

# NASA EARTH SCIENCE SENIOR REVIEW 2009

Submitted to:

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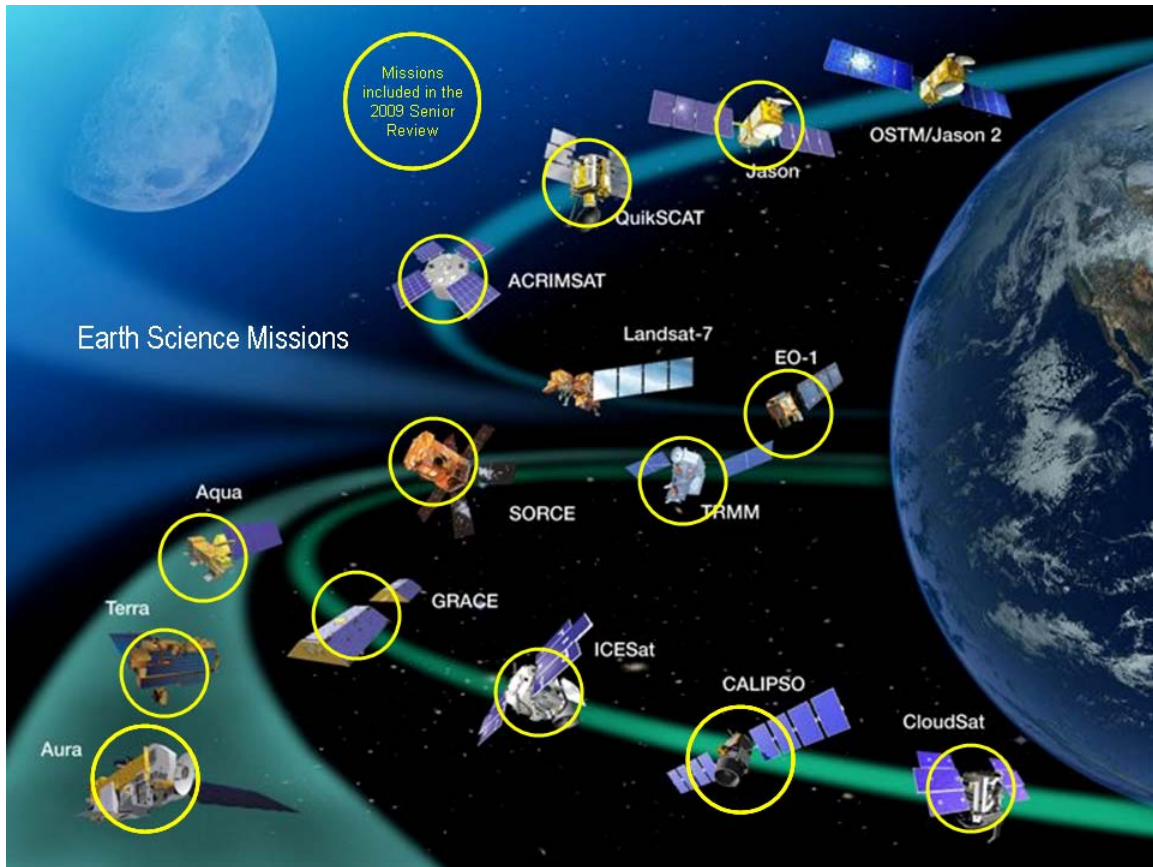


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## INTRODUCTION

The Senior Review Panel (SRP) first convened on April 25-27, 2007 to evaluate 13 ongoing NASA satellite missions: ACRIMSAT, Aqua, Aura, CALIPSO, CloudSat, Earth Observing Mission-1, GRACE, ICESat, Jason-1, QuikSCAT, SORCE, Terra and TRMM. All missions except Aura are currently operating beyond their prime mission periods; Aura is scheduled to enter its extended mission phase in October 2010. The Committee was tasked with reviewing proposals submitted by each mission science team for extended funding support for FY10-FY13. The panel focused on the scientific performance of each mission and the continued relevance of each mission to the NASA Science Strategic Plan. Performance factors included scientific productivity, contribution to national needs and the technical status and budget efficiency. Two sub-panels were formed to provide input to the science panel. The technical and cost sub-panel (chaired by W. Rodriguez) provided input on the health and viability of the operating satellites and instruments and the proposed mission operations and data analysis costs. The national needs subpanel (chaired by L. Friedl) provided input on the utility and applicability of the mission's data products to satisfy national operational objectives of non-NASA agencies. Where these findings of these two sub-panels are relevant to the science evaluation, they are summarized in this report; full findings and details of the sub-panel evaluations can be found in a separate document. The Senior Review Science Panel considered these reports in its evaluation of the scientific merit of each mission based on the applicability of the mission's science to NASA Earth science strategic plans and objectives. In its findings, the panel also considered the product maturity, the scientific merit of data records and data continuity. The Committee was not tasked to review the Education and Public Outreach aspects of the missions.

In addition, the SRP assessed the viability of a mission extension at the proposed in-guide funding level and, when applicable, requests for augmented funding (referred to as the optimal funding level). When proposals included requests for augmented funding, the SRP assessed the scientific importance of the proposed additional work and/or mission products, along with their relevance to NASA science objectives.

The panel's overall findings for the ESD extended missions for FY10 and FY11 were categorized as:

- Continue as base-lined (with in-guide budget);
- Continue with augmentation (all or part of the Optimal Proposal);
- Continue with reductions to the in-guide baseline;
- Preparation for close-out and finalizing dataset.

In addition, the panel was tasked to point out additional collaborations on overlaps between missions where synergies may exist. The panel was also asked to comment on the validation of, or suggested changes to, the proposed definition of core data products for each mission. Finally, we also have provided preliminary findings for FY12 and FY13.

## **REVIEW PROCESS**

Each mission team was asked to submit a proposal for mission extension for the period FY10-FY13. The request for proposals centered on the continuation of mission data products supported by an “In-Guideline” budget scenario as well as that supported by an “Requested/Optimal” funding scenario. The specific direction was provided to mission teams which included the following statement<sup>1</sup>:

- In-Guideline Scenario: Describe a plan which does not exceed the guideline of the current NASA operating plan (the “N2 budget”) in each year. The in-guideline scenario is assumed to be sufficient to achieve the basic mission science objectives, including its contribution to national goals. All efforts must be made to develop a detailed and justified in-guide budget. If the project believes the current budget guideline is insufficient to support the present set of products and activities, the project should identify the set of activities and products that will be supported, and the impacts of any adjustments in work content on the science return for the mission.
- Optimal Scenario: You may describe a funding level that leads to a more effective or efficient mission or improves data continuity/quality, but still recognizes the very tight fiscal constraints that NASA faces. In other words, the optimal scenario should be a carefully considered request, not a maximal request. The technical/science description of this scenario should clearly define the discrete items or activities mapped to the WBS (see Attachment A) and expected benefits compared to the in-guideline scenario. The required budget should include credible cost estimates and bases of estimates phased by year.

The SRP was first convened on March 25 via teleconference to review assignments and discuss review procedures. Weekly teleconferences were conducted to review status and address any issues. Initially, a team of three reviewers was assigned to each mission to assist in the development of questions about the proposals that would be transmitted to the mission scientist. These questions were discussed during the teleconferences and finalized during an all-day teleconference on April 30 and were sent to the respective mission teams allowing each team to tailor their formal presentations directly to the concerns of the SRP. During this one-day teleconference, the panel members also discussed their preliminary evaluation of all missions. Summary results of the Technical & Cost and National Needs subpanels were also provided to the SRP and when feasible were incorporated into the mission questions. The panel met on May 12-14 in Washington, DC with each mission making a 45 minute presentation (90 minutes for Aqua, Terra, Aura) focused specifically on addressing the panelists’ questions. Based on these presentations and additional discussions led by the individual mission panels, the mission panels were charged in developing and documenting a collective evaluation for each mission. The panel findings were organized by overall assessment, scientific merit, core mission data product maturity, relevance to NASA science goals, technical & cost, and national needs. The SRP findings are based on the following considerations:

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<sup>1</sup> From 2009 Call Letter ESD Senior Review

(1) The mission objectives and value of data products in the context of the science goals, objectives and research focus areas described in the NASA Science Strategic Plan. The SRP evaluated the scientific merits of the proposed returns from each mission.

Discussions included consideration of the value of and need for the continuation of long-term data records and overall data continuity. The panels were also charged to consider each mission independently and not attempt to compare merits between missions unless both missions dealt with redundant data products.

(2) The SRP evaluated the proposed activities under the “In-guide” and “Optimal” budget scenarios.

(3) The SRP evaluated the overall portfolio of data products for all missions under review, identifying possibly redundant or complementary products and searching for potential synergies.

(4) The SRP considered the sub-panels finding of the technology & cost aspects of the proposal.

(5) The SRP considered the National Needs sub-panel findings as an additional positive aspect of the mission, but did not deduct value if the panel had a low ranking of a particular mission.

(5) The SRP provided science-based findings for an implementation strategy for the NASA Earth Science Division extending missions to FY10 and FY11.

(6) The SRP provides preliminary assessments and findings for FY12 and FY13.

General findings are presented in the next session, followed by detailed summary for each mission.

### **SENIOR PANEL REVIEW SUMMARY FINDINGS**

The SRP recognizes that each of the 13 missions has made unique and important contributions to NASA research objectives. The interdisciplinary scientific achievements of these missions contribute to diverse fields like meteorology, hydrology, glaciology, solid Earth geodynamics, geodesy, oceanography, atmosphere and space physics, and climate-change. Observations from a variety of these platforms, as stand alone measurements and in combination with other instruments, provide a means of evaluating global climate models and their representation of atmospheric, particularly clouds and aerosols, and oceanic processes. The multi-disciplinary nature of these missions contributed to the objectives identified by the IPCC Assessment Reports and the National Research Council’s Decadal Survey. These missions address several critical issues of climate science, such as the determining the energy budget of the planet, mass balance changes of polar ice sheets, aerosol-cloud interactions, radiation feedback, cloud parameterization, cloud vertical structure, air sea interactions and the role of oceans in climate model forcing. Through these missions NASA is achieving new scientific insights on atmospheric chemistry. The observations of solar irradiance, and its spectral

distribution are clearly important for modeling the sun and supplying an important boundary condition for studying climate change and the natural variations in climate. Missions are meeting national needs such as supporting the Congressional mandate to monitor certain trace gases in the stratosphere, providing imagery during national disasters, and providing critical data to operational forecasting centers. The quality and volume of scientific discoveries from these 13 missions is outstanding, and the importance of these sensors to climate change research and high-value operational products cannot be overstated.

The panel was unanimous in its finding that the continuation of the 13 missions would make a critical contribution to enabling NASA to continue to meet its science objectives.

There are a few caveats to this finding as discussed below.

- (1) ACRIMSAT. The SRP finds that ACRIMSAT should be phased out during FY12-FY13. Part of this finding is associated with the redundant measurements from SORCE-TIM, and the delay of Glory and NPP. The discrepancy between ACRIMSAT and SORCE-TIM of TSI must be resolved during the next two years. This may only be accomplished through budgetary conditions tied to ACRIMSAT and SORCE future funding.
- (2) ICESAT. The ICESat mission has provided very valuable observations; however, it is unlikely that the measurements will be of high quality during the FY12-FY13 period, and NASA should prepare to close out that mission, unless laser performance is beyond expectations in the sense that high-quality cryosphere data sets can still be acquired.
- (3) EO-1. EO-1 continues to provide unique data but remains underutilized. There are efforts to increase tasking access to EO-1, eliminate cost and improve access to historic data and provide value added tools to develop L2 products. If these conditions result in increased usage of the data and the data remains of high quality, then extension in FY12-FY13 may be considered in the next review.

## ***MISSION-SPECIFIC SUMMARIES***

### **ACRIMSAT**

The conclusion of the 2007 Senior Review panel was that ACRIMSAT be extended through 2009, at which time it would be terminated. The present 2009 Senior Review Panel finds that the mission should be extended another two years (through 2011), at most. Since the proposed in-guide funding zeroed out the budget for 2010, the Panel supports sufficient optimal funding to cover the suggested ACRIM activities through 2011. There are two major reasons for this finding:

- (1) Provide TSI redundancy hedge against possible (though not likely) failure of SORCE/TIM until the launch and operational capability of the GLORY/TIM and NPP/TIM missions.
- (2) Allow the ACRIMSAT team to do the laboratory measurements necessary to sufficiently characterize their instrument in order to address the potential issues associated with the ACRIM data set (TSI offset, trends, and short-term variations). This should include, but not be limited to, the development of an ACRIM diffraction and scattered light correction. Doing so would give greater credence and validity to the long, unique, and potentially exceedingly valuable ACRIM data composite data set.

In keeping with the two reasons for the mission continuation conclusion given above, a condition of extending the ACRIM mission is that a plan of action and milestones be developed and implemented for conducting the necessary instrument characterization tests to understand the ACRIM/SORCE TSI offset as well as the current discrepancies with regard to the trends and short-term variations. The panel suggests that these characterization measurements be made at the new LASP facility. This plan should include obtaining sufficient data to develop and implement a scattered light and diffraction correction in the ACRIM science data. This plan must be executed before the beginning of FY10. It is also suggested that an independent party, such as NIST, lead the laboratory collaboration.

Although continuation of the mission through 2011 is considered worthwhile, it is noted that the panel was disappointed in the ACRIMSAT proposal. It did not adequately address in a satisfactory way the glaring potential issues with the ACRIM data set (TSI offset, trends, and short-term variations). Several questions on these issues were put to the ACRIM team to be addressed in their presentation. However, the Panel found their responses to be also unsatisfactory. For example, regarding the short-term variations, the PI suggested that similar variations are seen in the SORCE and VIRGO data sets (but in muted form) and also pointed to correlations of the ACRIM variations with sunspot number; however, these correlations were not at all evident to the panel. Furthermore, no attempt was made by the ACRIM team to do even a very simple quantitative correlation analysis between ACRIM data and SORCE or VIRGO (or with sunspot number) to illustrate the correlation. Moreover, the structure of short-term variations seems superficially to be consistent with potential uncorrected scattering and diffraction effects in the ACRIM instrument, and such potential corrections were not discussed in the ACRIM presentation.

## **Aqua**

The Aqua mission began on September 1, 2002, and is now well into the first year of its extended mission, after its prime mission was completed in September 2008. Five of the original six Aqua instruments are still operational and in good health, and should continue to operate successfully over the next four years (FY10-FY13) of the proposed continuation and beyond. Scientific accomplishments and current merits of the Aqua platform are excellent. These merits include data and discoveries from approximately 100

data products that address each of NASA's six interdisciplinary Earth science focus areas and 12 Applied Science Program Elements. The Aqua data are considered to be critical for the activities associated with the current or upcoming IPCC Working Group 1 Assessment Report 5 (AR5), 2009–2012, for regional to global climate change assessment and forecasting studies. The number of published citations using Aqua data now exceeds 7000 and counting, with more than 600 publications within each of the last two years. Aqua has adequate propellant for at least eight more years of normal operations, and five of the original six instruments still continue to perform well, obtaining data on a wide range of Earth system variables that directly address all of the NASA Earth science objectives. Continuation of the Aqua platform and data series is critical for continuity of many Earth system data records recommended by the recent NRC Decadal Survey and other agencies including the WMO and CCSP. The proposed mission continuation will likely continue to produce new discoveries and provide high quality science services to the global community. These services are not likely to be matched by the proposed NPP and NPOESS follow-on missions, so NASA should undertake any and all efforts necessary to sustain this irreplaceable mission.

Given the high level of science return, utility and continued value of the Aqua mission to the science and applications communities, the panel supports continuing the Aqua mission through 2013. However, we believe that most of the proposed baseline mission budgets are insufficient to maintain the current high level of productivity, product accuracy and utility of the Aqua mission. The panel supports continuation of the Aqua mission with augmentations to the current baseline budgets in accordance with proposed optimal budgets for the MODIS, AMSR-E and CERES instrument teams. The panel also supports funding of the AIRS/AMSU teams at the optimal budget for the FY10-11 period and that the team continue to explore development of the AIRS greenhouse gas products; but for the FY12-13 timeframe, the AIRS/AMSU teams be funded at the in-guide budget and that continuation of the AIRS greenhouse gas product activity be funded through a more competitive process under ROSES.

### **Aura**

The primary scientific missions of the Aura mission have been completed successfully. Three of the four instruments continue to operate well and continuation of the mission would have the benefits of continuing to measure trends (especially ozone and stratospheric chlorine), to sample interannual variability, to improve existing products and to develop new products. Aura's main missions are stratospheric chemistry and dynamics related to ozone depletion, tropospheric chemistry, and secondarily climate change. Aura is making great strides in extending satellite remote sensing to tropospheric chemistry and air pollution, which is a major practical and research issue that will grow in the future.

Three of the four instruments are likely to continue to operate well and the spacecraft has fuel for eight years and is operating nominally. The instruments are taking important data for which NASA has no plans to provide replacement instruments in the near future. Many of the measurements are unique. NASA has a Congressional mandate to monitor



ozone and chlorine trends in the stratosphere. Aura does that and also provides new scientific insights. The instruments are also providing novel measurements of importance for tropospheric chemistry. Some of the observations are used by the operational weather forecasting community.

The panel supports the base-level funding of all instruments that remain functional. HIRDLS is not currently operating because of a failed chopper motor, and TES has an increasingly balky interferometer control system. Even if the HIRDLS chopper motor cannot be restarted, the appropriate level of funding should be allocated for algorithm development for retrieving more chemical atmospheric constituents that can be applied to measurements already taken. In addition, augmentations toward the optimal funding profile that are all worth supporting are listed below in priority order.

1. The combined TES/OMI ozone product, which should definitely be funded, since better resolution of tropospheric and lower tropospheric information is possible with the combined retrievals, and is scientifically and practically important.

The same argument applies to the next two products, but less so.

2. The combined OMI/AIR SO<sub>2</sub> and dust product
3. The combined TES/MLS CO product.”
4. The HIRDLS increased vertical resolution product. HIRDLS can produce profiles with greater vertical resolution than other instruments, and this vertical structure information is scientifically important.

## **CALIPSO**

CALIPSO mission spacecraft and sensors are operating well with the transition to the backup laser meeting design specifications demonstrated NASA's capacity for long-term space-based lidar sensors. The CALIPSO Lidar (CALIOP) sensor provides unique vertical information on clouds and aerosols crucial to radiation feedback, cloud parameterization, polar stratospheric clouds and aerosols, marine boundary layer, and provides unique validation of satellite products and regional/global climate and aerosol models. However, even thin boundary layer clouds limit some applications including aerosol-cloud interactions and near surface air-quality applications. CALIPSO shows excellent synergy with existing A-Train platforms including CloudSat, CERES, MODIS and OMI and is heavily involved on generation of value-added fusion products. In addition, the mission data are crucial as a bridge to future satellite lidar missions ADM (2011), EarthCARE (2013) and ACE (2015). Combining CALIPSO with these future missions is essential to explore climate impacts of ENSO and PNA cycles. Product maturity has significantly improved including the release of Version 3 profile product including the inclusion of product errors. Fairly extensive preliminary validation efforts have been made through aircraft HSRL under-flights for both level 1 and level 2 products, but detailed analysis of errors in the level 2 products must still be investigated. CALIPSO products are beginning to be implemented in retrospective mode by agencies such as ECMWF, NOAA, NRL and EPA to statistically evaluate model forecast skill on the occurrence of clouds, and by NRL and EPA but long latency will limit near real-time applications although high return rate products (<12hrs) are being provided to specific users who need near real time data (at the expense of accuracy).

The SRP supports the proposed optimal request which asks for a very reasonable additional expenditure to develop a sub-setting software tool to improve data retrieval ease for user community. The panel suggests that the software sub-setting tool also search among multiple orbits allowing data merges to be implemented for a requested time interval.

### **CloudSat**

CloudSat is satisfying its mission goals, following a logical validation program, producing data that is already being used in scientific discovery, and demonstrating its potential for future scientific productivity and operational use. Good science is already coming from the CloudSat products; wider recognition of the value of these products will increase their use by the scientific and operational communities. The SRP applauds the PI's attempts to create operational use by convincing operational centers to accept post-doctoral associates, funded by NASA, to work in the centers on integrating CloudSat information into their operational models. The CloudSat validation plan is testing both the measurements themselves and the derived CloudSat products and is continuing into the future. The potential to combine CloudSat measurements with measurements from other instruments in the A-Train and its global coverage makes its products unique. The instrument performance and data gathering statistics are all above required levels and should not be a problem for an extended mission. The panel feels that CloudSat should receive both the proposed in-guide funding as well as optimal funding for, first, the completion of the precipitation products and, second, the development of the combined CloudSat/CALIPSO 2B-FLXHR-LIDAR product.

### **EO-1**

The unique status of EO-1 among NASA missions is notable. Although it was designed as a technology mission, EO-1 has successfully pioneered new techniques and now (since 2003) is in extended mode. It now collects data for special event imagery at high spectral and spatial resolution, contributes to long-term data sets and interoperability and contributes images and new techniques for coordinated synergistic data collections, especially for natural disasters and coastal monitoring efforts. The sensor has proven useful as a first look resource to assist in assessing disasters and events of a critical nature. This has been justified through the use of several thousands of images processed for disaster/weather monitoring and in the development of automated first response systems which automate data collection such as the innovative SensorWeb 2.0 development. Hyperion has also been very useful for sensor calibration through convolution of hyperspectral channels. The data is needed for gap-filling to supplement Landsat in the Mid-Decadal Global Land Surveys (GLS2005 and GLS2010); EO-1 addresses continuity for these key long-term data records.

The in-guide budget slated the mission to end in FY11. The SRP was unanimous in suggesting the in-guide budget for FY10-FY11. While EO-1 data continuity concerns were a major consideration, the majority of the panel (10-4) voted to close out the mission and finalize the data set in FY12-FY13 based primarily on the observations that

the data usage and tasking had not matured sufficiently over the last SRP. Consideration by the next SRP for modifying this finding should be based on EO-1 successfully providing the simulation tools needed to develop promised Level-2 products and the convenient hosting of free archival datasets that can be used by the broader scientific community. The panel believes these actions are necessary to achieve the desired increase in data usage.

## **GRACE**

The GRACE satellite mission has demonstrated significant technological and new scientific achievements. GRACE provides a unique measure of Earth's temporal gravity field, which includes climate-change signals. No other current satellite provides this type of measurement. The scientific achievement is truly cross-disciplinary, covering a broad range of NASA's Earth Science priority areas, including climate change, terrestrial water storage including groundwater variability, cryospheric changes, ocean circulation and sea level, and geodynamics. Approximately 500 refereed journal articles have been written on GRACE (~100 publications/yr), reflecting a range of disciplines in Earth Sciences. The relevance of GRACE to NASA's science goals is considered to be outstanding. At its appropriate spatial and temporal resolutions, GRACE is a unique and unprecedented tool to measure and study contemporary climate-change science. Continuing the GRACE mission to extend the geophysical time series is highly beneficial to NASA and the cross-disciplinary scientific community.

