NASA Earth Science Senior Review 2020

Submitted to:

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1. INTRODUCTION

The 2020 Senior Review evaluated 13 NASA Earth Science satellite missions in extended operations: Aqua, Aura, CALIPSO, CloudSat, CYGNSS, DSCOVR, ECOSTRESS, GPM, LIS, OCO-2, SAGE III, SMAP, and Terra. The Senior Review Panel was tasked with reviewing proposals submitted by each mission team that addressed both the FY 2021-2023, and FY 2024-2026 time periods. The review considered the scientific value, national interest, technical performance, and proposed cost of extending each mission. The Science Panel evaluated the proposals on scientific merit and relevance to NASA's Earth Science Division (ESD) Science Plan. Priority was given to unique extended datasets within the overall Program of Record (PoR) as described in the 2017 Decadal Survey following guidance from the *Call for Proposals – Senior Review 2020 for Extension of Earth Science Operating Missions*. The importance of long-term data sets and overall data continuity for Earth science research and the direct contributions of mission data to applied and operational uses in support of national interests were considered as well. Sub-panels were convened to provide in-depth evaluations of the value to national interests, technical performance, and costs of extending each mission. The missions were reviewed separately and independently from each other.

The 2020 Senior Review finds that the 13 missions have very high scientific merit and meet the requirements for very high relevance to ESD priorities for extension.

2. REVIEW PROCESS

The 2020 Senior Review process began on December 20, 2019, when ESD issued a Call for Proposals letter inviting 13 NASA missions in extended operation to submit proposals for continuation, due March 6, 2020. The Senior Review Science Panel first convened on March 2 via teleconference to discuss procedures and review assignments. Three reviewers, a Lead and two Secondary Reviewers, were assigned to each proposal. Over the next one and half months, bi-weekly teleconferences were held to review progress and address any issues. Dr. William Gail, co-Chair of the 2017 Decadal Survey, was invited to give a presentation to the Science Panel and to provide an overview of the PoR. In parallel with this process, the National Interests, Technical and Cost sub-panels were convened and met to review the proposals in these areas. A first Science Panel Plenary virtual meeting was held in May with telecons taking place over three days, May 13-15. During this meeting, the Lead Reviewers briefly presented each mission, and all Reviewers reported their evaluations and preliminary science ratings (Excellent, Very Good, Good, Fair, or Poor).

Each mission review team identified a set of follow-up clarification questions to the respective mission team (Questions to Mission Team, QMT) that was presented to the panel for discussion. The QMT were edited based on the panel's input, and the questions were forwarded to the mission teams on May 27 with replies due on June 30. The second and final Science Panel Plenary virtual meeting took place on July 7-14. During the first four days of this last meeting (July 7 - July 10), each mission team gave a presentation addressing the respective QMT. The missions were allotted 60 minutes for their presentation, except for Terra and Aqua which each had 70 minutes. Each presentation was followed by a 10-20 min overview and synthesis discussion

among science panel members in closed session with only the program scientists being present. Following these presentations and discussions, the panel developed a collective evaluation of each mission. The Chairs of the National Interests, Technical and Cost Sub-panels presented detailed briefings during both Science Panel Plenaries. Final reports from each can be found in Appendix 1, 2, and 3, respectively. The Science Panel met on July 13 to work collaboratively on the summary of the detailed findings for each mission (Appendix 4) and met July 14 for final approval. A briefing of the results was presented to ESD management on July 21 by the Science Panel Chair. The workflow chart for the ESD 2020 Senior Review is provided in Figure 1 for reference.

