation, evaporation and the water cycle changing?"*, *"How will water and energy cycle dynamics change in the future?", and "What are the consequences of changes in water availability and weather for human civilization?"* Having a long, accurate record of quasi-global precipitation

characteristics is critical to achieving NASA's Earth Science goals. Extension of TRMM for the next three years is consistent with these goals. TRMM provides data sets that address a number of key questions:

How are global precipitation, evaporation, and the water cycle changing? TRMM provides improved climatology of precipitation characteristics such as diurnal variations, vertical structure, extremes, seasonal cycle at finer resolutions. The TRMM products can be used to investigate inter-decadal change and trend-related processes associated with rainfall.

What are the effects of clouds and surface hydrologic processes on Earth's climate? TRMM provides refined latent heating profiles that help to characterize the effects of clouds. TRMM provides robust climatologies of convective system and lightning characteristics.

How do ecosystems, land cover, and biogeochemical cycles respond to and affect global change? TRMM products make it possible to study human impacts such as land use changes and pollution on rainfall. TRMM rainfall is used as an input to hydrologic models that investigate river flow and land runoff.

How do atmospheric trace constituents respond to and affect global environmental change? TRMM products make it possible to study human impacts such as aerosols on regional rainfall.

How are variations in local weather, precipitation, and water resources related to global climate variation? As the TRMM record length goes beyond 15 or more years and can potentially reach 18-20 years, this is the first global scale precipitation record that enables to characterize tropical seasonal-inter-annual climate variability in general, and the ENSO cycle. Detection of changes in convective system climatologies due to global climate change can also be assessed through changes in rainfall and lightning characteristics.

What are the consequences of land cover and land use change for human societies and sustainability of ecosystems? TRMM precipitation can be used to assess human impacts such as land use changes and pollution on rainfall climatologies and precipitation processes. TRMM data have been used to conduct insightful studies of rainfall modification in urban areas.

How can weather forecast duration and reliability be improved? How can predictions of climate variability and change be improved? TRMM products improve analysis and modeling of global water/energy cycle, which improves weather /climate prediction capability. TRMM data provide continued improvement of weather forecasting, especially monitoring and forecasting the tracks, intensity and associated rainfall of tropical cyclones (NOAA, DoD, WMO RSMC centers). An uninterrupted TRMM data stream will allow continued development of improved model analyses through ingestion of microwave radiances, precipitation fields, and SSTs in cloudy regions to improve initial conditions.

How will water cycle dynamics change in the future? TRMM provides improved critical rainfall inputs to hydrologic models, which are used for flood forecasting and water budget studies. Recently studies have also been published demonstrating potential for flashflood and landslide now casting. The longer the TRMM record length, the longer studies of hydrologic sensitivity can be conducted to examine differences in water cycle dynamics in dry and wet years, ENSO extremes, weak and strong monsoon regimes,etc.

<u>Weaknesses:</u>

None

Technical Panel:

Please see the technical panel report. Although various models and solar activity predictions can be used, the only concern at present is with regard to availability of fuel. The sensors are in excellent working condition. The support for this mission is reasonable for the value-added science, support of GPM pre-launch activities, and potential for cross-calibration with the future GPM mission. The bulk of TRMM/GPM science is funded through ROSES. It is important that the TRMM portion of the budget be preserved after the transfer of GPM related activities after launch.

National Interests Panel:

We note TRMM was rated "Very High" utility by the national interests panel (NIP), and the science panel concurs with NIP. The data serve national needs by providing unique datasets needed to improve existing models of weather and climate and provide the first part of Climate Data records for horizontal and vertical structure of precipitation, and improved latent heating profiles. In addition, TRMM provides a unique service by providing vital now-casting information on structure, intensity, and track of tropical cyclones that support the operations of the NHC and DoD. It could also be suggested that the now-casting properties of TRMM for extreme rainfall events could help in FEMA activities for disaster mitigation. TRMM data are used internationally to support weather and hydrologic forecasting activities in countries where there are no ground–based radars and raingauges are sparse if available (.e.g. Tropical South America, maritime subcontinent, etc) For example, see NASA's own SERVIR activities in South America and Africa in support of US's international aid and cooperation.

Other Comments:

The proposal provided an impressive summary of science discovery and applications that were enabled by TRMM, and there is no question regarding the high science level of the products being developed and the climate studies being addressed. Although the proposal was quite long as it is, because much emphasis is placed on the links between TRMM and GPM, especially in terms of extension budget allocation, a more detailed discussion of transition and legacy issues would have been helpful.