Since its launch, GRACE operates over 98% of the time has been producing data almost uninterrupted. The predicted mission life span is through 2013, represents a total mission span of 11 years after launch, far exceeding its mission design and requirement. The data products (Level 2) maturity is at *Stage III* (the most mature level). There is also synergy with other missions, including altimetry missions (ICESat, Envisat, Jason-1/-2, CryoSat), ESA's SMOS and NASA's Aquarius and SMAP, and ESA's GOCE missions.

The proposed new low-latency (~7 days after data acquisition) data product to satisfy hydrologic community requirement represents the new applied science topics. Although the National Interests Panel rated the GRACE mission extension as with "Very High Utility," primarily due to its critical contribution to the National Vertical Datum effort. It is suggested the GRACE team should extend itself for additional applications science.

The Technical & Cost (T&C) Review Panel identified 1 major and 5 minor weaknesses in instrument/flight systems, 2 minor weaknesses in mission cost estimates, and rated the GRACE mission extension as at *Medium Risk*. The one mentioned 'weakness' in cost estimate is the contingency of GRACE operations dependent on a successful MOU for DLR to operate flight system, at no cost to NASA. In summary, The GRACE sensors currently show minimal age related measurement degradation, with a projected mission life span extending through 2013, 11 years after launch.

In summary, the Panel supports GRACE for mission extension at the augmented level.

## ICESat

The panel recognizes the exceptional value of ICESat measurements for cryospheric science. The response of the cryosphere to global warming has significant ramifications for society. The ability to predict rates of global climatic change, melting ice, and rising seas through the next century relies on an accurate understanding (and modeling) of glacier and ice sheet behavior. Combination of high precision laser ranging (Geoscience Laser Altimeter System (GLAS)) with special attitude calibration methods enables ICESat to monitor ice sheet thickness changes with unprecedented accuracy and details, providing improved mass balance estimates of the Greenland and Antarctic ice sheets. ICESat is currently the only mission capable of accurately measuring ice sheet surface topography and changes in a synoptic scale, and therefore is a key contributor to the objectives identified by the IPCC Assessment Reports, the Arctic Climate Impact Assessments (ACIA) and the National Research Council's Decadal Survey.

The Technical and Cost Panel has classified the ICESat mission as high risk due to problems with the GLAS lasers. The system has only one operational laser left, which is currently operating at a low energy level of ~ 2 mJ. Preliminary results presented to the panel suggest that the continuation of the mission will allow the collection of useful measurements over most of the ice sheets as long as the laser energy doesn't decrease below a critical level. However, due to the increasing loss of useful returns, the degradation of ranging accuracy and increasing uncertainty in the recovery of pointing direction, the accuracy of surface change determination is eventually expected to fall below the science requirements, especially over the steep, marginal area of the ice sheets. Moreover, measurements made at reduced energy level will not meet the objectives of other applications, for example vegetation science.

Operating the GLAS laser at decreasing energy will result in a decrease of useful laser measurements and increased ranging error and pointing uncertainty. Unless a catastrophic failure occurs, the laser quality will degrade gradually. Therefore a set of criteria, based on the science requirements should be established for the mission termination. Moreover, as the 2007 Senior Review Panel noted, when the accuracy of laser quality degrades so the accuracy of surface change measurements are marginal, the accuracy of elevation measurements could still be sufficient for DEM production by collecting data along unobserved subcycles of the currently used 91-day repeat orbit. Therefore this panel strongly suggests that NASA convene an independent review panel/board to evaluate the best strategy for collecting observation during the remaining operation periods and for terminating the mission.

The principal science objectives of ICESAT are polar ice-sheet mass balance, atmosphere cloud heights and aerosol distribution, land topography, vegetation canopy heights, sea-ice thickness and freeboard mapping and changes. The panel was impressed by scientific contributions in all of these areas, despite the mission's technical difficulties. However, with reduced duty and power to the one remaining laser, some of these objectives can no longer be adequately addressed (e.g. atmosphere, vegetation). For these reasons, the panel finds that maintaining focus on the primary objective and reducing focus of secondary objectives, with associated cost savings, is warranted. The panel suggests in-guide funding for 2009-2011. Augmentation is suggested for 2012-13, but below the requested optimum level for mission closing and data reprocessing.

## **JASON-1**

Jason-1 should be approved for mission extension at a funding level for the Optimal Scenario. Jason-1 continues to contribute in substantial ways to both scientific breakthroughs and national needs operations.

The team has effectively identified important new science that requires a constellation of ocean altimeters (currently Jason-1 and OSTM). This includes the leveraging of the interleaved orbit with OSTM to perform enhanced resolution altimetry, which has allowed them to investigate eddy-scale sea surface height (SSH) and improve SSH knowledge in coastal regions. The new measurements are extending the knowledge of SSH to decadal scales and enabling retroactive science that improves SSH height knowledge for prior years. All of these measurements contribute substantially to climate science.

Extended funding through the planning period of this review is important to avoid premature transition to decommissioning. However, there is strong concern about Jason-1 not being capable of decommissioning as a result of catastrophic failure that precludes needed commanding or other required activities. The consequence would be to leave Jason-1 in an orbit that makes collision with the non-functioning TOPEX/Poseidon likely, producing an unacceptable level of debris in this critical orbit for satellite altimetry. The situation has critical consequences that go beyond this mission alone. Though ongoing Jason-1 operation is highly desirable, NASA and CNES should establish a joint agency-level decision process to monitor Jason-1 health and ensure a conservative process for decommissioning.

The Senior Review Panel believes the value of Jason-1 as a scientific (not operational) backup to OSTM was underemphasized in the proposal. There is no scientific backup to OSTM other than Jason-1, and none will be available until the launch of Jason-3 planned for 2013. Though OSTM is functioning well at the current time, this fact is considered important to the value of an extended Jason-1 mission. Finally, the mission team is encouraged to promote use of Jason-1 for new water vapor science, both through their community interaction and through ROSES proposals. This appears to be an additional area in which Jason-1 could contribute breakthrough science given its long data record of this important climate parameter.

## **QuikSCAT**

The SeaWinds scatterometer on QuikSCAT has performed superbly for almost ten years, and it has been the only U.S. mission producing such a long-term, global ocean vector winds data series appropriate for scientific research. These measurements have been recognized by the 2007 NRC Decadal Review as required to meet NASA science goals; and this has been reflected in NASA's climate, coastal, and hazards science plans. QuikSCAT is the primary source of global ocean surface wind vectors and wind stress for science applications such as ocean and climate model forcing, air-sea interaction studies,

and the study of unusual weather and climate phenomena such as hurricanes and El Niño. Further, for the foreseeable future, QuikSCAT is the only global ocean vector winds data set appropriate for climate studies to date. The continuation of the QuikSCAT mission, and its cross-calibration with other scatterometers such as the EUMETSAT ASCAT or the forthcoming Indian and Chinese scatterometers, provides the only means by which this ocean vector wind data set can be extended into the future as per Global Climate Observing System (GCOS) observing principles.

In addition to scientific contributions, QuikSCAT data is also available in near real time for operational weather analysis and forecasting applications and are routinely assimilated in numerical weather prediction models at the NOAA National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasting (ECMWF), and other European and Asian meteorological agencies. QuikSCAT backscatter data have become a significant resource to the cryosphere community for sea-ice monitoring, estimates of snow accumulation over ice sheets, and the operational tracking of icebergs at the National Ice Center. The National Interest Panel ranks QuikSCAT as “very high utility.”

The QuikSCAT spacecraft and instrument are healthy but down to single-string and the probability of completing the extended mission is estimated to be only 50%. Science data will continue to be acquired using the proven mission operations and data analysis capabilities at JPL, BATC, LASP, GSFC and PODAAC. Team members and mission responsibilities are the same as in the past, assuring a low risk and effective continuation of the basic mission. Having completed nearly ten years of successful operations, the QuikSCAT team is capable and efficient. Operations have been automated, processes and procedures have been refined, lessons learned and system idiosyncrasies have been documented. Further modest enhancements and some new products are planned, and the proposed budget is extremely modest!

The panel conclusion is to continue the project to the current baseline for 2010 and 2011 and to augment the funding for 2012 and 2013 to maintain funding at the 2011 level (adjusted for inflation) for a total of \$3.9M.

## **SORCE**

The purpose of the SORCE mission is to characterize the incoming solar spectral irradiance, an important boundary condition for studying climate change and the natural variations in climate. To address the science questions, the SORCE measures the solar spectral irradiance from four sensors co-aligned on a 3-axis stabilized low-Earth orbit spacecraft.

Continuing the SORCE spectral irradiance observations into cycle 24 is important to improving our understanding of the solar variations in total and spectral irradiance, thus improving modeling of the solar cycles. The primary data records from SORCE are the daily averaged (24-hour) Total Solar Irradiance (TSI) from TIM and the daily averaged Solar Spectral Irradiance (SSI) from SIM, SOLSTICE, and XPS.

Our findings support the continuation of the project with augmentation to the current in-guide budget, as described below.

1. Optimal budget values from the 2007 Senior Review budget values for FY10-FY11 are needed to meet the baseline mission. The in-guideline budget from HQ for FY12-FY13 includes a reduction in funding of 22% from the 2007 Senior Review Results for N2 Guideline budget. Other missions generally had 5% cut. This apparently came about due to a misunderstanding on \$3.17M cost savings (~3%) on the entire SORCE program from 1999-2008.
2. The SORCE Optimal Budget is slightly less than the 2007 Senior Review, and this optimal budget provides for a continuous SORCE mission with adequate support to resolve a couple anomalies per year.
3. Continue SORCE mission with only standard data products, no new data products (e.g. those listed in Table A-5).

The 2007 Senior Review report stated about SORCE (with a similar message to ACRIM): *The Committee finds the core mission merits funding through FY2009, during which time the discrepancy between ACRIM/TSI and SORCE/TSI measurements ought to be resolved to conclusion.* In reading both the ACRIM and SORCE proposals, it appears, unfortunately, that this discrepancy has not been resolved – each arguing why their measurements are correct. This remains a concern of the panel and needs to be addressed. Both the SORCE and ACRIM proposals claim that their instrument is the most accurate and precise. A consistent and well-documented picture of the accuracy and long-term stability of both the SORCE and ACRIM III TSI sensors has evidently not yet emerged.

The SORCE team is making excellent progress in the laboratory measurements recommended at the NIST workshop. Preliminary results show good agreement among the Glory TIM, the SORCE TIM witness instrument, and the NIST-calibrated cryogenic radiometer in the TRF on an absolute scale. The recent laboratory enhancements will help alleviate our understanding of these differences. It is a positive step that the PICARD PMO instrument (which is like the SOHO VIRGO instrument) is planned for a visit to the LASP facility for comparisons in late summer.

Extending the SORCE irradiance measurements will achieve the required overlap with future GLORY TSI measurements (currently expected to launch in 2010) and planned NPOESS TSI and SSI measurements (expected to launch in 2013).

## **Terra**

Terra is one of the flagship missions for NASA Earth System Science, enabling the scientific community to address a wide range of fundamental science questions articulated in NASA's Science Plan. The spacecraft and sensors continue to function well, with only a few non-critical failures to date. No further life-limiting issues are

anticipated for any systems during the mission extension period, with the exception of some concern regarding the solid state recorder. Robustness of the ground system is an ongoing concern that can be addressed with appropriate funding, as requested in the Optimal Scenario. The scientific and operational merits of Terra are outstanding. Terra provides long and critical data records; its continuation is of very high importance unless and until suitable follow-on/replacement missions are online. In addition to excellent science, its products have very high priority to applications that cut across many US agencies and other users. The Panel supports Terra for mission extension at the “Optimal Scenario” funding level to make important ground-system IT upgrades and to mitigate the effects of budget reductions since the last Senior Review. To ensure that the greatest possible science utility is being derived from the platform, alignment between the mission and science communities, particularly with regard to cross-instrument and cross-mission collaboration, could be improved; the panel suggests that the mission team put a higher priority on coordination with the science community conducting multi-instrument and multi-platform investigations.

### **TRMM**

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 11 years of precipitation measurements including details of the vertical structure of that precipitation in the tropical and extra-tropical regions of the world. The level of product maturity and types of products from multi-sensor on TRMM to multi-satellite is exceptional. TRMM provides answers to key science questions for both NASA’s Water and Energy Cycle and Weather focus areas. Examples of operational uses around the world include the use of near-real time images for tropical cyclone structure/intensity estimates, and integrating the TRMM SSTs into standard products. There are currently no other platforms that can provide the coverage and detail of rainfall observations that TRMM provides. Continued operation until the GPM launch in 2013 is necessary to ensure a continuing dataset for climate studies. In addition, some overlap between the missions will ensure calibration between the two missions and that adequate temporal coverage is maintained until the launch of the rest of the constellation.

The science team has provided convincing evidence that there are no platform, instrument, or subsystem-specific issues that will adversely affect extended mission status. The performance of all instruments on board is nominal, and there is no reason to think that this performance will not continue into the future. Any sub-system anomalies have mitigation plans. The basic mission extension will continue production of TRMM standard and real-time products. Thus, a multi-year extension of TRMM at the budgeted baseline level will provide a very high payoff for science and applications at a low additional cost to NASA.



## **APPENDIX. MISSION-SPECIFIC FINDINGS**

This section presents the findings of the panel for each mission. For each mission the panel reached a collective finding on the FY10-FY11 activities as noted. A few missions recorded dissenting opinions on the FY12-FY13 proposals as noted earlier. In each case, if there were conditions attached to the finding, it is included in this report. The four finding categories are:

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline (list them);
- Continuation of projects with reductions to the current baseline (list them);
- Close out and finalize data set.

The panel also ranked the mission proposals in terms of scientific merit, noting the perceived strengths and weaknesses of the mission and the value of the relevance to NASA ESD objectives as discussed below. The overall maturity of the core data products was also assessed. In general, the panel accepted the findings of both the Technical & Cost subpanel and the National Needs subpanel, making additional comments on occasion based on information gathered during the mission team visit with the panel.

Each of the following mission review summaries was written by a team of three panelists, so specific comments vary.

## **ACRIMSAT Mission Review**

### **Finding (20010-2001):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;
- Continuation of projects with reductions to the current baseline;
- Close-out and finalize dataset.

ACRIMSAT and the ACRIM sensor are both in excellent health, and the probability is high that the mission could continue uneventfully through 2011. However, there are currently no plans to fly future ACRIM missions. If this is to be the last in the ACRIM series, then there are questions concerning the scientific value of extending this mission for a few more years. On the other hand, redundancy is extremely important with regard to total solar irradiance (TSI) monitoring. Therefore, given the risk associated with the continuation of the SORCE mission, the panel recommends that the ACRIM mission be extended for another two years (through 2011). By that time the GLORY/TIM, and perhaps even the NPP/TIM, will be on orbit and their instrument characteristics understood. At this point the ACRIM mission should be terminated; however, a condition of extending the ACRIM mission is that a plan of action and milestones be developed for conducting the necessary instrument characterization tests to understand the ACRIM/SORCE TSI offset as well as the current discrepancies with regard to the trends and short-term variations. This plan should include obtaining sufficient data to develop and implement a scattered light and diffraction correction in the ACRIM science data. This plan must be executed before the beginning of FY10. Since the proposed in-guide funding zeroed out the budget for 2010, the Panel recommends sufficient funding to support the suggested ACRIM activities through 2011.

### **Scientific merits**

Outstanding       Very Good       Good       Fair       Poor

#### Strengths

The instrument consists of three totally independent ACR (Active Cavity Radiometer) modules, each consisting of a dual cavity, thermally balanced pyrheliometer with sensors B and C used only occasionally to check for degradation drifts in the main sensor. The ACR technology used in ACRIM III has heritage dating back to the SMM mission (1980-1989), and includes ACRIM II on UARS (1991-2005), and ACRIM III on ACRIMSAT. Together, data from these three instruments comprise a TSI data set extending from 1980 through the present (nearly 30 years), with only a single two year gap (1989-1991). This is by far the longest series of TSI measurements from a single instrument type yet obtained. The ACRIM data set (ACRIM I, II, and the present III) form an extremely valuable TSI record.

Measurements of the TSI are critical to understanding the sun and its relationship to Earth's climate. ACRIM makes important continuity measurements to the existing record of TSI.

#### Weaknesses

The Panel is not aware of any plans to fly future ACRIM missions. If this is to be the last in the series, this does lead to questions concerning the scientific value of extending this mission for a few more years.

There remain several important potential issues and problems with the ACRIM data set (explained in detail in the next section) that could impact its scientific value. These issues were not satisfactorily resolved in the proposal or oral presentation. The panel is particularly concerned that a diffraction and scattered light correction have not yet been implemented in the ACRIM science data.

The increase in TSI between the solar minimum years 1985, 1996, and 2006 is a potentially important result. However, discrepancies observed between ACRIM and SORCE in trends and short-term variations (discussed in the data product maturity section) does cast some doubt on the validity of this result.

#### **Core mission data product maturity;**

Outstanding       Very Good      X Good       Fair       Poor

The ACR instrument has an extremely good heritage dating back nearly 30 years.

There is a longstanding 0.35% average TSI value discrepancy between ACRIM III and SORCE/TIM. However, this discrepancy has been known for some time now, and evidently little progress has been made toward resolving the issue.

While the precise absolute value of the solar constant (resolving the difference between the ACRIM III 1366 and SORCE 1361 W/m<sup>2</sup>) is an important issue, trends, of course, are much more important. In that regard, the discrepancy between the trends observed in ACRIM III, and SORCE/TIM and VIRGO from 2005 and 2009 (SORCE/TIM: 80 ppm/yr, VIRGO: 90 ppm/yr, ACRIM III: 30 ppm/yr) is particularly troubling. The fact that the VIRGO trend is in much better agreement with SORCE than with ACRIM suggests that the problem may lie with ACRIM. If this is the case, it would suggest that the long-term stability of the ACRIM III instrument is significantly worse than the quoted value of 5 ppm/yr.

The ACRIM team has not yet performed the required instrument characterization measurements to implement diffraction and scattered light corrections in their science data. Modeling results from NIST suggest that these two corrections could be important for ACRIM.

The relatively large short-term (months) secular variations in TSI observed in the ACRIM III data set are also of concern. It appears as if both SORCE/TIM and VIRGO

should have the precision to corroborate these variations, but they do not. The arguments offered by the ACRIM team that these variations are real (correlation with sunspots, similar, but muted, features seen in VIRGO and SORCE) were far less than compelling. Not even a very simple correlation analysis was done to support the claim.

**Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

Strengths

Total Solar Irradiance is an extremely important climate variable that must be accurately and precisely monitored over time.

Weaknesses

The scientific value of extending this mission for another three years, given that no other ACRIM missions are scheduled, is somewhat questionable.

**Technical and Cost**

The Technical and Costs panel had the following comments with regard to ACRIMSAT:

The ACRIMSAT mission is rated as low risk. The T&C panel has identified one major strength and three minor strengths. The ACRIM3 instrument appears to be in excellent health and is expected to fully operate during the proposed mission extension period. The spacecraft appears to be in excellent health. The primary ground station has operated 99.8% error free throughout the nine-year mission, and is backed up by three NASA ground stations, of which a minimum of two communicate with the spacecraft for one orbit of commanding and data download each month. The mission proposes that they have been able to operate ACRIMSAT at annual cost savings of 30% since FY 08. The panel is confident the mission can operate through two-year (in-guide) or four-year (optimal) mission extensions. The cost risk is rated as low.

The costs for extending the mission are extremely reasonable.

**National Needs**

The Senior Review Panel concurs with the National Needs subpanel's finding that the importance of this mission for non-scientific uses is not high.

**Other Comments**

The SRP was extremely disappointed in this proposal. It did not adequately address in a satisfactory way the glaring potential issues with the ACRIM data set (TSI offset, trends, and short-term variations). Several questions on these issues were put to the ACRIM team to be addressed in their presentation; however, the Panel found their responses to be also unsatisfactory. For example, regarding the short-term variations, the PI suggested that similar variations are seen in the SORCE and VIRGO data sets (but in muted form)

and also pointed to correlations of the ACRIM variations with sunspot number. However, these correlations were not at all evident to the panel. Furthermore, no attempt was made by the ACRIM team to do even a very simple quantitative correlation analysis between ACRIM data and SORCE or VIRGO (or with sunspot number) to illustrate the correlation. Moreover, the structure of short-term variations seem superficially to be consistent with potential uncorrected scattering and diffraction effects in the ACRIM instrument, and such potential corrections were not discussed in the ACRIM presentation. Thus the Panel was left unsatisfied.

## ***Aqua Mission Review***

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;
- Continuation of projects with reductions to the current baseline;
- Close-out and finalize dataset.

The Aqua mission began on September 1, 2002, and is now well into the first year of its extended mission, after its prime mission was completed in September 2008. Five of the original six Aqua instruments are still operational and in good health, and should continue to operate successfully over the next four years (FY10-FY13) of the proposed continuation and beyond. Scientific accomplishments and current merits of the Aqua platform are excellent. These merits include data and discoveries from approximately 100 data products that address each of NASA's six interdisciplinary Earth science focus areas and 12 Applied Science Program Elements. The Aqua data are considered to be critical for the activities associated with the current or upcoming IPCC Working Group 1 Assessment Report 5 (AR5), 2009–2012, for regional to global climate change assessment and forecasting studies. The number of published citations using Aqua data now exceeds 7000 and counting, with more than 600 publications within each of the last two years. Aqua has adequate propellant for at least eight more years of normal operations, and five of the original six instruments still continue to perform well, obtaining data on a wide range of Earth system variables that directly address all of the NASA Earth science objectives. Continuation of the Aqua platform and data series is critical for continuity of many Earth system data records recommended by the recent NRC Decadal Survey and other agencies including the WMO and CCSP. With the recent failure of OCO, AIRS/AMSU now fills a critical gap in the production of global atmospheric greenhouse gas records. The proposed mission continuation will likely continue to produce new discoveries and provide high quality science services to the global community. These services are not likely to be matched by the proposed NPP and NPOESS follow-on missions, so NASA should undertake any and all efforts necessary to sustain this irreplaceable mission.