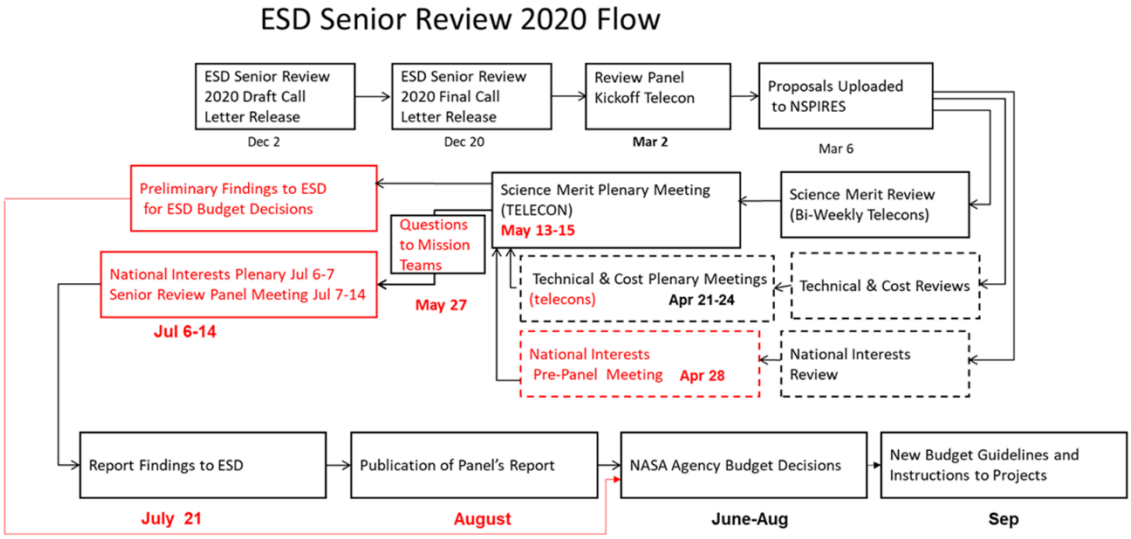


Figure 1 - 2020 Senior Review workflow chart and schedule. (Red highlighting indicates changes to accommodate COVID-19 impacts.)

3. GENERAL FINDINGS

For nearly twenty-five years, data sets from NASA's Earth Science Operating Missions have enabled transformative change in our scientific understanding of the Earth System. They have been used in myriad applications worldwide, prompting advances in forecasting, hazard response, and environmental management and stewardship with great benefit to society. The portfolio of thirteen missions in the 2020 Senior Review includes pioneer missions like Aqua, Terra, and Aura that have been operating for decades; aging missions like CloudSat and CALIPSO that have demonstrated the value of active atmospheric profiling technologies; mature missions like GPM, OCO-2, and SMAP that are producing high-quality data; technology pathfinder missions (e.g., CYGNSS), and instrument-missions that leverage access to the International Space Station (e.g., ECOSTRESS, LIS, SAGE III) and NOAA's DSCOVR. The Panel was unanimously impressed with the missions' continued role as science catalysts and was positive about the prospects for the extended data sets. The overall findings for the missions ranged between *Very Good* (2 missions) and *Excellent (*11 missions), and all missions were deemed *Excellent* concerning ESD relevance priorities (4.5-5 range). A summary of the Science Panel evaluations is presented in Table 1. The data quality range (3.8-5) is slightly broader as it includes missions with mature algorithms and

data products that were all found to be *Excellent* and missions proposing to Senior Review for the first time (e.g., ECOSTRESS, CYGNSS, and SAGE III) that were found *Very Good*.

Table 1 - Science Panel detailed review findings. Science scores are on a 1-5 scale, with 1 being the lowest ranking of "Poor" and 5 being the highest ranking of "Excellent."

NASA 2020 Senior Review Science Panel Summary

Mission	Science Merit		Relevance		Data Quality		Overall Score		Overall Science Findings
	Mean	*Median*	*Mean*	*Median*	*Mean*	*Median*	*Mean*	*Median*	
Aqua	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent
Aura	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent
CALIPSO	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent
CloudSat	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent
CYGNSS	4.7	5.0	5.0	5.0	4.0	4.0	4.6	5.0	Excellent
DSCOVR	4.5	5.0	4.5	5.0	4.1	4.0	4.4	4.0	Very Good
ECOSTRESS	4.6	5.0	5.0	5.0	4.1	4.0	4.6	5.0	Excellent
GPM	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent
LIS	5.0	5.0	4.5	5.0	5.0	5.0	4.8	5.0	Excellent
OCO-2	5.0	5.0	5.0	5.0	4.2	4.0	4.7	5.0	Excellent
SAGE III	4.0	4.0	4.8	5.0	3.8	4.0	4.2	4.0	Very Good
SMAP	5.0	5.0	5.0	5.0	4.2	4.0	4.7	5.0	Excellent
Terra	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	Excellent