Given the high level of science return, utility and continued value of the Aqua mission to the science and applications communities, the panel recommends continuing the Aqua mission through 2013. However, we believe that most of the proposed baseline mission budgets are insufficient to maintain the current high level of productivity, product accuracy and utility of the Aqua mission. The panel therefore recommends continuation of the Aqua mission with augmentations to the current baseline budgets in accordance with proposed optimal budgets for the MODIS, AMSR-E and CERES instrument teams. The panel also recommends that the AIRS/AMSU teams be funded at their proposed optimal budget for the FY10-11 period and that the team continue to develop the AIRS greenhouse gas products; the panel recommends that AIRS/AMSU teams be funded at their proposed baseline (in-guide) budget for the FY12-13 timeframe and that continuation of the AIRS greenhouse gas product activity be funded through a more competitive process under ROSES.

## Scientific merits

Outstanding       Very Good       Good       Fair       Poor

### Mission strengths and relative value of data record and overall data continuity

The Aqua mission began on September 1, 2002 and is now well into the first year of its extended mission. Five of the original six Aqua instruments are still operational and in good health, including MODIS, AMSR-E, AIRS/AMSU and CERES. These instruments should continue effective operations over the next four years (FY10-FY13), with significant potential for further operations beyond the 2013 time frame. Overall, the scientific merits of the Aqua platform are excellent; these merits include a relatively precise and well calibrated set of global data records and discoveries from approximately 100 data products that address each of NASA's six interdisciplinary Earth science focus areas and 12 Applied Science Program Elements. The number of published citations using Aqua data now exceeds 7000 and continues to grow, with more than 600 publications within each of the last two years. Continuation of the Aqua platform and data series is critical for continuity of many Earth system data records recommended by the recent NRC Decadal Survey and other agencies including the WMO and CCSP. With the recent failure of OCO, the AIRS/AMSU instrument suite now fills a critical gap in the production of global records of tropospheric greenhouse gases including CO<sub>2</sub> and CH<sub>4</sub>, and ocean radiances. Similar products from the NPOESS Preparatory Project (NPP) won't be available until after 2011 and their utility for research is under question.

The proposed Aqua science objectives include extending the records of nearly 100 climate variables that have been generated as core data products, including those considered "essential climate variables" by the Global Climate Observing System. These products and associated mission science activities effectively address all of the NASA Earth Science objectives. The continuation of these data will facilitate development of integrated climate data records, which will enable more precise analysis and separation of global change signals from natural climate cycles, including solar cycle effects, ocean-atmosphere oscillations, volcanic eruptions and ice sheet dynamics.

The Aqua sensors contain much synergy with each other and with other sensors and satellite platforms (e.g. Terra), and global climate model simulations. Many of these synergies have been explored, resulting in improved accuracy of core and new bio and geophysical products, and new understanding of the environment. A major science objective of the extended mission is to continue this exploration for the production of integrated climate data records spanning multiple related variables, and spatial and temporal scales. Highlights of these synergistic retrievals include comprehensive global observations of photosynthetic net primary productivity both on land and in the ocean from MODIS; improved understanding of diurnal variability and spatial distributions of global cloud optical, physical and radiative properties using MODIS on Terra and Aqua; analysis of diurnal heating derived from MODIS LSTs and SSTs from Terra and Aqua, and the affects of ocean surface winds from AMSR-E; production of blended AMSR-E

and MODIS SSTs and snow cover products; production of merged CERES, MODIS, CALIPSO and CloudSat products for studying atmospheric aerosol, cloud and radiative processes and interactions; the blending of AIRS/AMSU water vapor measurements with global climate model simulations confirming that upper tropospheric water vapor increases with warming to maintain nearly constant relative humidity and a strong, positive water vapor feedback. The Aqua mission is only just beginning to tap the potential of multi-sensor and cross-platform science activities and product development, which will likely be strengthened and further developed and exploited with a longer satellite record.

The Aqua mission continues to demonstrate its value for delivering a broad range of near real-time satellite information to the user community, including operational weather forecast and environmental monitoring centers, in the form of accurate weather forecasts and global environmental monitoring capabilities. The broad availability of direct broadcast data from the mission and the MODIS Rapid Response System are shining examples of successful observations to applications and should be strongly supported by NASA. These operational-oriented applications and associated user groups will likely benefit and expand under a continued Aqua mission. A continued mission will also eliminate potential gaps in these global environmental data records and critical services until the planned launch of similar satellites and data records, including NPP and GCOM-W.

The **MODIS** radiometer on Aqua provides an extensive set of measurements of atmospheric properties, ocean surface properties and land surface characteristics globally on a daily basis. Better spatial resolution, pointing knowledge, and substantially improved calibration and characterization of instrument performance have enabled MODIS to improve significantly upon longer-term measurements from the NOAA AVHRR heritage sensor. The Aqua MODIS sensor continues to provide critical information about the global carbon cycle, including changes in both land and ocean productivity, including photosynthetic net primary productivity, ocean chlorophyll concentrations, vegetation photosynthetic leaf area and land cover change. Co-located retrievals of tropospheric CO<sub>2</sub> and CH<sub>4</sub> from AIRS/AMSU should enable accurate assessment and monitoring of ocean and terrestrial sources and sinks of these greenhouse gases. MODIS also provides baseline and data continuity for eventual replacement by VIIRS on NPP (projected 2011 launch) and NPOESS. MODIS will also provide the inputs (MOD17 GPP) for a planned carbon assimilation product from the SMAP Decadal Survey mission (projected 2013 launch), that will help quantify land-atmosphere CO<sub>2</sub> exchange and the boreal carbon sink on land. However, many in oceanographic community doubt that VIIRS will be capable of providing research quality data. This makes the continuation of AQUA even more necessary.

**AMSR-E** provides a wide variety of atmospheric and surface state variables under virtual all-weather conditions including rainfall rates, ocean surface wind speeds, integrated water vapor and cloud water amounts, SSTs, sea ice coverage, snow water content and surface soil moisture. A major science objective of the Aqua continuation mission is to improve understanding of soil wetness retrieval methodologies in preparation for future



soil moisture satellite missions. The Aqua AMSR-E sensor provides useful baseline and data continuity information for future ESA, JAXA and NASA Decadal Survey missions for both soil moisture and freeze/thaw state; SMOS, GCOM-W and SMAP have projected launch dates in 2009, 2011 and 2013, respectively. The maintenance and operation of the AMSR-E instrument are handled by JAXA, and at no-cost to NASA. Continuity of AMSR-E during this time frame will enable synergistic cross-comparisons of radiometric measurements and derived similar products with these other missions, while providing valuable baseline information for the construction of continuous climate data records of these variables.

The **AIRS/AMSU/HSB** instrument suite provides well calibrated and stable global records of atmospheric radiance, temperature and moisture profiles, and key minor constituents as well as cloud and surface parameters with relatively high accuracy. Many of these products continue to be valuable in global operational weather forecasts. The Aqua AIRS/AMSU instrument suite is capable of providing regional and global maps of tropospheric CO<sub>2</sub>, CO, CH<sub>4</sub> and O<sub>3</sub>, enabling the global monitoring and analysis of terrestrial and oceanic sources and sinks of these important atmospheric greenhouse gases. With the recent loss of OCO, these products now fill a critical gap in the production of global climate records. Similar products are not likely to be available until the launch of NPP after 2011 unless an OCO replacement is launched. While the AIRS/AMSU instruments are showing signs of age the project team has proactively identified critical tasks to effectively mitigate against aging instrument behavior and improve radiance product quality and utility.

#### Potential weaknesses of the proposed Aqua mission continuation

Overall the proposed Aqua mission continuation plan is robust with no apparent weaknesses. However, the proposed Aqua mission continuation and science community would benefit from further support and guidance by NASA. First, while NPOESS is expected to largely replace Aqua (and Terra) as a global Earth Observing System, future continuity of many of the Aqua (and Terra) products and climate records is unclear. For example, the proposal highlights the unique capability of MODIS to derive phytoplankton physiology using sun-stimulated fluorescence line height, which enables the interpretation of iron- vs. nitrogen-limited ocean biology. This capability is currently not planned for VIIRS on NPP or NPOESS. Other Aqua (and Terra) core products are capable of being continued as part of the NPP and NPOESS missions, but are not currently planned for operational production. Given the projected overlap between Aqua and NPP (planned 2011 launch) and the value of the Aqua products for global monitoring and future missions (e.g. Aqua-MODIS GPP inputs for SMAP) the panel recommends that NASA develops a more robust plan for ensuring the production and continuation of a larger suite of Aqua/Terra products under NPP and NPOESS. In some cases, ensuring continuity of a critical product time series may involve the use of other satellites and instruments, such as continuity of AMSR-E SSTs under JAXA's GCOM-W mission.

There are many potential synergies between similar retrievals from MODIS sensors on Terra and Aqua, and other satellite instruments (e.g. ocean chlorophyll products from

SeaWifs and MODIS). Some of these synergies have been explored as noted in the proposal, but most of these studies appear to involve relatively simple comparisons of similar products. Many of these activities are supported as NASA ROSES investigations rather than mission team activities, though there appears to be some lack of coordination between ROSES funded investigations and team activities. The panel recommends that NASA encourage better coordination between mission team and ROSES funded activities to more fully explore and exploit multi-sensor synergies and facilitate the production of new and potentially improved global data records.

**Core mission data product maturity:**

Outstanding       Very Good       Good       Fair       Poor

The core mission data product maturity of each of the Aqua instrument classes is distinguished below. Each of the sensors offers a range of products and maturity levels ranging from poor (stage 1 maturity) to excellent (stage III maturity). The wide range of product maturity primarily reflects the later addition of new products to the original core product sets; these more recent products haven't had as much time to achieve maturity, though the proposed mission continuation activities appear sufficient to allow all core products to achieve level III (Excellent) maturity, while allowing many research and provisional products to achieve higher maturity levels as well.

The **AIRS/AMSU** derived core and research products represent a range of product maturity. All research products are in Stage 1 maturity, where product accuracy has been estimated using a small number of independent measurements for limited locations and time periods. These 4 research products include tropospheric CH<sub>4</sub>, sulfur dioxide, OLR, and HNO<sub>3</sub>. Most of the other 19 core products are under stage 2 or 3 validation status (i.e. S2: accuracy has been assessed over a wide distribution of sites and conditions via ground truth and validation efforts; S3: validation product accuracy assessed and uncertainties well established via independent measurements in a systematic and statistically robust way representative of global conditions), except the following: AIRS VIS/NIR radiance; LST; CO, CO<sub>2</sub>, land surface emissivity, and IR dust. It is likely that validation efforts will continue under the extended mission phase to upgrade core products to the highest possible stage of maturity. However, the proposal also notes that as the project has entered an extended mission phase and cost reduction is critical, support of science team research products will be reduced to a minimum. Because of their importance to the science community, CO and CO<sub>2</sub> products were recently added to the AIRS core product list. Priority should be given to upgrading these products to stage 1 maturity or better during the FY10-11 extended mission phase, given the recent loss of OCO. The CH<sub>4</sub> research product is also of similar importance to the science community and should be added to the core product list if possible. Potential synergies between these products and similar products being developed from MOPITT on Terra should be encouraged. Funding for these greenhouse gas product activities should continue to be supported by ROSES during the FY12-13 mission phase at cost savings to the mission. The transfer of these activities from mission team to ROSES support is reflected in the

panel recommended AIRS/AMSU optimal (FY10-11) and in-guide (FY12-13) funding guidelines.

The Aqua **MODIS** core products benefit from lessons learned and earlier calibration and validation activities from MODIS on Terra and SeaWiFS. There are currently 36 core MODIS products covering a wide range of maturity levels. Most of these products are listed at stage II maturity, while only two products (SST and polar winds) have stage III maturity. There are also two provisional products (ET and burned area) and eight other products at stage I maturity. Despite the relatively low level of product maturity, the Aqua MODIS core products have undergone 5 successive reprocessing phases and will undergo additional validation, refinement and improvement including a planned 6<sup>th</sup> reprocessing of core atmosphere and land products under the proposed extended mission. The mission continuation and related ROSES funded science activities will likely result in further improvement in product maturity and accuracy.

The **AMSR-E** core products include columnar cloud water and water vapor over the ocean; sea surface temperature (SST); sea surface wind speed; monthly rainfall; sea ice concentration and drift; snow depth on sea ice; and surface soil moisture. Most of the core products and algorithms are specified as level 2 and 3 maturity, and it is likely that the continuing mission will continue to improve product accuracy and maturity. The **CERES** core products include bidirectional scans; instantaneous top-of-atmosphere (TOA) radiative fluxes; monthly regional and geographic radiative flux averages; and monthly gridded TOA/surface fluxes and clouds. All of these core products algorithms are listed as mature, and product accuracy will likely improve under a continuing mission.

#### **Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

The continuing mission of the five operational Aqua sensors and associated science team activities address all six of the SMD Earth science focus areas (atmospheric composition; weather; carbon cycle and ecosystems; water and energy cycle; climate variability and change; earth surface and interior) and all seven of the major SMD Earth Science research objectives, including: 1) understanding changes in atmospheric ozone, air quality and atmospheric composition (AIRS/AMSU, MODIS, AMSR-E); 2) enabling improved weather prediction (AIRS/AMSU, MODIS, AMSR-E, CERES); 3) quantifying global land cover change and land/ocean productivity (MODIS); 4) quantifying the key reservoirs and fluxes of the global water cycle (AMSR-E, MODIS, AIRS/AMSU); 5) understanding the role of oceans, atmosphere and ice in the global climate system (MODIS, AMSR-E, CERES, AIRS/AMSU); 6) characterizing and understanding Earth surface changes (MODIS, AMSR-E). The coordinated measurements of the 5 Aqua sensors will continue to make valuable measurements, new discoveries and reduce uncertainties regarding the above research objectives and focus areas.

The Aqua continuity mission will provide valuable baseline information for the construction of climate data records and the development of future NASA, NPOESS, JAXA, and ESA missions. For example MODIS provides critical spectral information for the development of algorithms and climate data records that will be continued under VIIRS on NPP (launch in 2011) and NPOESS; the MODIS GPP (MOD17) product is a required input for a planned carbon product to be produced under the SMAP Decadal Survey Mission (launch in 2013); The AIRS/AMSU greenhouse gas products are helping to fill the void left by the recent failure of the OCO ESSP mission; the AMSR-E products are providing valuable baseline information for future soil moisture products from SMAP, and filling a potential data gap until launch of JAXA's GCOM-W mission (2011 launch) and GPM (2012 launch); CERES will continue to provide baseline information and fill a seamless climate data record of Earth's radiation budget in support of future CERES measurements on NPP (2011 launch) and NPOESS (2013 launch).

The Aqua mission fulfills all of the major SMD principles, including prompt and widely distributed access to research data, as indicated by the large number of national and international data downloads of Aqua data from NASA and other agency data distribution centers. The enormous success of the Aqua MODIS Direct Broadcast system is good example of timely and broad global distribution of these data, which enable a wide range of operational applications. These successful efforts should continue under the proposed Aqua mission continuation.

The Aqua data are considered to be critical for the activities associated with the current or upcoming IPCC Working Group 1 Assessment Report 5 (AR5), 2009–2012, for regional to global climate change assessment and forecasting studies.

There are no apparent major weaknesses of planned activities under the Aqua continuation in addressing NASA science goals. However, the proposed budgets for most of the sensor operations and science teams appear to be at a bare bones level. This doesn't appear to be any fault of the mission teams, but rather an effort by the mission teams to be responsive to NASA efforts to reduce costs. The proposed baseline budgets will likely reduce the current effectiveness of Aqua in meeting NASA Earth Science objectives and SMD principles.

### **Technical and Cost**

The science review panel concurred with the Technical and Cost subpanel (T&C) report, which is summarized as follows. The Aqua mission extension is rated as Medium Risk. The T&C panel identified 1 major and 2 minor strengths and 4 minor weaknesses. The Aqua spacecraft appears to be in excellent health and is expected to fully operate during the proposed mission extension. The MODIS sensor has had no issues or problems, has been fully operational, and has a high probability to remain functional through 2013. The AMSR-E sensor has performed well since Aqua was launched in May 2002 and is expected to perform through the mission continuation, even though there have been some torque excursions over the past two years. However, the AMSU sensor has lost or degraded 3 of its 15 channels and the project team's anticipation of further degradation

has led to the development of an AIRS-only retrieval algorithm. The proposal states that Autonomous Operations of the Solid State Recorder, while providing an unquantified cost savings, is predicted to result in a 1-3% data loss based on ground station performance over the last 12 months. Several operator error anomalies were also noted during this report and there was no clear indication that the root causes of those operator errors have been addressed to preclude recurrence. The staffing and budget reflected within the “in-guideline” budget is sufficient to safely fly the mission but not sufficient to bring the ground systems to compliance with NPR 2810-1A guidelines. The T&C panel felt that minimal problems exist; however, they can be overcome with management, good engineering, and trades. The cost risk is rated as Medium-Low (refer to Cost Form). The science review panel supports augmentation of the proposed baseline budgets in accordance with the proposed optimal budgets for MODIS, AMSR-E and CERES; this would markedly enhance mission success, including reducing mission cost risk, providing for ground systems compliance with NPR 2810-1A, and continuing Aqua’s very successful Direct Broadcast and MODIS Rapid Response Systems. The panel recommended that the AIRS/AMSU teams be funded at their proposed optimal budget for the FY10-11 period to allow IT compliance and continued development of the AIRS greenhouse gas products; the panel recommends that AIRS/AMSU teams be funded at their proposed baseline (in-guide) budget for the FY12-13 timeframe and that continuation of the AIRS greenhouse gas activity be funded through a more competitive process under ROSES.

## **National Needs**

The Aqua mission clearly addresses a range of national needs, particularly in the realm of its capacity and successful record of delivering near real-time information to the user community, including operational weather forecast and environmental monitoring centers. These contributions address a broad range of national objectives and applications, including weather forecasting; air quality monitoring; ecological forecasting, agricultural efficiency and carbon management; coastal, aviation, water, energy and disaster management; Homeland Security; invasive species and public health monitoring. Highlights of this activity include the distribution of satellite data with 3 hour latency worldwide through NOAA/NESDIS/STAR and NASA DISC operational centers, disaster management and Direct Broadcast users. Forecast model assimilations of Aqua data from AMSR-E, AIRS/AMSU and MODIS have resulted in demonstrated improvements to weather forecast accuracy and near real-time monitoring and forecasting of environmental phenomena including fires, hurricanes, dust plumes, and agricultural productivity. These operations will likely continue to be highly valued and further exploited by these operational stake holders under a continuing Aqua mission. The science panel clearly recognized the importance of the MODIS Direct Broadcast (Rapid Response) system which serves a wide range of operational users and national needs. The science panel encourages NASA to support this activity under the proposed optimal budgets.

The science review panel recognized that Aqua clearly supports a broad range of important national and international operational applications. The science panel fully

concluded with the findings of the National Interests sub-panel report, which designated Aqua as a Very High Utility mission. Justification for this ranking included multiple very relevant and highly valued data products which are routinely used by multiple participating organizations for important activities, and where loss of these data products would have a significant negative impact on national agencies and organizations. It is likely that the number of operational users will continue to increase under the proposed mission continuation as people become more familiar with remote sensing data. Problems with NPOESS and the failure of OCO also increase the importance of Aqua to the nation.

### **Other Comments**

The PI effectively addressed all reviewer questions. However, we are still uneasy about the availability of data from some of the sensors and how this could be reflected in the number of data users and publications. We understand the many factors that cause the MODIS publication record to be so large. However, the panel feels that the AIRS et al. and AMSR-E teams should redouble efforts to make data available and useful to the broader scientific community. We suggest using the ocean color group (<http://oceancolor.gsfc.nasa.gov/>) philosophy and methods for data handling and distribution as an example to follow. The science panel has no further comments or open issues.

## ***Aura Mission Review***

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline; list them
- Continuation of projects with reductions to the current baseline. List tem
- Close-out and finalize dataset

The primary scientific missions of the Aura Satellite have been completed successfully, but three of the four instruments continue to operate well and continuation of the mission would have the benefits of continuing to measure trends (especially ozone and stratospheric chlorine), to sample interannual variability, to improve existing products and to develop new products. Aura's main missions are stratospheric chemistry and dynamics related to ozone depletion, tropospheric chemistry, and secondarily climate change. Aura is making great strides in extending satellite remote sensing to tropospheric chemistry and air pollution, which is a major practical and research issue that will grow in the future.

Three of the four instruments are likely to continue to operate well and the spacecraft has fuel for 8 years and is operating nominally. The instruments are taking important data for which NASA has no plans to provide replacement instruments in the near future. Many of the measurements are unique. NASA has a Congressional mandate to monitor ozone and chlorine trends in the stratosphere. Aura does that and also provides new scientific insights. The instruments are also providing novel measurements of importance for tropospheric chemistry. Some of the observations are used by the operational weather forecasting community.

We support the base-level funding of all instruments that remain functional. However, HIRDLS is not currently operating because of a failed chopper motor and TES has an increasingly balky interferometer control system. Even if the HIRDLS chopper motor cannot be restarted, the appropriate level of funding should be allocated for algorithm development for retrieving more chemical atmospheric constituents that can be applied to previous measurements. HIRDLS can also produce profiles with greater vertical resolution than other instruments, and this vertical structure information is scientifically important.

For the optimal funding profile, we recommend, in order of priority, the following:

1. The combined TES/OMI ozone product, which should definitely be funded, since better resolution of tropospheric and lower tropospheric information is possible with the combined retrievals, and is scientifically and practically important. The same argument applies to the next two products, but less so.
2. The combined OMI/AIR SO<sub>2</sub> and dust product
3. The combined TES/MLS CO product
4. HIRDLS high resolution product. High vertical resolution is important in better understanding chemical and dynamical processes. HIRDLS was specifically designed for high vertical and horizontal resolution. Because of the blockage

inside the instrument, high horizontal resolution is not possible, but high vertical resolution is still possible along the open field of view and for the three years of record available.

5. MLS Noisy product
6. HIRDLS retrievals in the presence of PSCs.

### Scientific merits

Outstanding    Very Good    Good    Fair    Poor

#### Strengths

The scientific questions remain of high interest and are:

Is the ozone layer changing as expected?

What are the processes that control tropospheric pollutants?

What are the roles of upper tropospheric aerosols, water vapor and ozone in climate change?

The Aura instruments have produced an impressive array of atmospheric constituent measurements. Analyses of these measurements have resulted in scientific discoveries, constraints on atmospheric constituent budgets, and improvements in both diagnostic and predictive models. The Aura science team has addressed issues concerning their three science questions (changing stratospheric ozone; processes controlling tropospheric pollution; the role of upper tropospheric aerosol, water vapor, and ozone in climate change). The data products are mature and generally well validated. The plans for the future, which generally involve algorithm maintenance and upgrades along with a few new products, will support the excellent science that is proposed, and will enable Aura to produce data necessary for the analysis of longer timescale phenomena, such as NO<sub>2</sub> trends.

The range of scientific investigations undertaken with Aura data in the last two years is impressive. Aura data were featured in 90 papers published in scientific journals in 2008. This is reflective of continuing scientific insights provided by the Aura data, and suggests that continuation of the measurement and research program is warranted. Important aspects of the three Aura scientific goals have been addressed. For the stratosphere, some of the scientific results are related to dynamical and chemical processes, such as the ClO dimer issue in the Ozone Hole, while others are related to trends in ozone and stratospheric wave activity. For the troposphere, Aura measurements of atmospheric constituents such as NO<sub>2</sub>, O<sub>3</sub>, and HCHO provide important constraints on emission inventories of a number of important atmospheric constituents. For the UT/LS, the Aura measurements are being used to unravel the abundance and transport of atmospheric constituents in this radiatively sensitive region, which is important for understanding climate change.

The range of applications has grown rapidly in the last two years, and appears likely to continue to grow. The Aura data are being widely used to improve global models. Near-Real-Time data are used in the flight planning of large multi-investigator aircraft



campaigns. The use of the SO<sub>2</sub> and AI products to help aircraft avoid volcanic plumes is another important application.

The A-Train collaborations are numerous and productive.

One advantage of the spectroscopic techniques that are being used by the Aura instruments is that more atmospheric constituents can become data products, even for earlier times in the data set, once the spectroscopic parameters are known. Two examples are HDO and glyoxal. The science that is coming from the measurement of these two molecules has been strong.

### Weaknesses

The weaknesses are primarily the slow degradation of the instruments, and in the case of HIRDLS, the failure of the chopper motor.

### Value of data record and overall data continuity

Extending the data record is valuable. Additional information can be extracted from the data by developing new algorithms. The value of the data record is high and the overall data continuity is very good. The monitoring of Ozone and Chlorine is an important NASA responsibility. The data are valuable in assessing trends in the Brewer-Dobson Circulation that are predicted to occur in association with global warming.

### **Core mission data product maturity;**

X Outstanding       Very Good       Good       Fair       Poor

Outstanding: Core mission data product accuracy has been assessed and the uncertainties in the products are well established via independent measurements in a systematic and statistically robust way representing a broad array of conditions.

Aura products include more atmospheric constituents than all other A-Train satellites combined. There are some overlaps, such as the CO from TES and from AIRS, but these are beneficial because AIRS has a wider swath while TES has higher spectral resolution. The combination of MLS data with CloudSat and CALIPSO for ice water content (IWC) makes sense, but we are uncertain what an independent IWC from combined MLS/HIRDLS data provides to the data contributed from other sources. The Aura science team seems to be aggressive in looking for collaborations with other missions. The movement of Aura closer in position with CloudSat and CALIPSO is one example.

The core products for each instrument are good and are consistent with the continuity needed for understanding the long-term science of atmospheric constituents in the stratosphere, troposphere, and in between.

## Relevance to NASA Science Goals:

X Outstanding  Very Good  Good  Fair  Poor

### Strengths

The science proposed addresses well the Earth Science Division research objectives, particularly for atmospheric composition in the troposphere and stratosphere, and also fulfill a Congressional mandate to NASA to monitor ozone and chlorine.

The proposed science plan attacks issues that are the most current for furthering the understanding of the recovery of stratospheric ozone, the processes responsible for tropospheric trace gases distributions, including pollution, and the role of the chemistry and dynamics of the upper troposphere/lower stratosphere in the climate system. An important point to stress is that these measurements of atmospheric constituents are useful for understanding not only atmospheric chemistry but also atmospheric motion. Diagnosing changes in the Brewer-Dobson Circulation rate using the Aura data is one example.

### Weaknesses

Once again, the only weaknesses are related to the future health of the instruments, particularly HIRDLS and TES. OMI now also has a problem with field of view obstruction near the center of the scan. There are no better alternatives to these instruments for the measurements they are taking, however. Concerns about the future performance of these instruments must affect decisions about funding levels, but not necessarily fund or don't fund. For instance, as the proposal states, if the HIRDLS chopper motor cannot be restarted, improving the algorithms and developing retrievals for other atmospheric constituents is useful for providing improved data sets for the time period in which the instrument was working. These data will be useful for testing models and for gaining a better idea of global chemical and dynamical processes even if they cannot be used for studying long-term science problems or for assimilation into models. Several aspects of the HIRDLS data products are unique and can provide important insights, particularly the high vertical resolution data.

### **Technical and Cost**

Several ROSES grants have been funded to develop additional products. The augmentations are generally modest and could be supported with ROSES funding, or as additions under this senior review process.

### **National Needs**

This is an important mission for ozone assessment, a NASA mandate. Some of the data products can also be used operationally for weather forecasting, particularly OMI, which is available in real time via direct broadcast.

## **Other Comments**

The proposal was of excellent quality and adequately supports the case for continuation.

Aqua and Terra have made optimal funding requests to provide one-year funding to support personnel to bring the EOS Missions Operations System (EMOS) into compliance with NASA IT security policy. Aura, which shares EMOS with Aqua and Terra, is not asking for optimal funding for its contribution to this upgrade. However, if Aqua and Terra do not receive optimal funding for this upgrade, Aura along will not be able to fund it.

## **CALPSO Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations (Optimized budget)
- Continuation of projects with reductions to the current baseline. List tem
- Close-out and finalize dataset

We recommend the budget follow the proposed optimal request. In our opinion, the scientific output more than justifies a very limited budget request which is needed to fully integrate version 3 algorithm upgrades. While there have been lots of comparison and validation type science activities, it is clear that extended mission status will lead to more fundamental science results. In addition, the synergy between CALIPSO and other A-train components is vital and the measurements are crucial as a bridge to the next satellite lidar mission: the Atmospheric Dynamics Mission (ADM), the European Space Agency lidar scheduled for launch in 2011, as well as EarthCARE (2013) and ACE (2015). Combining CALIPSO with these future missions is essential if we are able to begin probing aerosol /cloud forcings mechanisms with sufficient time duration to retrieve signals within ENSO or PNA sensitivities.

These data are being assimilated in retrospective mode by agencies such as ECMWF and NOAA to statistically evaluate model forecast skill on the occurrence of clouds, and by NRL and EPA to assess transport model forecasts on the location of aerosol layers. In addition, high return rate products (<12hrs) are being provided to specific users who need near real time data (at the expense of accuracy).

Finally, there are no platform-instrument or subsystem-specific issues that will affect extended mission status. The performance of the lidar transmitters has been impressive. First transmitter performance was accurately assessed and predicted lifetime and smooth transition to second redundancy transmitter.

In making our budget recommendation, we note that the optimal budget is very reasonable with an additional expenditure of 2 years at ~\$140 and will allow the mission to create a subsetting software tool that will allow users to pull small sections of orbit by geographic limits. This is particularly important since current data granules are 440 MB and will be considerably larger in Version 3. In addition, they will also improve dissemination by including ASCII and NetCDF formats.

The panel suggests that the software subsetting tool also provide the feature that data be subsetted not only by geographic bounds but by time removing the need for users to identify dumps by data orbit numbers.

### **Scientific merits**

Outstanding  Very Good  Good  Fair  Poor

## Strengths

Since its inception, CALIPSO has been designed to fill an unquestioned hole in remote sensing providing vertical profiles of aerosols and clouds and allowing for the detailed observation of multiple cloud layers.

Science questions which are directly impacted by CALIPSO measurements include:

1) Direct Aerosol Radiative Forcing (DARF): Without vertical profile information, all estimates of DARF (such as those in IPCC) are limited to clear-sky conditions over dark surfaces or require model assumptions to estimate the global, all-sky DARF. CALIPSO's ability to retrieve simultaneously aerosols above clouds or other bright surfaces provides unique insight into modifications in the radiation budget.

2) Aerosol-Cloud Discrimination: For example, CALIPSO has shown how MODIS AOD products are significantly overestimated as cloud fraction increases proving cloud interference in the aerosol retrieval algorithms. This is particularly serious since such correlations can be viewed as "false" evidence of the Twomey effect.

3) Surface and Atmospheric Radiation Budget: The need to monitor surface radiation fluxes and assess atmosphere heating as well as partition the outgoing flux into ground and atmospheric sources requires accurate vertical information on aerosol and clouds. To address this, an advanced radiative flux product, the CALIPSO CloudSat-CERES-MODIS (C3M) product, is under development and improves on the existing CERES product with suitable atmospheric retrievals with CALIPSO, CloudSat and MODIS

4) Cloud-Radiation-Climate Feedbacks

CALIPSO and IIR (together with CloudSat) simultaneous retrievals of cloud properties, liquid and ice water etc. are providing useful information on cloud radiation. Examples include the impacts of thin cirrus (not seen by passive retrievals) in the Tropical Tropopause Layer (TTL) on net radiative heating, improved retrieval of Marine Boundary Layer (MBL) clouds and providing constraints to cloud models for Global Climate Models (GCM) including the distribution of ice-water phase clouds as function of ambient conditions.

5) Arctic Cloud –Aerosol Observations

CALIPSO offers new capabilities for observing critical atmospheric processes in the Arctic being the only sensor to observe aerosols through the Arctic, regardless of lighting and surface conditions, and also provides a greatly enhanced ability to reliably detect and profile clouds. Comparison measurements already show difficulties in passive measurements of clouds with strong artifacts observed in ice-sea interfaces. Such data are critical in constraining the large diversity in modeled distribution and properties of both aerosols and clouds in the Arctic which are needed to account for larger than expected heating gradients. In addition, the CALIPSO Data has been extremely useful in

understanding the dynamics of Polar Stratospheric clouds (not an original science question). This includes understanding the structure and formation of these objects and assessing their state by simultaneous observations of backscatter and depolarization.

6) Use of CALIPSO Data to Test and Improve Climate and Transport Models. CALIPSO is beginning to be used as constraints to assess existing global and regional air-quality and climate models. This includes the development of a “CALIPSO simulator” by the Laboratoire de Meteorologie Dynamique (LMD/IPSL) modeling group. Initial studies conclude that CALIPSO profiles represent a more powerful test of model cloud estimates than passive satellite observations and the simulator data is being recommended as a constraint to be assessed by all models participating in the next Intergovernmental Panel on Climate Change (IPCC) . In addition, aerosol extinction profiles from GEOS-5/GOCART models are being constrained significantly and show significant weaknesses in modeling transport processes with particular difficulties in vertical layering. In addition, an assimilation system has been developed for the Regional Atmospheric Modeling System/Chemical. Weather FORecasting System (RAMS/CFORS) model allowing 4D-VAR assimilation of aerosol profile data and climatologies from Calipso are being used by NRL for retrospective tests to refine their forecast models.

7) Assessment of existing passive satellite products.

Significant assessment of cloud detection and cloud top properties from passive sensors has been performed. Clear weaknesses in the passive retrieval include strong biases in cloud top due to poor clear sky temperature retrievals in marine environments due to strong temperature inversions. Difficulties and biases using CO<sub>2</sub> slicing techniques have also been elucidated and have lead to improved retrieval products for the passive approaches.

8) Merged Products:

Additional CALIPSO data is helping improve existing passive sensor retrievals. These include improved absorbing aerosol indices from OMI by providing vertical information critical for absorbing aerosols. In addition, a merged cloud product combining CloudSat and CALIPSO has been developed

### Weaknesses

1) Calipso will probably not assist in the aerosol- cloud indirect effect problem: In particular, there is enough signal to penetrate even below thin COD < 0.3 clouds and provide sufficient quantitative aerosol below cloud to assess aerosol cloud interactions directly. Perhaps, only looking at clear sky patches in thin broken clouds will work but 40-km horizontal resolution is needed for extinction retrievals

### Value of data record and overall data continuity

1) Extended mission status will provide the beginning of a crucial data set (combined with data from additional missions (see below) to capture significant inter-annual modes

of variability that influence climate on seasonal to decadal scales (e.g., ENSO – El Nino Southern Oscillation, Pacific-North American Oscillation), develop sufficient statistics and clustering to quantify relationships between aerosols and clouds (aerosol-cloud microphysical and radiative interactions) and cloud-radiation-climate feedbacks

2) Data continuity will also strengthen existing synergies with the A-Train crucial in supporting future overlap of the APS aerosol sensor on Glory mission scheduled to join the A-Train constellation in 2010 providing crucial evaluation of the performance and retrievals from APS.

3) Coincident CALIOP-APS observations will also provide detailed expertise for the future Aerosol- Cloud-Ecosystems (ACE) satellite mission where polarimeter and depolarization lidar measurements will be used in tandem as well as providing a bridge to the next satellite lidar mission: the Atmospheric Dynamics Mission (ADM), the European Space Agency lidar scheduled for launch in 2011.

4) CALIOP is the beginning of long-term climate data record of the vertical distribution of clouds and aerosols to be continuously extended with future EarthCare and ACE missions

5) Provide critical engineering information gained on laser performance for extended space observations and help in design of the next generation of lidar instruments as called for in the NRC Earth Science Decadal Survey.

**Core mission data product maturity;**

Outstanding       Very Good       Good       Fair       Poor.

The mission products are unique and vital to a number of climate and air transport studies and are not redundant. The CALIPSO team has shown an unusually strong capability in providing synergy for developing fused active-passive products, validating and assessing existing products and developing tools which allow simple integration into global and regional models. The product processing is not trivial and requires significant support in improving core products, value added products and data records. Most of the algorithm maturities are assessed as moderate but version 3 will now include complete profile data including error estimates and will be released in June 09.

The nature of the vertical products makes validation difficult and the most useful validations are provided by simultaneous aircraft profiles from HSRL systems that do not suffer from assumptions (or calibration weaknesses). At present 81 underflights have been done over the continental USA, Alaska and coastal waters. Results illustrate good matchups in the level 1B attenuated backscatter with biases due to stratospheric aerosols < 4% for both lasers. However, detailed analysis of errors in the level 2 products must still be looked into.

The retrieval of cloud and aerosol optical depth is a critical parameter for this mission and is listed as only “moderate” and “fair” in Maturity. This is a difficult and yet important science product. Further efforts to improve retrieval have been identified as part of the extended mission and are being investigated.

**Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

CALIPSO provides data sets that address a number of SMD recommendations

*How is atmospheric composition changing?*

CALIPSO provides important observations of the vertical distribution of aerosols and observes aerosols in previously inaccessible regions such as the Arctic. The data set can result in unique climatologies on cloud and aerosol properties

*What trends in atmospheric constituents and solar radiation are driving global climate?*

CALIPSO’s ability to detect aerosols both above and below clouds allows significantly improved quantification of aerosol forcings beyond Clear Sky Forcings reported by passive sensors.

*How do atmospheric trace constituents respond to and affect global environmental change? What are the effects of global atmospheric chemical and climate changes on regional air quality? How will future changes in atmospheric composition affect ozone, climate and air quality?*

Aerosol profiles will provide synergy with existing trace gas constituents such as Ozone (OMI) and will allow for better modeling of transport through assimilation and retrospective analysis - allowing better assessment of transport on regional air quality, changes in environmental forcings.

*How do ecosystems, land cover, and biogeochemical cycles respond to and affect global environmental change?*

CALIPSO aerosol observations provide a new tool for investigating aerosol-land surface-vegetation feedbacks and aerosol-monsoon interactions.

*How can predictions of climate variability and change be improved?*

Improved aerosol and cloud profile information will allow more sophisticated tests of the models used to predict climate and improve cloud parameterizations and is already being ingested into models at different levels.

*What are the effects of clouds and surface hydrologic processes on Earth’s climate?*



Cloud multi-layering information from CALIPSO - and in combination with CloudSat - allows a more quantitative analysis of the effects of clouds on the surface radiation budget and the partitioning of heating between the atmosphere and the Earth surface.

*How are global precipitation, evaporation, and the cycling of water changing?*

Aerosols can affect precipitation through their effects on cloud formation processes. Detailed vertical profiles between and above clouds provide new information to characterize these effects.

### ***Weaknesses***

Low SNR of aerosol products makes it difficult to apply to aerosol-cloud interactions in the lower troposphere and may not provide sufficient signal to explore aerosol pollution quantitatively including such areas as PM<sub>2.5</sub> near surface concentrations.

### **Technical and Cost**

It is our opinion that the support for this mission is very reasonable for the value added science and the difficulties in maintaining high quality output and data availability. We would like to commend their team on the release of V3 in June 2006 which will provide general access to L2 products including vertical profiles and the need for quick data processing return times

### **National Needs**

The data serve national needs by providing unique datasets needed to improve existing models of climate and air quality and provide the first part of Climate Data records for vertical structure of aerosols and clouds.

Unfortunately, it seems that these data could also be of great use to the operational community if they could be made available in near-real time. Unfortunately hardware limitations of the CALIPSO X band antenna (Single Stream) prohibits increased transmission which would threaten the mission lifetime.

### **Other Comments**

We would like to comment that the proposal was extremely well designed and informative and was crucial in convincing us of the high science level of the products being developed and the climate studies being addressed by them.

## **CloudSat Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;
- Continuation of projects with reductions to the current baseline.
- Close-out and finalize dataset

CloudSat is beginning to meet its mission objectives: evaluating the representation of clouds in global models; evaluating the energy balance for different cloud systems; evaluating the cloud retrievals of other satellite instruments; improving the understanding of aerosol indirect effects. Its data products are highly relevant to NASA's mission, especially in the area of the role of clouds in climate. In the short term, CloudSat products are being used to test a wide range of global atmospheric models, leading to improved simulation of clouds and cloud processes. In the longer term, CloudSat's products could be assimilated into weather prediction models to improve forecasts. The instrument performance and data gathering statistics are all above required level and should not be a problem for an extended mission.

CloudSat data is also understood to be complementary with measurements from TRMM. In particular, Cloudsat's ability to monitor weak precipitation events provided added value to TRMM data and additional synergy with A Train instruments provides unique atmospheric state measurements inaccessible to TRMM.

Maintaining CloudSat's 3-D cloud profiling capabilities over the length of important atmospheric cycles, like the El Nino- La Nina cycle and the solar cycle, will maximize CloudSat's use in climate research. Data continuity is also critical both as a bridge to EarthCare and ACE Missions and to provide sufficient statistics to analyze precipitation, clouds and radiation forcing over different climate conditions.

Finally, the Panel finds that optimal budget should be supported to continue the development of both the development of an enhanced 2B-FLXHR-LIDAR product and the completion of the 2C-RAIN-PROFILE, 2C-SNOW, and 2C-ICE products. Allocation for the precipitation products is 230K for FY10 and a 200K allocation for validation experiments at DOE ARM site in FY11. The Panel concurs with the CloudSat PI that the precipitation products have higher priority because they have a broader scientific use and a much greater potential to be used as near-real-time products. Completion of the 2B-FLXHR-LIDAR product will allow inclusion of small COD clouds and can affect flux estimates on average of approx 20% Allocation for this is ~ 260K over FY10-11

### **Scientific merits**

X Outstanding  Very Good  Good  Fair  Poor

#### Strengths

CloudSat's Cloud Profiling Radar (CPR) is giving an excellent view of global clouds, cloud distribution, and cloud structure and is enabling scientific research toward meeting CloudSat's original four goals: evaluating the representation of clouds in global models; evaluating the energy balance for different cloud systems; evaluating the cloud retrievals of other satellite instruments; improving the understanding of aerosol indirect effects. The science goals that were proposed for the last two years are appropriate for such a potentially powerful tool. A perusal of the publications and potential publications shows the natural progression of papers about the instrument and methods, then methods papers interspersed with the first papers that include CloudSat information as a part of other data sets, then next to both of these types of papers and also science from CloudSat alone or combined with other satellite measurements. Thus, in terms of science, some excellent publications have already emerged, but potentially many more are yet to be written.

The words "beginning to" are frequent in this proposal, and rightly so. With such a short time since CloudSat began operations, it is not surprising that it would take this long or longer for scientists in the user community to learn how to implement CloudSat products into their research. At the present, CloudSat science should probably be judged as much by what could be, based on this proposal's information about research in its early stages, as by what has been already delivered in the last two years.

The summary of results contains some quite interesting science, including the modification to the estimate of the contribution of clouds to the global energy budget, and the combination of CloudSat with other A-Train instruments to develop a better understanding of the transition between cloud drop growth by condensation and by collision-coalescence. Some of the scientific results, such as the improved representation of convection in global models and the understanding of aerosol effects on clouds and precipitation, are just beginning but show promise. These last two are important for climate studies and are central to NASA's Earth science mission.

CloudSat's contributions to climate science can be huge beyond simply improving climate model representations of clouds. Building a continuous record of clouds, even if all of that information is not immediately used, is valuable. CloudSat will create the only global record of the 3-D cloud distributions until EARTHCare in 2013. Furthermore, it is important that the CloudSat measure through important climate cycles, such as the MJO and the El Nino-La Nina cycles, in order to improve the understanding of the cyclical variability of cloud statistics.

### Weaknesses

The operational use of CloudSat data in weather prediction has not yet come close to its capability. CloudSat products are being used to test models, which is important for improving them and helping them assimilate current observations better. However, CloudSat data have not been assimilated into models and assimilation may not occur for a few years, although CloudSat personnel have ideas about how to speed up this process.

### Value of data record and overall data continuity

The value of the data record is high and the need for data continuity well into the future is great. Continuing the mission beyond 2009 will provide a greatly extend the tropical storms database as a function of environmental properties (e.g. changing sea surface temperatures, environmental shear, dust outbreaks, etc.); a larger statistical sampling of atmospheric cycles like the MJO, El Nino – La Nina; greatly extended near-coincident matches of CloudSat and TRMM; and an increased volume of data, and thus the sample size, thereby facilitating the development of various types of Level 3 products that can be grouped by storm types, cloud types, meteorology, and other environmental conditions; and a bridge to EarthCARE and ACE observations and support the development of climate data records of vertical structure and precipitation.

#### **Core mission data product maturity;**

Outstanding      X Very Good       Good       Fair       Poor

The core products are valuable to the scientific community. The data return from CloudSat appears to be excellent. The incremental costs for the optimal activities are rather modest and justified. The ranking of “Very Good” simply reflects the relative “newness” of this mission; the CloudSat team is on track to create data products that meet the definition of “mature”. For example, CloudSat products are already mature enough to be used in future IPCC model comparison studies like the “Cloud Feedback Model Intercomparison Project”.