The Science Panel integrated the input of the Technical and Cost Panels and National Interest Sub-panel scores with the overall science findings to determine the mission extension findings presented in Table 2. The Panel's polling options for each mission's extension were as follows: 1) Extend/in-guide: mission extension would be limited by the funds currently planned for the mission in the approved agency budget. This is considered the 'baseline' budget. For some missions, that would limit extension to less than three years; 2) Extend/over-guide: mission extension would be consistent with the mission's 'optimal' proposal, requiring additional funds allocated to the mission beyond what is planned currently in the approved agency budget. For most missions, the 'optimal' proposals assumed full operations for both 3-year intervals; 3) Extend/other: mission extension would be modified as specified by the panel. This could include reduced or added scope, which would result in a different funding line than baselined or proposed by the mission; and 4) Do not extend: mission operations would terminate beginning FY 2021, but the mission team would be funded to complete final processing and archival of the mission's datasets.

The utility score from the National Interests Sub-panel captures the breadth of the user base and applications. Aqua and Terra were the only two missions given a *Very High* utility score reflecting the ubiquitous use of their products and, in particular, MODIS products, across federal and state agencies and the private sector. Missions with focus on particular data sets such as

DSCOVR, CloudSat, LIS on ISS, and OCO-2 received a score of *Some* utility due to the smaller size of their user base. All other missions received *High* scores from their respective users.

Table 2 - Overview of 2020 Senior Review assessment and mission extension findings.

NASA 2020 Senior Review Extension Findings Summary						
Mission	**National Interest Panel**	**Technical Risk**	**Cost Risk**	**Science Overall Findings**	**Mission Extension**	
					FY 2021-2023	**FY 2024-2026**
Aqua	Very High	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
Aura	High	Medium-Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
CALIPSO	High	Medium	Medium	Excellent	Extend /Over-guide	N/A /Over-guide
CloudSat	Some	Medium-Low	Medium	Excellent	Extend /Over-guide	Extend /Other
CYGNSS	High	Medium-Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
DSCOVR	Some	Low	Low	Very Good	Extend /In-guide	Extend /In-guide
ECOSTRESS	High	Medium	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
GPM	High	Medium	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
LIS	Some	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
OCO-2	Some	Low	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
SAGE III	High	Low	Low	Very Good	Extend /In-guide	Extend /In-guide
SMAP	High	Medium	Medium	Excellent	Extend /Over-guide	Extend /Over-guide
Terra	Very High	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide

The technical risk is generally low and medium-low for most missions, increasing to medium for CALIPSO, GPM, ECOSTRESS, and SMAP. The mission teams provided a detailed account of mitigation strategies and risk management plans that were further expanded in their replies to QMT. The risk of exceeding the proposed budget is generally *Low* to *Medium-Low*, except for missions like CALIPSO, CloudSat and SMAP, in which case a *Medium* cost risk is assessed in anticipation of the potential need to rescope mission operations and, or mission science tied to technical risk. Overall, the risk profile of the thirteen missions assessed during the 2020

Senior Review is in line with expectations of extended mission operations, and the national interest is high. The Panel found that all missions meet ESD priorities for extension.

The Panel has the following specific findings concerning the missions and the future of Extended Science Mission Operations activities:

General Comments

The Panel is cognizant of the tremendous scientific progress and unprecedented engineering feats of NASA's Earth Science Data Systems (ESDS) program. In particular, the panel highlights NASA's role in establishing the world's first and most rigorous open access repository of Earth data. The paradigm of developing high-quality well-documented science-grade remote-sensing products along with transparent algorithms enabled scientific progress by reducing the barriers to use of remote-sensing data outside of small expertise niches, by providing standards for reproducibility of scientific results, and by nurturing the development of a vibrant ecosystem of developers of Earth Science Applications. Presently, flagship missions such as Aqua, Terra, and Aura approach end-of-life, and budget constraints emerge due to new missions in response to the 2017 Decadal Survey. While there is a growing number of governmental agencies that are following NASA's lead internationally and sharing their data with the public, and while there is growing private sector participation in remote sensing of the environment, a framework for quality retrievals and development of derived products with well-characterized errors and uncertainty that are necessary for science and advanced operations is missing. The Panel suggests this is a most critical gap where ESD can build on the legacy of NASA'S pioneering Earth Observing System (EOS) and continue to play a crucial leadership role in Quality Data Systems and in facilitating equitable access to quality data. The Panel urges NASA ESD to plan for continuity in the next epoch of Earth Science and Applications from Space, leveraging national and international collaborations and partnerships to maintain development, production, and access to high-quality Earth data.

2020 Senior Review Specific Comments

(1) The Senior Review Science Panel is concerned that upcoming Aqua and Terra orbit changes in 2022 will bring about significant changes in the quality, and consequently, the utility of the data. The changes will be especially dramatic for Terra, which is the only morning satellite in the MODIS spectral range, as Mean Local Time (MLT) crossings begin to drift from 10:30 AM to 9 AM by 2025 as proposed. Aqua MLT will drift from 1:30 PM to 3 PM by 2025. During the 2020 Senior Review, the Panel generated detailed QMT, explicitly asking for quantitative diagnostics of the impact of orbit changes and corresponding algorithm changes on Terra data sets and MODIS products specifically. The Aqua and Terra mission teams responded to these questions by producing largely qualitative preliminary estimates of uncertainty based on expert knowledge. The Panel recognizes the challenges of developing working algorithms to derive quantitative estimates during the Senior Review. However, the quantitative assessment needs to be established before MLT drifts by more than 15 minutes. The Panel suggests that a Special Review of Terra algorithms and data sets be conducted no later than 2022 to assess the anticipated increases in uncertainty and the effectiveness of mitigation strategies. It is expected that an MLT drift of 15 minutes will curtail the utility of some of the data for climate studies, in particular for

quantification of subtle trends and small anomalies of key geophysical variables as specified in the 2017 Decadal Survey. Additionally, given that the uncertainty increase in specific Aqua and/or Terra products is deemed tolerable, and given new science opportunities, the Panel suggests the organization of a Users' Workshop to communicate changes in the data sets and to prepare users for mission end-of-life, including the evaluation of continuity products.

(2) The Panel finds that the Senior Review process is meticulous, and the guidance received was very helpful throughout the process. In recent years, the portfolio of missions considered for Review is more diverse, including instruments on platforms of opportunity. The Panel finds that there are significant differences in how missions balance science and operations, including whether missions have science teams or not, and whether independent science teams are selected via competitive ROSES calls for proposals. These differences have a measurable impact on data usage and scientific outcomes (for example, CloudSat vs. GPM vs. DSCOVR vs. SAGE III). The increasing number of PI-led satellite missions selected through either Earth Venture Mission (EVM) or Earth Venture Instrument (EVI) programs in next 3-6 years will further diversify ESD's mission portfolio. The Science Panel suggests that guidance on this aspect be provided upfront in future Senior Reviews, including a possible adaptation of the evaluation criteria for different types of missions.