The mission has undertaken significant validation efforts of both level 1 and level 2 products. Examples include cloud reflectivities using coincident ARM ground radar, Level 2 validations using airborne simulator analysis, point – point comparisons of derived products between TRMM and Cloudsat and is working hard on developing targeted validation testbeds such as the Light Precipitation Validation Experiment (LPVEx)

Many of the auxiliary products map information from other satellites to the CloudSat footprint and are useful merges for a variety of studies. The addition of AN-CERES and AN-COSMIC are both potentially very useful products. Getting the moisture data from COSMIC with the cloud data from CloudSat could be useful for both microphysical and climate research.

The 2B-FLXHR-LIDAR data product will be highly useful for climate-related research, expands the dynamic range of “clouds” to thin clouds and aerosol, and should be supported. However, it is my understanding that some cirrus clouds are too thin to be seen by CloudSat but too optically thick to be penetrated by CALIPSO and yet can be seen by MLS on the Aura satellite. The CloudSat PI should consider adding MLS data to this product. This is a worthwhile addition as an optimal product.

The Cloudsat products fill a unique niche although there is a small overlap with TRMM products. The fact that Cloudsat is on the A train makes their data particularly unique and vital. Cloudsat has an impressive record of coordinating their activities with other assets including Calipso, MODIS. These efforts include improved product developments (such as the FLUX and heating products) as well as assisting in coordinating efforts to match relevant satellites to the CloudSat footprint.

**Relevance to NASA Science Goals:**

X Outstanding       Very Good       Good       Fair       Poor

Strengths

CloudSat data has the potential to contribute significantly to addressing some of the greatest uncertainties in the climate models, to testing the understanding of clouds and their distributions as a function of atmospheric oscillations and cycles, and to beginning to build the capability to assess the trends in clouds and their distributions. Extending the mission will increase the chances of sampling ENSO and MJO, and possibly the beginning of a solar maximum. Extension of the mission would provide more overlaps with TRMM and a bridge to EarthCARE.

Cloudsat is also highly relevant to national efforts at weather and climate forecasting such as the US Air Force Weather Agency where the AFWA Model Analysis Team uses CloudSat data to verify the World Wide Merged Cloud Analysis (WWMCA) and the Diagnostic Cloud Forecast (DCF) model and is being assimilated at various levels into ECMWF as well as provide prototypical data to evaluate Cloudy Fast Radiation Transfer codes such as JCSDA's CRTM model

Weaknesses

The most serious weakness to date is the somewhat limited use of the CloudSat data by the atmospheric science community so far. The publication list indicates fairly heavy use by the PI and by a few others known for their work in clouds and microphysics, and then less use by a wider set of scientists. This statement is not so much a concern as a suggestion. The PI and his team have developed a strategy that promotes the wider use of CloudSat data not only within the atmospheric science research community and also in the operational weather forecasting community.

**Technical and Cost**

**National Needs**

CloudSat is highly relevant to national efforts at weather and climate forecasting such as the US Air Force Weather Agency where the AFWA Model Analysis Team uses CloudSat data to verify the World Wide Merged Cloud Analysis (WWMCA) and the Diagnostic Cloud Forecast (DCF) model and is being assimilated at various levels into ECMWF as well as provide prototypical data to evaluate Cloudy Fast Radiation Transfer

codes such as JCSDA's CRTM model. CloudSat data are not used in civilian weather forecasting yet, but the CloudSat management has followed a strategy that has the potential to accelerate the use of CloudSat data for weather forecasting.

### **Other Comments**

CloudSat is satisfying its mission goals, following a logical validation program, producing data that is already being used in scientific discovery, and demonstrating its potential for future scientific productivity and operational use. Good science is already coming from the CloudSat products; wider recognition of the value of these products will increase their use by the scientific and operational communities. The CloudSat validation plan is testing both the measurements themselves and the derived CloudSat products and is continuing in the future. The potential to combine CloudSat measurements with measurements from other instruments in the A-train and its global coverage makes its products unique.

The Panel is impressed with the CloudSat PI's strategy to create the demand for CloudSat products by the operational forecasting community. It is a good idea to provide funding for post-docs at the operational centers to work on projects for improving the forecast models using the CloudSat products and for assimilating the CloudSat data into the forecast models. NASA should consider creating a system to implement this strategy more broadly in order to get the data products from all of its platforms into the operational realm.

## **EO-1 Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined.
- Continuation of projects with augmentations to the current baseline.
- Continuation of projects with reductions to the current baseline.

The unique status of EO-1 among NASA missions is notable. Although it was designed as a technology mission, EO-1 has successfully pioneered new techniques and now (since 2003) is in extended mode. It now collects data for special event imagery at high spectral and spatial resolution, contributes to long-term data sets and interoperability and contributes images and new techniques for coordinated synergistic data collections, especially for natural disasters and coastal monitoring efforts. The sensor has proven useful as a first look resource to assist in assessing disasters and events of a critical nature. This has been justified through the use of several thousands of images processed for disaster/weather monitoring and in the development of automated first response systems which automate data collection such as the innovative SensorWeb 2.0 development. Hyperion has also been useful as a calibration resource of sensors through convolution of hyperspectral channels. The data is needed for gap-filling to supplement Landsat in the Mid-Decadal Global Land Surveys (GLS2005 and GLS2010), EO-1 ensures continuity for these key long-term data records.

The in-guide budget slated the mission to end in FY11. The SRP was unanimous in suggest the in-guide budget for FY10-FY11. While EO-1 data continuity concerns were a major consideration, the majority of the panel (10-4) voted to close out the mission and finalize the data set in FY12-FY13 based primarily on the observations that the data usage and tasking had not matured sufficiently over the last SRP. Consideration by the next SRP for modifying this finding should be based on EO-1 successfully providing the simulation tools needed to develop promised Level-2 products and the convenient hosting of free archival datasets that can be used by the broader scientific community. We believe these actions are necessary to achieve the desired increase in data usage.

### **Scientific merits**

Outstanding       Very Good       Good       Fair       Poor

#### Strengths

EO-1 is the first high spectral/high spatial resolution satellite. It has two instruments: Hyperion and the Advance Land Imager (ALI). These instruments provide important data for the LCDM, National Operations in response to critical events, preparation for Decadal Survey mission(s), and science questions articulated in the NASA Science Plan.

There is great value in having advanced instruments with capabilities like Hyperion and ALI up and running in orbit for testing and development. Extension of EO-1 will continue to provide the only global high spectral/high spatial resolution data needed to

initiate and address important science topics related to ecosystem function, disturbance, Earth surface and shallow waters. The agility (flexibility) to focus on disasters is a vital national (and international) asset and could potentially lead to important mitigation improvements.

The previous Senior Review noted the lack of articulation of projects to address NASA science goals, that the mission was currently “below the radar”, and recommended organizational changes and additional support/emphasis on this. To address this issue, new automated campaign manager online tool for requesting scenes has been developed which is a significant improvement. In addition, since the last Senior review, the project has initiated 70 science investigations.

Finally, EO-1 has shown an impressive track record in developing coordinated satellite and ground network tasking/observations including improved scheduling to avoid cloud scenes.

#### Weaknesses

Availability of EO-1 data from the USGS archive at no cost is only now being instituted, and this change should increase the breadth of scientific use, beginning June 2009. The rather ad hoc use of EO-1 which was noted in the last review seems to have improved and this broader usage can hopefully improve more after the August pricing changes at USGS.

Level 1R and 1G data products are now available for the most recent 8 months of EO-1 products and can be processed on request for the entire archive. However, the scientific value of these datasets hinges on the capability of the mission in delivering on their promise (by end of 2009) to obtain level 2 products such as atmospherically corrected reflection data for Hyperion (ATREM/ACORN corrections) and ALI (6S corrections). Also of importance is the delivery of Level 2 datasets such as Vegetation Indices, Land cover classifiers, coastal bio-markers etc during 2010-2011 since these products are crucial in interfacing with ecosystem managers and disaster monitor personnel.

However, as delineated by the mission, due to resource constraints, Level 2 products will have to be generated by users, and the mission is in the process of providing on-line toolkits (i.e Geokit) to help with this process are promised, though not yet available. With these tools, retroactive analysis can be performed increasing science demand beyond the community of first responders. It is hoped that these tools will develop interest beyond the present community. Unfortunately, the mission must rely on outside developers to develop these software kits so a strict accounting of quality and delivery are beyond mission control and no schedule of these resources coming on line can be made.

Furthermore, it must be pointed out that the present usage of the instrument (now 12-15 scenes/day) can only be grown modestly before reaching hardware capacity (estimated at 20 scenes/day). Therefore, despite progress on software scheduling and mission coordination, the mission will remain “below the radar” of many scientists.



We conclude that the value of the science activities, beyond those as an incubator mission, to NASA Science Goals are limited because of the moderate capacity and access although increased access to archives from USGS will improve the situation.

The previous senior review noted lack of effort at obtaining long-term data records, and commented that scene acquisition was ad hoc. The growing user communities, automated data requests acquisition algorithms are an important advance on the latter .but real improvement of these issues remain a concern and must be monitored over this period.

#### Value of data record and overall data continuity

This value is very high because the instruments produce high quality results, so that continuation of the mission results in collection of high quality data that is not available in comparable form. These data and the atmospheric corrections applied are all necessary components to NASA HypsIRI Mission defined by the National Research Council's Decadal Survey (NRC-DS) and the Landsat Data Continuity Mission (LDCM). In addition, the data also is needed for gap-filling to supplement Landsat in the Mid-Decadal Global Land Surveys (GLS2005 and GLS2010), EO-1 ensures continuity for these key long-term data records.

#### **Core mission data product maturity;**

Outstanding       Very Good      X Good       Fair       Poor

The maturity of data products is good. This rating is affected because only level one data is readily available and level 2 data products must be user-derived for new and archived data and these procedures have not yet been integrated.

#### **Relevance to NASA Science Goals:**

Outstanding      x Very Good       Good       Fair       Poor

#### Strengths

Advancing hyperspectral satellite applications is a critical goal that this mission addresses. This includes the cross-calibration of a number of sensors including Landsat-5, Landsat-7, and other sensor systems such as MODIS, AVHRR; and Advanced Thermal Emission and Reflectance Radiometer, ASTER, etc.) made possible from the extended multispectral - hyperspectral coverage. The system also plays a key role in developing the needed instrument and algorithm expertise needed for the NASA HypsIRI Mission and to fill gaps in the Landsat Data Continuity Mission (LDCM). Vegetation, land use – land cover and coastal biosystems applications of relevance to NASA will be increasingly well served with the development of promised L2 products.

Furthermore, EO-1 fills a unique place in providing high spatial and spectral resolution data for specific targets of interest through agile, pointable sensors. The imagery and analysis have proven their value in helping to support a number of natural hazards

applications from thermal signatures to flood monitoring. In particular, gaps in coverage of earth's global surface changes at high spatial resolution are filled by this mission.

Cost of an additional two years of operation is reasonable and consistent with previous allocations especially when it appears that usage will continue to grow to capacity, especially if level 2 processing toolbox products are available soon. Further increased usage in science applications is also expected due to free release of level 1R and 1G archive products.

#### Weaknesses

The value of the science activities, beyond as an incubator mission, to NASA Science Goals are not appreciated by all.

In Jan 2012 the fuel will be spent and therefore, the orbit will begin drifting depending on different orbital scenarios. This includes a drift of Mean Local Time from 10 towards 9:45. The proposal states a degradation of the products due to this drift but does not quantify the difficulties involved making it somewhat difficult to evaluate the optimal budgeting scenario.

#### **Technical and Cost**

Rated as Medium risk by the T&C Panel. We note the T&C panel concerns about drifting of Hyperion lamps and Solid State Power Control. We also note concerns about costs of extending the mission as the EO-1 has had a long life.

The ALI solar calibrations were discontinued in 2007 due to failure of the solar mechanism. Also, the calibration lamps, which serve as a stability reference, indicate a 6% drift for some of the bands over the last 8 years. This appears to result in reduced calibration accuracy. It is not clear if this issue will be properly incorporated into Level 1 and Level 2 products.

#### **National Needs**

We note a disconnect among the ratings of the National Interest Panel ratings and ours, with theirs being lower (some utility) than panel members (very good), although we also note the bimodality (very high and some) of the National Interest panels evaluations with a high standard deviation.

The high national interest value is clearly driven by the fact that the EO-1 instruments provide data that address a very clear national need for ecosystem and disaster monitoring. Their objectives of demonstrating new, high quality and efficient instruments and exploiting the agility of EO-1 to acquire data on disasters seem to be compelling. On the other hand, for science users, there is frustration in some sense in the limited capacity of the data in comparison to other platforms and the pointing (non global nature) combined with cost in image acquisition and scheduling. However, as mentioned earlier, improvements in software tools and the free access of archive data should improve the situation.

**Other Comments**

Since this project was a demonstration project and was never intended to have long data collection and highly developed data products, funding was not built into the project for those purposes, and the instrument capacity was never designed to support very many users. Thus, it seems inappropriate to expect advanced data products and a huge user community. Nonetheless, the agility and high data quality makes it advantageous for this sensor to continue, especially if it can provide service to disaster situations, where its high spatial and spectral resolution could have very high value. Therefore, efforts to get the L2 processing tools optimized must be encouraged.

## **GRACE Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline; list them
- Continuation of projects with reductions to the current baseline. List them
- Termination of projects

Include a succinct statement of benefits in continuing the mission (including relevant topics such as science capability, future products, climate science, data continuity, applied sciences, operational partners, instrument health, etc.)

### Statement of Benefits in Continuing the Mission

*Science Capability.* The GRACE mission has the primary scientific objectives to accurately measure Earth's climate-sensitive mass exchange signals manifested in the temporal variations of gravity field. In 2007 GRACE fulfilled its minimum mission requirements with gravity field retrieval accuracies within 1-cm geoid height at 300-km or longer spatial resolution. The measurements of global mass redistribution at the monthly time scales and at a scale longer than ~350 km are only possible with GRACE. GRACE data represent results of an innovative technological and significant scientific achievement: they provide a unique geophysical time series with the potential to quantify dynamical processes of the Earth system, including anthropogenic climate change. The interdisciplinary scientific achievements demonstrated by GRACE so far, contribute to diverse fields like hydrology, glaciology, solid Earth geodynamics, geodesy, oceanography, atmosphere and space physics, and climate-change science including the observations of present-day sea-level rise. Recent science highlights include new observations of global gravity field anomalies in response to regional droughts and recovery; documentation of recent interannual climate variations and impacts to cryosphere, ocean and terrestrial water storages; new observations of spatial and temporal variability Greenland and Antarctica ice-sheet mass balance changes; GRACE based assessment of terrestrial water and ice-sheet contributions to sea-level rise. The recent contributions also include quantification of ocean mass variations and its role in sea-level rise, which are possible recently due primarily to the improved accuracy of the GRACE data products (improved from the so-called Release 1 Level 2 data product to the RL04 L2 data product).

*Future Products.* The proposed generation of Release 5 (RL05) data products includes the Level-2 data products consist of global monthly spherical harmonic coefficients presumably complete to degree 60 or 120. It has been stated that the *improvement in ocean tide models and rapid hydrological variability* are among the improvements in the RL05 data products. The product generation latency will be shortened from the present 30-day time period, to approximately 7 days, using a 15-day overlapping data consolidation window. In addition, a quick-look low-latency gravity field data product will be generated with the epoch of the data product ~7 days in the past, and that the

newest data will be 1-day old. This data set is to satisfy the requirements of hydrologic community. The GRACE Team will also generate regional solutions (mascon) globally as a *new* Level 2 data product.

*Climate Science.* The GRACE mission data contributes to interdisciplinary science including climate-change science. In particular, GRACE addresses the NASA Earth Science Directorate's Focus Areas: Climate Variability and Change, Water and Energy Cycle, and Earth Surface and Interior; and contributes to the objectives of US Climate Change Science Program (CCSP), and the World Climate Research Programme (WCRP). The accuracy and spatial and temporal resolution of GRACE data enables or potentially enables the eventual definitive quantification of ice-sheet mass balance, hydrologic fluxes, oceanic mass variations, each of which represents critical measurements of measuring and understanding anthropogenic climate change. The key here is the ability to separate noise (e.g., data noise including geographically correlated high-frequency error) and *background* models including barotropic response of the atmosphere and ocean, ocean and solid Earth tides, as well as tectonics (including earthquakes) and mantle processes (including glacial isostatic adjustment) for climate science. In summary, at its appropriate resolution, GRACE is a unique and unprecedented tool to measure and study contemporary climate-change science.

*Data Continuity.* Since its launch on March 17, 2002, the GRACE flight system operates over 98% of the time and meets its goal of micron-level inter-satellite range rate accuracy. The GRACE mission, with the exception of the time period during the initial cal/val mission phase, has been producing data almost uninterrupted (except for about 3-24 hours of loss data in 2006, see below) up to now. The predicted mission life span is through 2013, represents a total mission span of 11 years after launch, exceeding its mission design and requirement. The data products (Level 2) are well-calibrated and the level of maturity is *Stage III* (the most mature level). Data (and mission) continuity is critical for many of the contemporary scientific problems being addressed by GRACE. With the uncertain future GRACE-follow-on mission launch plan, it is critical to continue the current GRACE geophysical observational time series to as long as possible.

*Applied Sciences.* The proposed new low-latency (~7 days after data acquisition) data product to satisfy hydrologic community requirement represents the new applied science topics. The National Interests Panel rated the GRACE mission extension as with “*Very High Utility*”, among the best of all satellite missions under the Senior Review.

*Operational Partners.* The DLR/GFZ operates the GRACE flight system at no cost to NASA. The other partners, JPL, GFZ, and NASA/GSFC (mission management), appear to work very well with UTCSR in running the mission and generating validated science data products to the community. The Technical & Cost (T&C) Review panel identified that the potential uncertainty of DLR funding commitment represents a *minor* weakness as part of the cost estimates for the extended mission proposal.

*Instrument Health.* The Technical & Cost (T&C) Review panel identified 1 major and 5 minor weaknesses in instrument/flight systems (2 in instrument, IPU and ICU; 3 in flight

systems, operation requires a two-satellite system, battery cell, CESS head sensor thermistors), and 2 minor weaknesses in mission cost estimates. Overall, the T&C Review Panel rated the GRACE mission extension as *Medium Risk*. However, and in summary, The GRACE sensors currently show minimal age related measurement degradation, with a projected mission life span extending through 2013, 11 years after launch.

*Summary.* Continuing the GRACE mission to continue the geophysical time series is highly beneficial to NASA and the global scientific community. There were approximately 6244 unique GRACE data users from August 2004 through December 2008, with a 3-fold increase from the 2007 Senior Review period. Approximately 500 refereed journal articles have been written on GRACE (~100 publications/yr), reflecting a range of disciplines in the Earth Sciences, including geodynamics, hydrology, oceanography, atmospheric and solid Earth fields. These results indicate a fairly successful mission and valuable data record. The number of new discoveries, scientific publications, users and volume of GRACE data downloads should continue to grow over the proposed mission continuation. GRACE is a joint NASA and DLR mission; the DLR is responsible for 24/7 operations of the GRACE flight system at no cost to NASA. The proposed *Optimal Funding* over the *Baseline Funding* level (see Table below, an average of \$5.136M per year, FY09 through FY13) is a relatively modest request for two years (\$473K and \$517K for FY10 and FY11, respectively). The following is the budget request summary (in thousands of dollars) proposed for GRACE mission extension:

GRACE *	FY09	FY10	FY11	FY12	FY13	Total	%
GRACE In-Guide							
*	\$6,347	\$4,662	\$4,773	\$4,891	\$5,009	\$25,682	3.7%
GRACE Optimal	\$6,347	\$5,135	\$5,290	\$4,891	\$5,009	\$26,672	3.6%
Delta	\$-	\$473	\$517	\$-	\$-	\$990	

Given the level of science return from a continuing mission through FY13 the reviewers are in consensus to recommend **the continuation of the GRACE mission with augmentations to the current baseline** according to the optimum budget.

**Scientific Merits:**

Outstanding       Very Good       Good       Fair       Poor

Science section should describe the science merits of the program and specific contributions of the instruments. It includes current science objectives for the mission and a summary clearly focused on what has been accomplished in the past two years.

Strengths

The GRACE satellite mission has demonstrated significant technological and scientific achievements. The scientific achievement is truly cross-disciplinary, covering a broad range of NASA’s Earth Science priority areas, including climate-change, global

hydrologic cycles, cryospheric changes, oceanography, geodynamics, and to a lesser extent, atmospheric science and space physics via its radio occultation instrument. Since the launch of the GRACE satellite in March 2002, GRACE has achieved a factor of 100 improvement in Earth's mean gravity field, making its spaceborne gravity sensor the most accurate ever to measure climate change signals. GRACE data have enabled improved confirmation of the Lens-Thirring effect; have allowed the discovery of an asteroid induced Permian-Triassic crater under the Antarctica ice sheet; estimation of recent Greenland and Antarctic ice-sheet and rapid glacier melt; enabled studies of large river basin hydrologic fluxes and continental aquifers; observed ocean tides underneath Antarctic ice shelves; quantified deep ocean bottom in the tropical Pacific, the Southern Ocean, and Arctic Ocean; observed global ocean mass variability and its role in present-day sea level rise; the discovery of multidomal ancient ice structures in Laurentia, modeling of the Tibetan Plateau Moho, and provided new constraints on Glacial Isostatic Adjustment and mantle convection; and observed coseismic and post-seismic deformation associated with Sumatra-Andaman undersea earthquake. These achievements resulted in publications of over 500 referred journal articles, some in *Science*, representing 100 publications per year.

The development and provision of reduced latency, near real-time gravity field data products under the proposed mission continuation will likely improve operational hydrological assessments of terrestrial water storage changes and anomalies from regional water availability and drought monitoring. The relatively precise GPS radio occultation data from GRACE are also likely to become increasingly valuable for improving regional weather forecasts by assimilating these data into operational weather forecast models, as is currently being done by ECMWF/UKMO. A continuing GRACE mission would also lead to potential overlap with planned hydrological satellite missions, including ESA SMOS (2009 launch) and NASA SMAP (2013 launch). The combination of GRACE water storage information with SMOS/SMAP based soil moisture information should yield improved resolution and accuracy of basin scale water budgets. The science impact of these various applications would clearly benefit from a longer GRACE temporal record under a continuing mission, by providing the means to distinguish a climate change signal from year-to-year natural variability.

The proposed mission extension will provide next-generation (RL05) gravity field data products (spherical harmonic and regional 'mascon' solutions) that will have an increased data span allowing better discrimination of inter-annual variability and longer-term secular changes over current (RL04) products. The proposal notes that improved accuracy implies increased spatial resolution and that RL05 will reflect multi-faceted improvements to the data products over RL04 (a projected factor of 3 improvement in accuracy and with the appropriate improvement in spatial resolutions). Some of these improvements include better models of ocean tides and rapid hydrological variability, and improved Science Data System error screening and correction. Additional improvements under the proposed continuity mission include the introduction of a new low-latency (7-day) quick-look level 2 gravity field product directed toward the hydrological community and to be made available on a daily basis. These activities should dramatically enhance the potential for operational hydrological monitoring and drought assessment.

## Weaknesses

The accuracy and spatial resolution of the temporal gravity field solutions are presumably, at present, limited by the accuracy of the so-called background models, including the de-aliasing data products (to correct GRACE data for spatial and temporal aliasing including atmospheric pressure and barotropic oceanic response effects over land and over ocean, respectively), signal (e.g., hydrologic) aliasing and the ocean tide model. However, the latter two effects have been addressed in the proposal. The other potential error sources include signal leakage along land-ocean-ice boundaries, stability of long wavelength gravity signals (e.g., low degree zonal coefficient changes), computation of loading effects especially when using the mascon approach, and adequate separation of various signals. While the list seems long, they are not weaknesses of the proposal, rather, perhaps represent a list of potential improvements which may be feasible during the proposed continued mission time period.

## Value of Data Record and Overall Data Continuity

New results include the verification of the accelerometers at the specified noise levels of  $0.1 \text{ nm/s}^2$ , and the center of mass of each GRACE satellite is maintained at the center of the accelerometer proof masses to within  $50 \text{ }\mu\text{m}$  ( $100 \text{ }\mu\text{m}$  is the requirement). The residual error of the primary GRACE instrument, the K-Band inter-satellite ranging (KBR) system is claimed to be  $<0.2 \text{ }\mu\text{m/s}$  (or  $< 2 \text{ }\mu\text{m}$  in range residual), for the current data product (RL04), versus  $0.3\text{--}0.5 \text{ }\mu\text{m/s}$  from the RL01 data product. The value of data record and its continuity are excellent and robust. Since its launch on March 17, 2002, the GRACE mission has been producing data products with almost an interrupted time series up to the present. The predicted mission life span is through 2013, represents a total mission span of 11 years after launch, exceeding its mission design and requirement. The overall user community currently consists of scientists from hydrology, oceanography, climate-change, glaciology, and geodynamics.

### **Core Mission Data Product Maturity:**

Outstanding       Very Good       Good       Fair       Poor

The level of maturity (Stage I, II, III; III being the most mature) of the GRACE products was unspecified in the proposal, however, it was adequately addressed by the Project team presentation. GRACE Core mission Level-2 data products have been developed, refined and validated (from RL01 to RL04, RL02 was discontinued and RL03 was abandoned to be consistent with GFZ data product release). They have reached a level of maturity that requires algorithm maintenance only. The Level-2 data products and cal/val studies using different regional solutions (mascon, energy conservation approach and regional inversion) have been validated and compared with *in situ* hydrologic data (and models), satellite altimetry and hydrographic data (Argo), and ocean bottom gauge measurements. The Level 2 data product's maturity level is at *Stage III*, and we concur.



In addition, based on the range of science results and applications presented in the proposal the Level 1-2 GRACE product maturity is *outstanding* (i.e. Core mission data product accuracy has been assessed over a widely distributed set of conditions, locations and time periods via several ground-truth and validation efforts). For example, the GRACE gravity anomalies and derivatives (e.g. ET, water storage changes) have been compared against regional hydrological model outputs and measurements over a diverse global range of large basins. GRACE gravity measurements of Greenland ice mass variations have also been compared against other in situ and remote sensing measurements, while GRACE based ocean bottom pressure variations have been compared against sparsely distributed in situ measurements.

Potential collaborations identified in the proposal include Jason-2/OSTM for oceanic and sea-level studies, radar and laser altimetry (not explicitly identified by the mission proposal but could include ERS-1/-2/ENVISAT, ICESat and CryoSat-2) for ice-sheet mass balance studies, ESA's SMOS (Soil Moisture and Ocean Salinity mission) and NASA's SMAP (Soil Moisture Active Passive mission) for constraining soil moisture and ground water storage signals, and ESA's GOCE (Global steady-state Ocean Circulation Experiment) for enhanced ocean circulation and geodynamic studies. In addition, potential synergy exists for NASA's Aquarius (the ocean salinity mission) to constrain the halosteric component of the sea level and to potentially validate the GRACE-observed land water freshening of the ocean.

**Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

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

Strengths

The proposed GRACE mission continuation will provide unique data and information about variations in the Earth's gravity field, and contributes to interdisciplinary science including climate-change science, water cycle and geodynamics. These data and the proposed science activities will contribute to addressing NASA Earth Science Directorate's Focus Areas: Climate Variability and Change, Water and Energy Cycle, and Earth Surface and Interior. Specifically, they address the following NASA Earth Science questions, including: (1) how the global Earth system is changing; (2) how global ocean circulation is varying on interannual and decadal time scales; (3) how changes are occurring in the mass of Earth's ice cover; (4) motions of the Earth's interior and how they impact our environment; (5) how global sea level is changing and being influenced by natural variability and human-induced changes. The proposed GRACE mission continuation also directly addresses the following NASA research objectives to quantify the key reservoirs and fluxes in the global water cycle, and characterize and understand Earth surface changes and variability of Earth's gravitational field. The proposed mission continuation will continue to advance these NASA focus areas and objectives, including:

new retrievals of seasonal ocean bottom pressure changes (climate variability and change focus area); longer records and more precise measurements (sub-300km spatial resolution) of the global water balance including terrestrial water storage changes and ET (Water and Energy Cycle); improved time-averaged gravity field measurements enabling more accurate assessments of mantle viscosity, ice-sheet history, and national gravimetric reference systems (Earth Surface and Interior); relatively precise GPS radio occultations contributing to improved spatial patterns and temporal variability in atmospheric temperature/pressure/water vapor profiles (Weather forecasting and climate change).

### Weaknesses

None.

### **Technical and Cost**

The summary of the Technical & Cost (T&C) Review for GRACE mission extension is rated at *Medium Risk*. There are 1 major risk (USO) and 7 minor weaknesses (5 on instrument/flight systems, and 2 on cost). The two instrument/flight system minor weaknesses are the IPU and ICU. The three minor weaknesses are in the flight systems, including the operation requires a two-satellite system, battery cell problem, and the CESS head sensor thermistors failure. The other 2 minor weaknesses are related to mission cost estimates. They include that “the estimated cost at UTCSR staffing and funding levels remain constant and do not include increased budget for increased staff efforts required in FY10 to generate RL05 data products”, and that the “MOU between DLR and NASA for GRACE operations ends at the end of 2009, and that the negotiation the MOU extension of the MOU through 2015 will be in place before the end of 2009”. For the last concern was addressed by the mission project presenter in that the negotiation with DLR is currently underway.

One week after launch, the GRACE-1 USO failed, and it has been switched to the redundant USO, which have been used for the past 7 years. This is identified as the major risk. At present there have been no signs of intermittent power comment to the redundant GRACE-1 USO or the two GRACE-2 USO's. In May 2007, GRACE-2 experienced an apparent failure in one side of the Instrument Processing Unit (IPU), and since switched to the other side. Operation has been nominal since then. In June 2007, an IPU software upgrade has apparently corrected the problem of KBR “missed interrupts” which has caused data outages of 3-24 hours in summer and fall 2006. There were two accelerometer main Instrument Control Unit (ICU) failure or problem for GRACE-1 and GRACE-2 in May 2003 and September 2006, respectively. After switching to redundant ICUs, the operation has been nominal.

The GRACE-2 battery experienced a battery cell failure in August 2007. The battery on GRACE-1 exhibited a temporary cell short in November 2006, with occasional periods of a weak cell since then. The satellites were designed to operate with one failed cell. If a second cell were to fail, science data collection would be constrained to periods of favorable sun beta angles. The Project presentation addressed this concern, that if

another battery cell fails, it would shut down the science instruments for 45 days in every 162 days, causing a significant impact on resolution of science data (L1 and L2) quality, resolving seasonal and episodal signals, however, secular signals would not be affected. However, the Project team presentation indicates that there is no apparent battery problem at present, and that the battery is closely monitored and being fine-tuned to maximize its lifetime.

In summary, the T&C Panel rated that the GRACE mission extension is at medium risk, and we have no further concerns or open questions.

### **National Needs**

The National Interests Panel rated the GRACE mission extension as having *Very High Utility*. The GRACE data set and proposed continuity mission meets a range of National needs. First, GRACE provides a unique measure of Earth's temporal gravity field, which can be used to measure and interpret ocean circulation and sea level rise, ice-sheet mass balance, and terrestrial water storage including groundwater variability. No other current satellite provides this type of measurement. However, the clearly identified 'application' is that GRACE contributes substantially to the *National Vertical Datum* needs (by the National Geodetic Survey). GRACE also provides relatively precise GPS radio occultation information. These data are currently being used in operational weather forecasting and are being developed for new hydrological applications. Improved weather forecasts and regional assessments of water availability, drought impacts and groundwater storage are clearly important to National needs. A longer GRACE data record will also improve the diagnosis and understanding impacts of anthropogenic climate-change to ocean circulation, global heat transport and sea level rise, which are also critical to furthering our understanding of global climate change impacts and our future vulnerability to these changes. The proposed mission extension tasks include providing low latency data products for hydrologic assimilation effort. The proposed effort will significantly enhance GRACE's ability to contribute to National Interests.

### **Other Comments**

The proposal's quality and completeness is sufficient for the review. The Project PI has adequately addressed all of the Reviewers' questions.

## **ICESat Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline; list them: in-guide funding for FY10-11 and augmentation (but below optimum level) for FY12-13.
- Continuation of projects with reductions to the current baseline. List them
- Close-out and finalize dataset

*Science Capability:* The main objective of the ICESat mission is to determine the mass balance of polar ice sheets and their contributions to current sea level change. Combination of high precision laser ranging (Geoscience Laser Altimeter System (GLAS)) with special attitude calibration methods enables ICESat to monitor ice sheet thickness changes with unprecedented accuracy and details, providing improved mass balance estimates of the Greenland and Antarctic ice sheets. Recent science highlights of the mission also include mapping of Arctic sea ice freeboard distribution and the decline of sea ice cover, the first global mapping of vegetation canopy height, characterization of terrestrial water storage, and retrieval of atmospheric aerosols and blowing snow distribution.

*Climate Science:* ICESat is an important multi-disciplinary mission contributing to the objectives identified by the IPCC Assessment Reports, the Arctic Climate Impact Assessments (ACIA) and the National Research Council's Decadal Survey. The mission addresses several critical issues of climate science, such as the mass balance changes of polar ice sheets and resulting sea level rise, the decline of Arctic sea-ice pack and the possible opening of transpolar shipping routes. Other goals include mapping and monitoring atmosphere-cloud height, aerosol distribution, vegetation canopy heights and global biomass estimates. Moreover, ICESat data also provide important boundary conditions for ice sheet and atmospheric modeling.

The response of the cryosphere to global warming has significant ramifications for society. The ability to predict rates of global climatic change, melting ice, and rising seas through the next century relies on an accurate understanding (and modeling) of glacier and ice sheet behavior. Recent observations have revealed dramatic changes in the behavior of many ice streams and outlet glaciers in Greenland and Antarctica, ranging from complete shutdown of ice streams to manifold increases in velocity. In addition, iceberg calving in Antarctica has increased in frequency and millennia-old floating ice shelves are disintegrating. These observations challenged the traditional view of ice masses responding sluggishly to external forcings. Consequently, it is important to investigate these rapid changes and put them in long-term context in order to understand how the ice sheets may respond to future climate changes. The National Research Council (NRC) Decadal Survey has ranked the continuation of the ICESat mission (ICESat-II) to be one of its highest priority recommended missions, to be launched in the 2010-2013 timeframe. ICESat-II is now under development for launch in 2014(15).

Operating ICESat-I until 2011 will provide critically needed data about the evolution of the cryosphere and limit the gap between the ICESat missions.

*Future Products:* The principal science objectives of ICESAT are polar ice-sheet mass balance, atmosphere cloud heights and aerosol distribution, land topography, vegetation canopy heights, sea-ice thickness and freeboard mapping and changes. The panel was impressed by scientific contributions in all of these areas, despite the mission's technical difficulties. However, with reduced duty and power to the one remaining laser, some of these objectives can no longer be adequately addressed (e.g. atmosphere, vegetation). Therefore the panel suggests that additional algorithm development should be limited for improving the accuracy of ice sheet altimetry products. Especially important is further refinement and validation of higher level products, such as firn compaction and sea ice freeboard, as well as the detection of blowing snow distribution and clouds from the 1064 nm laser channel.

*Instrument Health:* The Technical and Cost Panel has classified the ICESat mission as high risk due to problems with the GLAS lasers. The system has only one operational laser left, which is currently operating at a low energy level of ~ 2 mJ. Preliminary results presented to the panel suggest that the continuation of the mission will allow the collection of useful measurements over most of the ice sheets as long as the laser energy doesn't decrease below a critical level. However, due to the increasing loss of useful returns, the degradation of ranging accuracy and increasing uncertainty in the recovery of pointing direction, the accuracy of surface change determination eventually is expected to fall below the science requirements, especially over the steep, marginal area of the ice sheets. Unless a catastrophic failure occurs, the laser quality will degrade gradually. Therefore a set of criteria, based on the cryospheric science requirements should be established for the mission termination. As the 2007 Senior Panel noted, when the accuracy of laser quality degrades so that the accuracy of surface change measurements are marginal, the accuracy of elevation measurements could be still sufficient for DEM production by collecting data along unobserved subcycles of the currently used 91-day repeat orbit. Therefore this panel recommends that NASA should convene an independent review panel/board to evaluate the best strategies for collecting observations during the remaining operation periods, and for terminating the mission.

*Summary:* The ICESat mission measures the Earth's surface and atmosphere with unprecedented three-dimensional detail. It has delivered critically needed information about the temporal evolution of polar ice sheets and sea ice cover, provided estimations of global distribution of vegetation canopy height and biomass, atmospheric properties and land surface hydrology and precise elevation data for improving the terrestrial reference frame. As the Decadal Survey notes, the gap between the ICESat mission and its follow-up (ICESat-II) is critical to monitoring and understanding cryospheric changes. With each successive operation period ICESat will continue to reduce this gap. Continuing the ICESat mission is highly beneficial to NASA and to the global scientific community and therefore this panel recommends continuing the mission at least until completing the 2011 winter campaign. The proposed data acquisition, product development and validation efforts are key to meeting NASA's cryospheric objectives. However, due to the loss of the 532 nm laser channels and the significant reduction of the

1064 nm laser energy ICESat is no longer able to map land surfaces, vegetation or provide atmospheric products. The panel finds that maintaining focus on the primary objective of mapping ice sheet surface changes and reducing focus of secondary objectives, with associated cost savings, warranted. The panel recommends in-guide funding for FY2009-2011. Augmentation is suggested for FY2012-13, but below the requested optimum level for mission closing and data reprocessing.

### Scientific merits

Outstanding      X Very Good       Good       Fair       Poor

*Strength:* The ICESat mission has the primary scientific objectives to accurately measure the melting or growth of Earth's polar ice sheets and their impact on global sea level rise, the decline of the Arctic sea-ice pack, atmosphere-cloud heights, aerosol distributions and the Earth's radiation balance and temperature; and finally vegetation canopy heights and global biomass estimates. ICESat is detecting ice-sheet elevation changes with a accuracy that meets the prime science objective of the mission and suitable for derivation of accurate estimates of ice sheet mass balance changes and for characterizing the dynamics behavior of outlet glaciers. ICESat observations detected surface expressions of subglacial water movement, resulting in the discovery of several active, widespread subglacial water systems under the Antarctic Ice Sheet. ICESat data enabled the refinement of ice sheet grounding lines, the development of improved ocean tide models over regions covered by sea ice and ice shelves, and the generation of accurate digital elevation models of the Greenland and Antarctic ice sheets. For the first time ICESat satellite laser altimetry enabled the monitoring of sea ice thickness and depicted the decline of sea ice cover in the Arctic region. Estimates of sea ice thickness from the measured sea-ice freeboard together with the calculation of the age of multiyear ice indicated that most of the observed ice loss are explained by the decline of multiyear ice cover. Other scientific accomplishments include measurements of river discharge, lake and wetland water storage; the improvement of the geoid in the Arctic region, and retrieval of atmospheric aerosols and blowing snow distribution. The simultaneous operations of the ICESat and GRACE satellites enables the combination of altimetry and gravity data for improving the mass balance estimates of polar ice sheet by separating the signals related to the Glacial Isostatic Adjustment and ice sheet thickness changes. The land topography application compliments existing data products such as SRTM/ASTER DEMs, which are widely used for land-cover and hydrologic research and applications.

*Weaknesses* Due to the problems of the GLAS laser instrument, the record of surface elevation changes is not continuous, but limited to 1-month long operational phases covering 33-day subcycles of 91-day repeat orbits, repeated 2-3 times each year. This revised operation also results an increased distance between neighboring ground tracks. While the resulting coverage is sufficient for deriving long-term trend of surface elevation changes and estimating ice sheet mass loss on a drainage basin scale, the recovery of annual and seasonal changes, especially at the marginal zone of the ice sheets characterized by complex topography and ice dynamics, is still problematic and subject of ongoing research.

The ICESat mission is the first that provides an accurate record of ice sheet surface elevation changes on a global scale. ICESat observations combined with data from NASA's Operation ICE Bridge and the planned ICESat-II mission will provide a long enough time series to establish the climate sensitivity of ice sheet mass balance and decadal trends.

**Core mission data product maturity;**

Outstanding       Very Good       Good       Fair       Poor

Core ICESat mission data products include global altimetry and atmospheric products as well as altimetry products developed to characterize different surface types (ice sheet, land, sea ice, ocean). While the general processing is the same for all data, corrections are determined independently for each mission phases and differences in laser performance and satellite operations result in different accuracy. The precision orbit and attitude determination of the ICESat spacecraft, which is required to determine accurate surface elevations, are exceptional, delivering radial orbit accuracy of 2-3 cm and pointing knowledge of better than 1.5 arcsec. The validation of the altimetry products, mostly restricted to crossover analysis, shows that the precision of surface elevation measurements met the requirements for the mission for the best calibrated data sets. Further work includes the validation of range error corrections to account for waveform distortion caused by FOV shadowing, saturation, and atmospheric scattering, the validation of surface reflectivity, and the atmospheric optical depth derived from 1064 ocean surface returns.

Simultaneous operation of the ICESat and GRACE satellites enables the combination of altimetry and gravity data for improving the mass balance estimates of polar ice sheet by separating the signals related to the Glacial Isostatic Adjustment and ice sheet thickness changes. Other synergisms include combined use of ICESat data with satellite radar altimetry (JASON for ocean and seal level studies; ERS, ENVISat, CryoSat-2 for ice sheet mass balance and sea level change), with stereo imaging or InSAR for topographic mapping (ASTER, ALOS, TERRASAR-X), and with MODIS imagery and atmospheric data for characterizing surface conditions. Data from a variety of sensors (e.g., MISR, POEM, TOMS, Cloudsat, AMSR-E, etc.) can be combined with data from ICESat's atmospheric channels for atmospheric science studies.

**Relevance to NASA Science Goals:**

Outstanding     Very Good       Good       Fair       Poor

*Strengths:* The ICESat mission provide critically needed information for NASA's Earth Science Focus Area of Climate Variability and Change to describe ice sheet elevation change, sea ice thickness change, vertical cloud structure and ocean topography. In particular ICESat has a demonstrated potential to provide improved estimates of ice sheet mass balance and describe the evolution of sea ice thickness on a regional scale. By measuring surface topography ICESat also provides an important boundary condition for ice sheet and atmospheric modeling.

In addition to major contributions to the Climate Variability and Changes focus area the ICESat mission provides information to each of the other five Earth Science Focus Area and associated core questions.

*Weaknesses:* None identified

**Technical and Cost**

The panel concurs with subpanel forms.

**National Needs**

The panels concurs with subpanel forms

**Other Comments**



## **Jason-1 Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined
- Continuation of projects with the proposed Optimal Scenario baseline
- Continuation of projects with reductions to the current baseline
- Close-out and finalize dataset

Sea surface height and changes to ocean circulation rank highly among the most critical of climate measurements. Ongoing uncertainty in future sea level rise, coupled with the considerable climate impact that could arise from changes to ocean circulation, underscore both the scientific and practical needs for uninterrupted, high quality altimetry.

Jason-1 has completed its primary gapfiller mission (between TOPEX/Poseidon and OSTM), but continued operations in conjunction with T/P and OSTM promises enhanced understanding of sea level and the processes that alter it. The most important science contributions of J-1 arise from its ability to provide backup to OSTM for critical sea level data, the improved coverage provided with multiple altimeters, and the ability of J-1 operating in combination with OSTM to provide >50% better spatial resolution than is available by any other means. The J-1 orbit was chosen to maximize science from the J-1/OSTM combination. The altimetry community has called out the importance of multi-satellite constellations, which can perform science that cannot be accomplished with a single altimeter.

J-1 involves close partnership with CNES and more recently with NOAA/EUMETSAT. Science investigations involving all three satellites were recently awarded by NASA/CNES for the period 2009-2012. Operational partners such as NOAA/NCEP advocate for the operational benefit of J-1 as an adjunct to OSTM due to increased coverage and enhanced spatial resolution. Operational uses include improved safety for shipping and boating from storm monitoring and wave height measurement, river and lake monitoring, and hurricane forecasting.

Mission health is moderate, though the mission is largely single string. Estimated probability of failure is 23% in 2010 and 33% in 2011. There has been no significant change in spacecraft health since the prior Senior Review. As noted below, however, failure has very high consequences and should be addressed carefully.

Science products are mature, having been used for cross-calibration with OSTM during 2008. Ongoing enhancements to some products are still being made.

**J-1 should be approved for mission extension at a funding level for the Optimal Scenario.** J-1 continues to contribute in substantial ways to both scientific breakthroughs and national needs operations. Extended funding through the planning period of this review is important to avoid premature transition to decommissioning. However, there is

strong concern about J-1 not being decommissioned as a result of catastrophic failure. The consequence would be to leave J-1 in an orbit that makes collision with the non-functioning T/P likely, producing an unacceptable level of debris in this critical orbit for satellite altimetry. The mission team is monitoring the situation and preparing for immediate decommissioning should the spacecraft health deteriorate (loss of the final comm transmitter would make decommissioning difficult, which is a particular concern). However, the situation has critical consequences that go beyond this mission alone. Though ongoing operation is highly desirable, **NASA and CNES should establish a joint agency-level decision process to monitor J-1 health and ensure a conservative process for decommissioning.**

Notably, the Senior Review believes the value of J-1 as a scientific (not operational) backup to OSTM was underemphasized in the proposal. This may have resulted from faulty communication between NASA and missions and did not influence the Review in either a positive or negative way. However, discussion revealed that there is no scientific backup to OSTM other than J-1 and none will be available until the launch of J-3 planned for 2013. Though OSTM is functioning well at the current time, this fact is considered important to the value of an extended J-1 mission.

Finally, the mission team is **encouraged to promote use of J-1 for new water vapor science**, both through their community interaction and through ROSES proposals. This appears to be an additional area in which J-1 could contribute breakthrough science given its long data record of this important climate parameter. Existing J-1 data products (wet path delay) support water vapor science, though some additional work is required on the part of the individual investigator to extract the right information from the data records.

### Scientific merits

Outstanding       Very Good       Good       Fair       Poor

J-1 science is excellent, though more limited in scope than that of the multi-sensor platforms. Over the last two years, J-1 has focused on its primary missions: a) monitoring to fill the gap between T/P and OSTM, and 2) cross-calibration with OSTM following its launch in June 2008. Additional science accomplishments during this period largely reflect the importance of extending the long time-series started by T/P, though important new science at eddy-scales has been revealed through the recent availability of higher-resolution data from the combination of J-1 and OSTM. Science objectives for the extended mission focus on the ability of J-1 (working in conjunction with T/P) to provide enhanced ocean topography data at high resolution. This can be used for both improving historic datasets and for new discoveries.

Particularly valuable aspects of J-1 science include:

- Longer data set will help understand better tidal biases, especially in coastal regions.

- Combination of OSTM and J-1 data in the interleaved orbit is necessary to resolve mesoscale features, which results in improved effective spatial resolution by almost a factor of 3 over what is achievable from OSTM alone.
- The need to operate J-1 in this capacity has become even greater since many of the satellites used in the past to provide additional altimeter coverage (e.g., GFO, ERS-2, and ENVISAT) have been lost or are operating in a reduced capacity.
- Ocean topography can be significantly improved by combining altimetry and geoid data from GRACE.
- Discrepancies between ARGOS and other in-situ sensors can be resolved with longer altimetry records. Improvements in the sea level rise budget are enabled.
- If OSTM fails, J-1 has enough fuel to be repositioned to the science orbit and satisfy all L1 science requirements.

### *Strengths*

1. Continued operation of J-1 sea surface height measurements with resolution at least twice as good as would be otherwise possible. The new orbit configuration will dramatically increase the effective temporal and spatial sampling of the two satellites (J-1 and OSTM), which will significantly reduce the sampling error in the altimeter record. This supports science that would not otherwise be possible, addressing eddy processes and their role in large-scale ocean circulation.
2. The science team has developed expertise in retroactive science - the ability to use new measurements that enable refinement of prior datasets. By better understanding fine scale ocean structure, for example, they are able to improve prior global ocean surface topography data. Further, by continued analysis of the sea level anomaly data and geophysical corrections such as surface wave height and wet path delay collected during the cal/val phase, this will contribute to improved global sea surface height (SSH) and associated science. The primary accomplishment is improving understanding of ocean tides in coastal regions, an obvious contributor to understanding how rising sea levels will impact coastal populations. This reanalysis has significant implications for climate science with its need for long temporal baselines having high quality.
3. Enhanced spatial resolution has allowed the science team to make entirely new discoveries as well as improve prior datasets. The recent identification of zonal jet-like features in ocean circulation is a primary example. There is some possibility that the earliest indications of changes to ocean circulation arising from climate change could occur at these scales.
4. Widespread use of data beyond physical oceanography, such as by the ocean biology community.
5. Outstanding publications record: to date, 2,812 publications have been produced based on T/P and Jason-1 data—an average of 175 per year.

### *Weaknesses*

1. J-1 science is highly focused on a small number of Earth science variables (though of appropriate scope for a mission of its size).
2. The ability to observe water vapor is not adequately exploited by the science team.

*Value of data record and overall data continuity*

1. The science team has properly recognized the challenge of separating spatial and temporal elements of ocean surface topography. Accomplishing this is essential to understanding how climate change impacts sea level, and revealing how ocean currents change in response. Among other things, it is important to know whether observed features are transient over decadal scales or permanent features of circulation. Both multi-satellite datasets and long-time series are critical in this process. Fortunately, J-1 has completed its role in bridging between T/P and OSTM. With extended mission funding, it can focus on further refinements to our understanding of the complex space-time variability of ocean topography.

**Core mission data product maturity;**

X Outstanding       Very Good       Good       Fair       Poor

Core mission data is at a high level of maturity, driven by the need for these data to be a reference for cross-calibrating with both T/P during 2001-02 and OSTM during 2008. The mission produces five core data product families, all mature. Two of the five envision no further improvements, while the other three expect ongoing enhancements.

The primary core product (SSH) is well calibrated and has provided valuable continuity from the T/P mission. Data are accessible to the scientific community through well-maintained data distribution systems. The maturity of the data product is demonstrated in two important ways. First, it is used in science that is not directly related to the core use of the product. Many scientists in the fields of biology, biogeochemistry, etc., use ocean altimetry data to explain observations made by in-situ and other satellite sensors in coupled physical-biogeochemical modeling. Second, SSH is widely used by operational groups, as is well-documented in this proposal.

The newer data products for uses like ocean topography (combining altimetry with GRACE) data are not as mature, nor are the attempts to reconcile ARGOS with altimetry data. However, these efforts seem to be covered by other budgets (such as ROSES) along with funding by other national and international agencies.

Synergies with other altimeter missions and GRACE are already actively pursued. Additional collaboration in water vapor science may be possible through cooperation with water vapor instruments on other platforms (AIRS being one that has expressed interest).

**Relevance to NASA Science Goals:**

X Outstanding       Very Good       Good       Fair       Poor

J-1 claims relevance to five of the 24 specific NASA Earth Science questions, but likely contributes in an indirect fashion across more than these five.

### *Strengths*

1. The mission's focus on physical oceanography allows it to address aspects of NASA science that cannot be addressed at all by other non-altimeter missions, notably topography/circulation and their role in climate change.
2. The science team has identified new science enabled by the ability to work at higher spatial resolutions, including the role of eddies. It is probable that this work is not reproducible by OSTM alone. Since such science provides the earliest indications of how ocean circulation responds to climate change, it is critical to NASA's climate science mission.

### *Weaknesses*

1. J-1 is largely focused on fine-tuning science (except as noted) rather than fundamental breakthroughs.

### **Technical and Cost**

Technical and cost is rated "Medium Risk", with cost risk rated "Low". Please refer to sub-committee report, which is accepted as is.

### **National Needs**

National needs is rated "Very High". Please refer to sub-committee report, which is accepted as is.

### **Other Comments**

The quality and completeness were sufficient to perform the review. The proposal is a bit repetitive, but some of this is an effort to comply with the mandated proposal structure.

From a NASA programmatic perspective, J-1 provides an excellent example of the value of both multiple observing platforms and long time-series in performing science that involves coupled space and time variability, particularly over seasonal to decadal time scales.

## ***QuikSCAT Mission Review***

### **Finding (2010-2011):**

- Continuation of projects with augmentations to the current baseline

Recommend “above guidelines funding” for 2012 and 2013, which maintains funding at 2011 level (adjusted for inflation) for a total of \$3.9M.

The SeaWinds scatterometer on QuikSCAT has performed superbly for almost ten years, and it has been the only U.S. mission producing such a long-term, global ocean vector winds data series appropriate for scientific research. These measurements have been recognized by the 2007 NRC Decadal Review as required to meet NASA science goals; and this has been reflected in NASA’s climate, coastal, and hazards science plans. Further, for the foreseeable future, QuikSCAT is the only global ocean vector winds data set appropriate for climate studies to date. The continuation of the QuikSCAT mission, and its cross-calibration with other scatterometers such as the EUMETSAT ASCAT or the forthcoming Indian and Chinese scatterometers, provides the only means by which this ocean vector wind data set can be extended into the future as per Global Climate Observing System (GCOS) observing principles.

In addition to scientific contributions, QuikSCAT data is also available in near real time for operational weather analysis and forecasting applications and are routinely assimilated in numerical weather prediction models at the NOAA National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasting (ECMWF), and other European and Asian meteorological agencies. The National Interest Panel ranks QuikSCAT as “very high utility”.

The QuikSCAT spacecraft and instrument are healthy but down to single-string and the probability of completing the extended mission is estimated to be only 50%. Science data will continue to be acquired using the proven mission operations and data analysis capabilities at JPL, BATC, LASP, GSFC and PODAAC. Team members and mission responsibilities are the same as in the past, assuring a low risk and effective continuation of the basic mission. Having completed nearly ten years of successful operations, the QuikSCAT team is capable and efficient. Operations have been automated, processes and procedures have been refined, lessons-learned and system idiosyncrasies have been documented. Further modest enhancements and some new products are planned and the proposed budget is extremely modest!

## Scientific merits

Outstanding       Very Good       Good       Fair       Poor

QuikSCAT is a NASA research mission carrying the SeaWinds Scatterometer designed to make global measurements of surface radar backscatter cross-section and accurate retrievals of surface wind speed and direction over the ice-free global oceans.

## Strengths

- QuikSCAT is the primary source of global ocean surface wind vectors and wind stress for science applications such as ocean and climate model forcing, air-sea interaction studies, and the study of unusual weather and climate phenomena such as hurricanes and El Niño.
- QuikSCAT backscatter data have become a significant resource to the cryosphere community for sea-ice monitoring, estimates of snow accumulation over ice sheets, and the operational tracking of icebergs at the National Ice Center.
- QuikSCAT data are routinely assimilated in operational numerical weather prediction models at meteorological agencies worldwide, and have revolutionized the analysis and short-term forecasting of winds over the oceans.
- In 2008, the prestigious William T. Pecora Award given by the Department of Interior and NASA to the QuikSCAT team in recognition of its “advancement of Earth science research and contributions toward improved environmental prediction”.
- QuikSCAT data are used routinely in operational centers around the world for the monitoring, analysis, and prediction of high impact weather such as tropical and extratropical cyclones. These data are of particular importance in those regions where no routine aircraft surveillance is available (i.e., everywhere except the Caribbean and Atlantic oceans U.S.A.).

## Weaknesses

- There is a high probability that there will be a gap in the ocean vector winds time series because the QuikSCAT follow-on mission is not likely to be launched before 2016.
- Funding guidelines for 2012 and 2013 would leave the mission operations teams at JPL, Ball and LASP severely understaffed, unable to respond to flight or ground system anomalies and unable to reliably deliver core or near realtime data products. JPL management has determined that operating the mission on those terms poses unacceptable risk and without \$3.9M additional funding would require QuikSCAT to cease operations in mid-year 2012.
- The other currently available scatterometer product (ASCAT), which could be used in the event of a shortened QuikSCAT mission, has a smaller swath and significantly reduced spatial sampling. In addition, there are inconsistencies between the QuikSCAT and ASCAT wind retrievals, which would adversely affect the climate time series.
- Other scatterometers from the India Space Agency and the Peoples Republic of

China which will be launched during the next 3-4 years could be cross-calibrated using the QuikSCAT to extend the ocean vector winds climate series; however much work is needed to establish data sharing policies and other collaborative agreements.

### **Value of data record and overall data continuity**

Due to its longevity and superior spatial and temporal sampling, the QuikSCAT data set constitutes the only global ocean vector winds data set appropriate for climate studies to date. The continuation of the QuikSCAT mission, and its cross-calibration with other scatterometers such as the EUMETSAT ASCAT or the forthcoming Indian and Chinese scatterometers, provides the only means by which this ocean vector wind data set can be extended into the future as per Global Climate Observing System (GCOS) observing principles.

#### **Core mission data product maturity;**

Outstanding       Very Good       Good       Fair       Poor

QuikSCAT core mission products have excellent maturity. Having completed nearly ten years of successful operations, the data capture and science data processing are efficient and routine. Operations have been automated and lessons learned and system idiosyncrasies have been documented. The QuikSCAT core data products can be divided into five distinct classes: Level-1 radar backscatter; Level-2 swath-based ocean vector winds; a near real-time wind product; Level-3 mosaic wind product; and a variety of research data products.

The QuikSCAT Level 2B products are swath-based ocean vector wind products, which address the main science goals of the mission. A similarly organized Level 2A cross section product containing calibrated radar cross sections has increasingly been used by ROSES investigators for non-ocean vector wind applications, such as ice, snow, vegetation, or urban studies.

A near real-time wind product is operationally produced at NOAA and JPL and supported by the QuikSCAT project. This product is used by NOAA forecasters and is made available via the internet for other users.

Level 3 mosaic wind products are produced and made available by the NASA Physical Oceanography DAAC (PODAAC) at JPL.

A variety of research products, derived from the Level 1 and Level 2 data, have become standards in the science and operational community. Most notable are the ocean vector wind products produced by Remote Sensing Systems; the high resolution hurricane winds produced for NOAA by BYU; the QuikSCAT project; the wind stress product produced by FSU; ice operational products produced for the National Ice Center by BYU; and the OSCAR surface currents produced by combining QuikSCAT and altimeter data.



**Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

QuikSCAT relevance to NASA science goals is outstanding, and the ocean vector wind measurements enable NASA to meet many of its Earth Science plans and objectives. The Climate Variability and Change focus area specifically calls for systematic ocean vector winds measurements for the observation of ocean circulations. QuikSCAT also contributes to the Water and Energy Cycle focus area by providing measurements of sea-ice, and water transport into the oceans, and to the Weather focus area goal of enabling improved predictive capability for weather and extreme weather events. Thus, the Mission addresses six of the Science Questions in NASA's Earth Science Plan dealing with changes in: global ocean circulation; global precipitation, evaporation, and the cycling of water; the mass of the Earth's ice cover; weather forecast duration and reliability; and predictions of climate variability and change.

**Strengths**

The nearly decadal ocean vector winds data record has enabled a number of climate studies and results not possible without QuikSCAT's contribution. For the first time, a number of climatologies have been developed to help characterize winds over the ocean.

- Risien and Chelton [2006, 2008] provided the interactive Climatology of Global Ocean Winds based on 5 years (August 1999-July 2004) of QuikSCAT satellite measurements of wind speed and direction, as well as its spatial derivatives (wind divergence and stress curl), and show that persistent small-scale features resolved by the QuikSCAT data make evident 'topographic, SST gradient, and ocean current influences on surface winds'.
- Sampe and Xie [2007] focused on high winds (> 20 m/s), based on seven years of QuikSCAT data. Extreme high winds are not well represented by models, and the QuikSCAT observations provide evidence that over coastal regions, land orography is the major cause of high winds, in the northern hemisphere, however, they are more common in the open Southern Ocean.
- Liu et al. [2008] generated a climatology of the wind power available over the oceans. The QuikSCAT data reveal regions of high wind power associated with flow distortion by land, wind channeled by land topography, and buoyancy effect on turbulent stress driven by ocean fronts. These results are of importance for generation of electricity by ocean wind farms.
- Milliff, van Loon, and Morzel [2009] have recently used QuikSCAT to provide new insights into global weather phenomena, namely the El Niño/Southern Oscillation (ENSO) warm events that have important social consequences.
- Lee and McPhaden [2008] studied the oceanographic climate implications of the

QuikSCAT and ERS winds and altimeter sea surface height observations on the decadal variability and connections of oceanic and atmospheric circulations in the Indo-Pacific region. In particular, the scatterometer and altimeter data suggest an anti-correlated decadal variability of the meridional overturning circulations (MOCs) and heat transports in the Pacific and the Indian Oceans, such that the Pacific- and Indian-Ocean MOC play opposite roles in regulating tropical heat content that is important to interannual and decadal climate variability.

- Minobe et al. [2008] studied the climatic influence of the Sea Surface Temperature fronts in modulating the winds and wind stress using a combination of operational weather analyses, satellite observations, including QuikSCAT, and an atmospheric general circulation model. Their results revealed that there are mechanisms that provide a pathway by which the Gulf Stream can affect the atmosphere locally and possibly also in remote regions by forcing planetary waves.
- Chelton et al. [2006] have continued to use QuikSCAT ocean vector winds and a Weather Research and Forecasting (WRF) mesoscale model to gain a better understanding of the response of tropospheric winds to the small-scale surface winds that are generated by SST. They observe that presence of small-scale surface wind divergence alters the vertical mixing of momentum near the top of the troposphere, but has relatively little effect on the vertical mixing of heat. From these idealized simulations, they infer that the mechanism for communicating surface divergence to the tropopause may be dominated by vertically propagating gravity waves.
- Nghiem et al. [2007] used QuikSCAT to study the extent of Arctic perennial sea ice, the year-round ice cover, and his results showed that found that it was significantly reduced between March 2005 and March 2007. QuikSCAT data also revealed potential mechanisms contributing to the perennial-ice extent loss: ice compression toward the western Arctic, ice loading into the Transpolar Drift together with an acceleration of the Transpolar Drift carrying excessive ice out of Fram Strait, and ice export to Baffin Bay. Dynamic and thermodynamic effects appear to be combining to expedite the loss of perennial sea ice.
- Two novel applications of QuikSCAT data that will result in improved monitoring and understanding of tropical cyclones in the future. First, Gierach et al. [2008] have developed a new method for identifying tropical disturbances using a combination of surface vorticity derived from QuikSCAT winds and IR cloud top temperature from GOES and shown how convection and surface vorticity become more closely collocated as the system develops. Also, Williams and Long [2008] have developed a new retrieval method for hurricanes which supplements the QuikSCAT observations with a simple hurricane model to obtain hurricane circulations and centers which are significantly improved relative to earlier retrieval algorithms.

## **Weaknesses**

None perceived

## **Technical and Cost**

The technical aspects of the proposal are excellent. As noted above, the technical aspects of the mission have been streamlined over the 10-y period of operation. The budget is minimal and the additional \$3.9M in the optimal budget is more than justified by the continued impacts on operations as well as research outcomes.

## **National Needs**

QuikSCAT serves national needs by providing a unique dataset that is vital to improved monitoring of high impact weather that affect national interests. Today, OVW measurements from QuikSCAT are an intrinsic part of everyday forecasting and warning processes at NOAA National Weather Services (NWS) operational centers and offices. The high impacts of the loss of QuikSCAT data on NWS products and services are listed in the NOAA report by Jelenak and Chang [2008]. For example, from Fall 2006 through 2008, the Ocean Prediction Center (OPC) identified and issued warnings for 115 separate extratropical cyclones (64 events in the Atlantic and 51 in the Pacific) that reached hurricane force (HF, wind speeds > 64kts) intensity. Further, a study by Ahmad et al. [2008] investigated the detection of hurricane force wind events in extra-tropical storms from October 2007 through May 2008, by QuikSCAT, ASCAT on European METOP-A satellite, in-situ data such as buoys and ships, and NCEP Numerical Weather Prediction model analyses. During this eight month time period, QuikSCAT identified 195 hurricane force events; ASCAT identified 2, ships and buoys together 15, and NCEP NWP model analyses 38. Based on this study it was concluded that the loss of QuikSCAT data would result in an 80 to 90% loss in detection capability for HF extratropical cyclones.

Further, the National Needs Panel identified the requirement for coastal wind measurements. Many agencies identified high utility could result by reducing the “land-mask” and extending wind retrievals closer to the coast. This panel agrees that the QuikSCAT project should try to improve the wind vector product with priority for North America coastal waters.

Therefore, an extension of the current data set will continue to serve these needs as well as improving the utility of the dataset for climate studies.

## **Other Comments**

While the QuikSCAT spacecraft and instrument are healthy and capable of completing the extended mission, there are concerns about the lack of back-ups for several critical satellite systems and one instrument subsystem. These are fully documented in the proposal; however, in the light of full disclosure they are listed below:

## Satellite

1. The primary and back-up GPS receivers have both had failures, and the system has been operating since March 2007 on six of twelve receiver channels in the primary subsystem. Mitigation: A ground processing approach using ground station angle tracking data was developed to provide a full backup capability in case the on-board GPS function is lost.

2. The wideband science telemetry transmitter back-up unit was powered-on following a failure of the primary in July 2006 after 7 years of trouble free service; and the back-up wideband transmitter is expected to operate for many years. **Mitigation: NONE - with no other path for the science data downlink, a second failure would end QuikSCAT's science mission.**

3. The Power Control Unit (PCU) provides charge control for the battery and fault detection/response functions, and the back-up PCU failed in November 2008.

**Mitigation: NONE -if the primary PCU were to fail, the spacecraft could not longer support the mission objectives and the QuikSCAT science mission would be terminated.**

4. The spacecraft power subsystem battery is performing well, but the sole spare common pressure vessel (CPV) was connected in November 2007 to compensate for a single weak cell that is unable to hold a charge during eclipses. Mitigation: Procedures for operations are in place that are able mitigate this (and any further) battery degradation by setting the charge control parameters, fault limits and allowable discharge voltage appropriately.

## SeaWinds Instrument

Antenna spin bearings are the only elements that have shown any degradation, and they exhibit a phenomenon known as “cage wind-up” where the friction in the bearings increases temporarily due to imperfections in the mechanical assembly. For the past several years, these events have increased in frequency, and their severity will continue to worsen. Mitigation: Because the motor has a significant torque margin, it is reasonable to expect several more years of service. Further, if the motor is unable to supply the torque required, then the rotation rate will decrease until bearing friction balances the available torque. Even under this scenario, useful science data would be captured, so the mission would remain viable.

## **SORCE Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;  
Augmentation as requested in “Optimal Scenario”
- Continuation of projects with reductions to the current baseline.
- Close-out and finalize dataset

Continuing the SORCE (Solar Radiation and Climate Experiment) irradiance observations into cycle 24 is important to improving our understanding of the solar variations in total and spectral irradiance, thus improving modeling of the solar cycles. Our findings support the following augmentations to the current in-guide budget

1. Optimal budget values from the 2007 Senior Review budget values for FY10-FY11 are needed to meet the baseline mission. The in-guideline budget from HQ for FY12-FY13 includes a reduction in funding of 22% from the 2007 Senior Review Results for N2 Guideline budget. Other missions generally had 5% cut. This apparently came about due to a misunderstanding on \$3.17M cost savings (~3%) on the entire SORCE program from 1999-2008.
2. The SORCE Optimal Budget is slightly less than the 2007 Senior Review, and this optimal budget provides for a continuous SORCE mission with adequate support to resolve a couple anomalies per year.
3. Continue SORCE mission with only standard data products, no new data products (e.g. those listed in Table A-5).

### **Scientific merits**

Outstanding       Very Good       Good       Fair       Poor

The purpose of the SORCE mission is to characterize the incoming solar radiation, an important boundary condition for studying climate change and the natural variations in climate. To address the science questions, the SORCE instrument complement includes the four following sensors co-aligned on a 3-axis stabilized low-Earth orbit spacecraft:

- The Total Irradiance Monitor (TIM) measures the total solar irradiance with accuracy (combined standard uncertainty) of 0.035%.
- The Spectral Irradiance Monitor (SIM) measures the solar spectral irradiance from 200 nm to 2400 nm with a resolution ranging from 1 nm to 27 nm and an accuracy of 2%.
- The SOLar STellar Irradiance Comparison Experiment (SOLSTICE) measures the solar spectral ultraviolet (UV) irradiance from 115 nm to 320 nm with a resolution of 0.1 nm and an accuracy of 5%.
- The soft Xray (XUV) irradiance in the range of 0.1 nm to 27 nm is measured by the XUV Photometer System (XPS) with each photometer having a bandpass of about 7 nm.

## **Strengths**

### *Accurate Value of Total Solar Irradiance*

Measurements of the TSI are critical to understanding the sun and its relationship to Earth's climate. The SORCE TMI makes important continuity measurements to the existing record of TSI, and overlap with continued measurements on missions such as GLORY will support an important climate record.

### *Irradiance Variability in the NUV-Visible-NIR*

SORCE begins a new and unique database of near UV, visible, and near infrared solar spectral irradiance. The variability in the UV is almost a factor of 10 in the 200-400 nm range over a model based on UARS ultraviolet observations. Observations of the SORCE far UV irradiance for another epoch of maximum solar activity would provide valuable and unique sequence of observations. Trends in the spectral regions in the rising phase of solar cycle 24 would be valuable to understanding solar physics.

The TSI varies by 0.1% per 11-year solar cycle, but SORCE observations indicate that some wavelength regions vary considerably more than this. The SIM observations indicate that the variations in TSI resulted from larger and partially offsetting trends in different parts of the spectrum.

### *Secular Trend in Solar UV Irradiance*

Preliminary analysis shows that throughout the FUV, the quiet Sun irradiance was slightly larger in 1996 than it was in 2008 (both low solar activity). These SOLSTICE results suggest a small long-term (secular) trend downwards in the FUV irradiance. Throughout the FUV the quiet Sun irradiance was slightly larger in 1996 than it was in 2008. Current models do not predict these differences, nor explain them. These measurements should continue through the solar cycle.

## **Weaknesses**

The 2007 Senior Review report stated about SORCE (with a similar message to ACRIM): *The Committee finds the core mission merits funding through FY2009, during which time the discrepancy between ACRIM/TSI and SORCE/TSI measurements ought to be resolved to conclusion.*

In reading both the ACRIM and SORCE proposal, it appears, unfortunately, that this discrepancy has not been resolved – each arguing why their measurements are correct. This remains a concern of the panel and needs to be addressed. Both the SORCE and ACRIM proposals claim that their instrument is the most accurate and precise. A consistent and well documented picture of the accuracy and long-term stability of both the SORCE and ACRIM III TSI sensors has evidently not yet emerged. If the TSI offset

issue has not yet been resolved, it is difficult to claim, on page 1 of the SORCE proposal, that the SORCE/TIM 1361 W/m<sup>2</sup> TSI value is a fundamental discovery.

The NIST report (quoted in the proposal) states the following:

*Two intercomparison proposals were discussed. One proposal is to perform a laboratory intercomparison using lasers at NIST. The other is to perform a mountain-top intercomparison using the Sun. These two proposals can be viewed as complementary, so that both could eventually be performed. However, the laboratory intercomparison is probably less costly, has the lowest uncertainty, provides a direct link to the SI, and is the easiest and quickest to implement, so it is the recommended place to start. In the following we first elaborate a bit more on the mountain-top proposal, then give a much more lengthy description of the NIST TSI laboratory intercomparison plan. This discussion begins with an introduction, continues with a description of the proposed optical configuration and experimental procedure, and concludes with estimates of the uncertainty budget.*

The SORCE team is making excellent progress in the laboratory measurements recommended at this workshop. Preliminary results show good agreement among the Glory TIM, the SORCE TIM witness instrument, and the NIST-calibrated cryogenic radiometer in the TRF on an absolute scale. The recent laboratory enhancements will help to alleviate our understanding of these differences. It is a positive step that the PICARD PMO instrument (which is like the SOHO VIRGO instrument) is planned for a visit to the LASP facility for comparisons in late summer. However, it is unfortunate that the SORCE TSI team did not take advantage of the mountain-top comparison with the ACRIM team. We recognize the limitations of this comparison, but this could have been an important step forward in resolving these differences.

### **Value of data record and overall data continuity**

SORCE has observed solar cycle (SC) 23 declining phase and cycle minimum. An extended mission will observe SC 24 rising phase, which could lead to valuable observations of the sun, which is predicted to be different than cycle 23. These SORCE solar cycle results will help to improve reconstruction of the solar irradiance (TSI & SSI) back to the Maunder Minimum (1600s).

Extending the SORCE irradiance measurements will result in overlap with future Glory TSI measurements (expected to launch in November 2009, but probably delayed due to recent Taurus XL failure) and planned NPOESS TSI and SSI measurements (expected to launch in 2013).

The TIM observations are redundant; however, such an instrument is needed until measurements from NPOESS and Glory are in place. So TIM should continue the observational climate record of the solar irradiance. Though it is not clear how much

overlap with NPOESS and Glory is needed, given the current continued discrepancy with ACRIM.

**Core mission data product maturity;**

Outstanding       Very Good       Good       Fair       Poor

The primary data records from SORCE are the daily averaged (24-hour) Total Solar Irradiance (TSI) from TIM and the daily averaged Solar Spectral Irradiance (SSI) from SIM, SOLSTICE, and XPS. The panel is rating the product maturity as *Very Good* because of the continued disagreement with the ACRIM discrepancy in TIM observations have been resolved. This is counter to the 2007 Senior Report which stated:

*The Committee finds the core mission merits funding through FY2009, during which time the discrepancy between ACRIM/TSI and SORCE/TSI measurements ought to be resolved to conclusion.*

This has not yet been resolved at a level accepted by the solar community.

**Relevance to NASA Science Goals:**

Outstanding       Very Good       Good       Fair       Poor

**Strengths**

The SORCE mission measures both the total and spectral solar irradiance (UV, VIS to near IR, and X-rays) from space. Improve the understanding of how and why solar irradiance varies, estimate past and future solar variations, and investigate climate responses. The observation of solar irradiance is clearly important for modeling of the sun. In addition, SORCE measures the spectral distribution of incoming solar energy, an important boundary condition for studying climate change and the natural variations in climate. The observations are finding useful results that should support improved modeling of the sun. For example, the IR irradiance is out of phase with solar cycle, unexpected results from the SORCE SIM, for example the UV decreases towards solar minimum and while the visible is similar to TSI.

**Weaknesses**

It is not clear that there is agreement that the SORCE TSI is the accepted standard by the general community. It is unfortunate that once again a senior review panel is asking that the discrepancy in the TSI observations needs to be resolved.

The proposed Optimal Budget products might better be handled through a ROSES competition. For example, while interesting, the heating rate figure adds little knowledge to our understanding of atmospheric heating. The importance of incoming spectral energy is recognized, but the presentation does not include error bars of the model in these spectral regions. Nor are errors associated with the radiative transfer model stated. It is the finding of the panel that the team should focus on resolving the differences in observations of TSI and not add resources to enhance products.



## Technical and Cost

The T&C subpanel consensus review rated *SORCE* technical as high risk, and the cost as medium-high (see subpanel reports.) The T&C panel made the following summary of the proposal:

The *SORCE* mission is rated as high risk. The T&C panel has identified 1 major weakness, 4 minor strengths, and 3 minor weaknesses. The Total Irradiance Monitor (TIM) operation is normal and meets its performance requirements. Degradation of the two Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instruments has been small through the first six years of the mission and the cross calibration has been effective. The XUV Photometer System (XPS) remains in very good health. Except for the single battery and reaction wheels, with the deactivation of reaction wheel #3, all systems are fully redundant and only the primary strings have been used. However, the project, in combination with the hardware vendor, has determined that probability of premature failure for each remaining operational reaction wheel is 50%. Multiple anomalies have resulted in up to 6%/yr degradation in the UV output of the Spectral Irradiance Monitor (SIM). The data and command systems have had multiple anomalies. The battery is experiencing a reduction in eclipse exit voltage. The proposed “in-guide” budget guideline reflects a 22% budget cut rather than the expected 5%. The panel has determined that, because of the systematic fault in the reaction wheel design, and because of the undetermined repercussions of each successive failure, there is concern that the mission may not survive through the extended mission period. The cost risk is rated as medium-high.

Discussions following the *SORCE* team presentation to the panel suggest that the premature failure of a reaction wheel may not be as high a risk as initially rated. Indeed, the more time that passes without an incident the more unlikely a problem will emerge. This should be considered in future considerations of the continuation of the ACRIM mission.

## National Needs

The National Interests panel recognized that *SORCE* supports space weather forecasting and applications, which provides indirect benefits to all organizations that use the data products for applied and operational uses. The sub-panel rated it as high utility (see subpanel reports.).

Some *SORCE* measurements are directly used by organization that do space weather forecasting, especially near- real-time monitoring of solar flare events. There is also value as a back-up to primary GOES XRS sources; NESDIS plans to use *SORCE* XPS if GOES-14 not available when GOES-10 is shut down.

*SORCE* Quicklook Mg II index data product began production in 2005 to satisfy a request by the space weather operational community, namely Air Force and NOAA

Operational space weather users of SORCE Mg II index data automatically check the SORCE ftp site for updated data files twice a day to get the latest observations.

**Other Comments**

The panel felt that the SORCE proposal was generally less than satisfying with regard to its somewhat cavalier treatment of technical issues concerning the accuracy and precision of SORCE/TIM and those of other existing sensors. However, the proposal team was very responsive to our questions and provided informative information on the status of the differences between observations in TSI during their presentation.

The panel also appreciates that SORCE effectively returned \$3.1M to NASA in 2008 as cost savings (3%) over its 9-year program (development and 5-year core mission).

## **Terra Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;  
Augmentation as requested in “Optimal Scenario”
- Continuation of projects with reductions to the current baseline.
- Close-out and finalize dataset

Terra is the flagship mission for NASA Earth System Science, enabling the scientific community to address a wide range of fundamental science questions articulated in NASA’s Science Plan. The spacecraft and sensors continue to function well, with only a few non-critical failures to date. No further life-limiting issues are anticipated for any systems during the mission extension period, with the exception of some concern regarding the solid state recorder. Robustness of the ground system is an ongoing concern that can be addressed with appropriate funding, as requested in the Optimal Scenario. The scientific and operational merits of Terra are outstanding. Terra provides long and critical data records; its continuation is of very high importance unless and until suitable follow-on/replacement missions are online. In addition to excellent science, its products have very high priority to applications that cut across many US agencies and other users. Terra should be approved for mission extension at the “Optimal Scenario” funding level to ensure that prior year budgets reductions are restored and the project has the resources to make important ground-system IT upgrades. To ensure that the greatest possible science utility is being derived from the platform, it is also recommended that the team put high priority on efforts to better align the mission and science communities, particularly with regard to cross-instrument and cross-mission collaboration.

### **Scientific merits**

Outstanding  Very Good  Good  Fair  Poor

Terra is the flagship mission for NASA Earth System Science. Its primary purpose is to enable the scientific community to address fundamental questions articulated in NASA’s Science Plan under the broad theme “How is the Earth Changing and what the consequences for life on Earth are”. Its 5 sensors yield 72 data products that have been used in >3500 peer-reviewed publications, and cited in thousands more. Demand for these data products continues to increase as the Earth System it was designed to observe evolves ever more rapidly. Terra’s data products are of very high scientific importance to a broad range of communities. They provide critical data continuity over decadal time scales, a key to unraveling the science of changing climate. The satellite and its instruments are relatively healthy, enabling ongoing scientific investigations of high quality.

Terra’s 5 science instruments provide important data to the scientific and other user communities. Its “keystone” instrument MODIS provides daily global broad spectrum

coverage of the land, ocean, and atmosphere, yielding 35 data products of value to multiple science and user communities. ASTER provides high-resolution stereoscopic data for fine-scale processes. CERES makes observations on the role of clouds, aerosols, water vapor, etc.. to infer the Earth's energy balance. MISR provides data on the physical structure of the surface and atmosphere. MOPITT observes CO total column and mixing ratios at 10 pressure levels.

Terra's multi-instrument platform provides unique opportunities for multi-instrument integrated science. Key examples include the use of MODIS to detect land surface fires, MISR smoke plumes, MOPITT emitted CO, MODIS/MISR emitted smoke, ASTER/MODIS burned area, CERES energy balance impact. There are many others. There are also important synergies with other satellite missions including AQUA, LDCM, NPOESS, CLOUDSAT, CALIPSO, and others.

The growing importance of information about climate change and Earth resources confirms that the need for this platform is even stronger today than when it was first launched. In addition to observing capability that cuts across all of the 24 science goals, Terra provides several key measurements for which there is no alternate source. Among these is use of ASTER as a partial gapfiller for Landsat, and use of much of the Terra sensor suite as an NPOESS morning orbit gapfiller.

The team has responded well to the recommendations of the last Senior Review (2005). For example, during the past two years MISR data utility and access have improved, MODIS collection 5 has been completed, and MOPITT was selected for an in-hand mission. Eight new products have been added.

While noting these impressive strengths, it is also important to note that Terra is a large, complex, and relatively expensive mission. It is not clear that all of its data products are of equal value, and if not, which products should potentially be augmented, and which reduced or eliminated. Key examples of multi-instrument/ multi-satellite science are given, but more could and should be done (the team appears to share this concern). The panel noted the pros and cons of increasingly relying on ROSES opportunities for innovative interdisciplinary and multi-instrument scientific research, and questioned whether complete reliance on ROSES for new science is optimal given the depth and complexity involved.

**Core mission data product maturity;**

Outstanding  Very Good  Good  Fair  Poor

Terra produces 72 data products (MODIS 35, ASTER 12, CERES 11, MISR 7, MOPITT 7), with eight having been added since the 2007 Senior Review. The original core data products are high maturity, and the eight added products are at various levels of maturity. The level of science support to maintain these products is reasonable. The relationship of Terra to other satellites is important and widely noted. The use of Terra in multi-satellite science should continue to be strengthened and supported.

Data products from Terra are of high value and are widely used by the scientific community. After nearly ten years on-orbit, observations from the Terra platform continue to have important science applications and continued science discoveries. In addition to discoveries, data continuity is important for both historical applications (combining with AVHRR and HIRS) and the future (VIIRS).

**Relevance to NASA Science Goals:**

X Outstanding  Very Good  Good  Fair  Poor

Terra’s 72 data products from five instruments are critical to enabling the scientific community to address the fundamental Earth Science Questions articulated in the NASA Science Plan under the general headings: “How is the Earth Changing and what are the consequences for life on Earth.” The size and quality and length of the mission provide data resources of unparalleled breadth and potential. Moreover, the changes to the Earth System that Terra was designed to observe are even more important to understand today than when the mission was conceived. More should be done to utilize the full potential of this mission, especially in the areas of multi-instrument/multi-satellite interdisciplinary science.

**Technical and Cost**

The panel noted and concurs with the findings of the Technical and Cost Panel of “Medium Risk”, and that problems can be effectively addressed with management and engineering solutions. It noted and concurs with the need for augmentation funding to support compliance with NPR 2810-1A IT guidelines. Additional support is needed for potentially important new multi-instrument/multi-satellite inter-disciplinary science here and/or through future ROSES opportunities. Refer to the Technical and Costs Panel report for additional information.

**National Needs**

The panel noted and concurs with Terra’s “Very High” utility rating by the National Interests Panel. It also noted in particular the importance of the MODIS Rapid Response System to this rating. Refer to the National Interests Panel report for additional information.

**Other Comments**

The panel noted sizable reductions in the costs of the mission since launch, and since the last Senior Review. Augmented funding is needed to mitigate negative effects of recent budget reductions including in particular compliance with new IT guidelines to improve security, maintenance of the MODIS Rapid Response System, and restoration of CERES and MISR efforts as requested in the “Optimal Scenario”.

## **TRMM Mission Review**

### **Finding (2010-2011):**

- Continuation of projects as currently baselined;
- Continuation of projects with augmentations to the current baseline;
- Continuation of projects with reductions to the current baseline;
- Close-out and finalize dataset

The review panel recommends that the budget follow the proposed baseline request. The TRMM and GPM budgets are inextricably tied together and it is clear that the algorithm development for GPM is vital to final success of this TRMM follow-on mission. In our opinion, the scientific output of first TRMM, and then in the future, GPM, more than justifies support of the project at the full in-guide amount to ensure full support of the GPM retrieval algorithms development prior to GPM launch in 2013. The in-guide budget will provide adequate funding to ensure that the GPM goals prior to mission launch are met.

### **Reasoning:**

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 11-y of precipitation measurements including details of the vertical structure of that precipitation in the tropical and extra-tropical regions of the world. The precipitation radar (PR) is the only space-borne rain radar (until the GPM launch in 2013) and provides the 3-D structure of rain as well as quantitative information over both land and ocean of rainfall amounts. 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, 0.5 degree 8-y 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-h to inter-annually and beyond. The science objective of an 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, both fundamental to NASA's Earth Science strategy. TRMM provides answers to key science questions for both the Water and Energy Cycle and Weather focus areas. Examples of operational uses around the world include the use of near-real time images for tropical cyclone structure/intensity estimates, and integrating the TRMM SSTs into standard products.

Compelling reasons to continue this mission include the following:

- There are currently no other platforms that can provide the coverage and detail

of rainfall observations that TRMM provides. Continued operation until the GPM launch in 2013 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 is needed to calibrate and validate the GPM algorithms after GPM launch. In addition, this calibration will make it possible to ensure a continuous dataset back to 1997 when any GPM algorithm upgrades are implemented in the future;
- The full constellation of GPM satellites will not be launched until a year after GPM and TRMM will ensure that adequate temporal coverage is maintained until that time.

The proposal provides convincing evidence that there are no platform-instrument, or subsystem-specific issues that will affect extended mission status. The performance of all instruments on board is impressive and there is no reason to think that this performance will not continue into the future. The basic mission extension will continue production of TRMM standard and real-time products. Thus, a multi-year extension of TRMM has a very high payoff for science and applications at a low additional cost to NASA.

***Suggestions:***

The panel urges the mission team to think about new, innovative science that can only be accomplished with a constellation of rain radar satellites, such as could occur if TRMM is still operational after GPM is launched. While the desirability of co-flying with GPM for cross-calibration, validation, and redundancy is clear, it is conceivable that there may be innovative science not feasible with a single precipitation radar satellite alone. Identification of such science could further strengthen the case for mission extension in future years.

**Scientific merits**

Outstanding       Very Good       Good       Fair       Poor

***Strengths:***

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, convective systems, and storms, and their associated hydrometeor structure and latent heating distributions. TRMM provides an 11-y rainfall dataset that covers the tropics and much of the extra-tropics. This dataset is now 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.

NASA objectives and Science questions that are directly impacted by TRMM measurements include:

1) Climate-related research: TRMM has provided multiple rainfall datasets extending back 11 years for the study of climate-related water questions. 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 detailed global and regional lightning climatologies to be developed. 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 relationship among aerosols, land use change, rainfall, and lightning has yielded information on the human impacts on the climate system. TRMM measurements help improve SST analyses.

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 led 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 ( $0.25^\circ$ ) and temporal (3-h) resolution than would be available from one satellite alone.

4) Data Assimilation: 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) Other research: 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. In addition, this dataset makes it possible to globally monitor crops, and potential for floods, and landslides.

6) Algorithm and model development: LIS data has been used to help develop the new lightning monitoring strategy 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:***

None perceived



***Value of data record and overall data continuity:***

At the request of NASA, the National Academies (NA) completed an 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.”*

The TRMM data set extends back over 11 years. 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 4 years, (the projected lifetime of TRMM), it may be possible to characterize interannual variability and ENSO cycles. A suitable overlap with the GPM mission makes this a definite possibility.

**Core mission data product maturity:**

**Outstanding**       Very Good       Good       Fair       Poor

The core mission rainfall measurements 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. A number of level III products are produced for both real time and research applications. A total of over 40 products from stage I to III are produced. In addition, TRMM operations, ground validation sites, and algorithms are being used as the basis for algorithm development for the future GPM mission.

**Relevance to NASA Science Goals:**

**Outstanding**       Very Good       Good       Fair       Poor

***Strengths:***

TRMM provides data sets that address a number of SMD recommendations:

*How are global precipitation, evaporation, and the water cycle changing?* TRMM provides improved climatology of precipitation characteristics such as diurnal variations, 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 systems 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?* If TRMM remains flying through the launch of GPM then with 15 or more years of rainfall data and the follow-on GPM data it will be possible to use the inter-annual variation in precipitation to characterize tropical seasonal-inter-annual climate variability in general, and the ENSO cycle in particular. The response of convective system climatologies 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.

*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 the global water/energy cycle, which improves weather/climate prediction capability. TRMM data provide support for weather forecasting, e.g., monitoring the tracks, intensity, and associated rainfall of tropical cyclones (NOAA, DOD, WMO RSMC centers). A continued TRMM datastream of microwave radiances, precipitation fields, and SSTs in cloudy regions will allow continued improvement of model initial conditions.

*How will water cycle dynamics change in the future?* TRMM provides improved rainfall inputs to hydrologic models used to study water runoff. Continuation of the TRMM data will allow inputs to be used that cover a wide range of current climate conditions (e.g., ENSO extremes).

### ***Weaknesses:***

TRMM provides these measurements within a constrained latitude range (35°N to 35°S). The launch of GPM will allow a global dataset to be developed of which TRMM will have provided 14 years in the tropics and part of the extra-tropics. The single channel PR misses the light rain events. This will be fixed with the launch of the dual frequency PR on GPM in 2013.

### **Technical and Cost**

It is our opinion that the support for this mission is very reasonable for the value added science and the algorithm development that are included in support of the GPM mission. A majority of TRMM science is already funded through ROSES. The budget here is in support of two missions – TRMM maintenance, and GPM science algorithm development, which provides economy through shared science project management. For all other matters we defer to the expert findings from the Technical and Sub-cost panel, which has given the TRMM mission an overall rating of “*medium*”.

### **National Needs**

The overall summary from the National Needs Subpanel rates TRMM as the highest category of “*very high utility*”. 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 used by the NHC and DOD. Please refer to the National Needs subpanel report for more details.

### **Other Comments**

The proposal was extremely well designed and informative and was very helpful in convincing us of the high science level of the products being developed and the climate studies being addressed by them.