4. MISSION SPECIFIC FINDINGS SUMMARY

Aqua

The Aqua satellite, the first in the A-Train constellation, was launched on 4 May 2002. The spacecraft bus is still in excellent condition. Four working instruments (AIRS, AMSU, CERES, and MODIS) are still healthy, except that some channels have been degraded, which do not have a significant impact on data quantity and quality. The data quality and algorithm maturity are very high. Aqua-collected data are highly relevant to the NASA SMD Science Plan, the PoR, and the 2017 Decadal Survey priorities for observables. Aqua data has been used to answer four of NASA's key science questions and has provided seven of fourteen priority targeted observables and one of three targeted observables not allocated to flight programs. Recent research has shown that AIRS long, stable, high-precision data can reliably monitor our changing climate, such as finding changes in the surface temperature, cloud properties, atmospheric composition, and extreme weather. AIRS and AMSU data are routinely used for data assimilation in Numerical Weather Prediction (NWP) models for operational forecasts with demonstrated superior contribution to forecast skill. Moreover, the CERES instrument on Aqua, together with other CERES instruments on Terra, Suomi NPP and NOAA-20, has contributed to the critical Earth Radiation Budget (ERB) climate data record. As a member of the A-Train constellation, and with wide swaths for a majority of the data, Aqua has also provided data for retrieval products of other non-A-Train satellites. Due to fuel limitations, Aqua will lower its orbit and exit from the A-Train in January 2022. At that time, Aqua's MLT will start drifting from 1:30 PM to 3 PM by 2025. The in-guide (baseline) budget will support Aqua's operation until April 2023, while the over-guide budget requests an additional 2.4-year operational time until September 2025. After that, the changes of MLTs and solar zenith angles will have an impact on some Aqua data products. In particular, a lower zenith angle could cause a minor to moderate degradation in the quality of the

cloud mask and surface energy flux-related products. Impact on AMSU and AIRS radiances, which are critical to weather forecasts in both national and international operational centers, is anticipated to be minimal.

The Senior Review Science Panel unanimously finds there is enormous potential benefit in continuing to receive Aqua data, given that the majority of the data products can remain at the same or a similar quality level pending the proposed modifications to algorithms. The Senior Review Panel finds in support of Aqua's extension with the over-guide budget for both FY 2021-2023 and FY 2024-2026.

Aura

The two operational instruments on Aura are the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI). Aura will continue operating nominally through 2024 with anticipated end-of-life in 2025. With its long-term record of high-quality measurements, the MLS on Aura has become the gold standard for vertical profiles of atmospheric gases (including H_2O, O_3, ClO, HCl, HNO_3, CO, SO_2, and N_2O), cloud ice water content, and temperature from the upper troposphere to the upper stratosphere. No other satellite instrument in the PoR, either currently operating or planned for deployment can look above 100 hPa for profiles of these species. OMI has used its nadir-looking, wide-view, UV-Vis hyperspectral imaging capability to give long-term daily global coverage for column amounts of several gases (including O_3, NO_2, SO_2, BrO, HCHO), aerosol types (smoke, dust, sulfates), and cloud-top pressure. Its long-term, stable solar irradiance measurements, widely recognized as the gold standard by which other solar irradiance measurements are evaluated, will be available until 2024 when Aura must leave its orbit and descend. As attested by the increasing number of high-quality publications, OMI's measurements of atmospheric reactive gases are finding increasingly more extensive use in science, air quality management, health studies, and economic analysis, including the economic impacts of COVID-19 that received wide public attention.

The Senior Review Science Panel unanimously finds that continuing MLS through 2025 will extend its long-term record of unique and excellent science, including studying the recently discovered apparent shift in stratospheric dynamics and, in 2020, the observed Arctic ozone hole, smaller than, but as deep as an Antarctic ozone hole. Continued operation will also give OMI more time to provide the long-term, high-accuracy, and stable gas measurements to test and to help improve the measurements of its successor, TROPOMI, and the emerging constellation of geostationary trace gas monitoring instruments. The Senior Review Panel supports the extension of the Aqua mission with the over-guide budget for both FY 2021-2023 and FY 2024-2026.

CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission, launched in April 2006, is entering its 15^{th} year of successful operation, providing unique observations of global aerosol and vertical cloud profiles. The CALIPSO instruments include a two-wavelength polarization-sensitive lidar (Cloud-Aerosol LIdar with Orthogonal Polarization, or CALIOP), a three-channel infrared imaging radiometer (IIR), and a single-channel wide field-of-view camera (WFC). Both CALIOP and IIR have operated well so far. The WFC stopped operating on 11 April, 2020, but no primary CALIOP products depend on the WFC. CALIPSO's

vertical profile measurements of clouds and aerosols provide an unparalleled resource for evaluating and improving weather and climate and air quality models, and models used to forecast the dispersion of volcanic and fire plumes. CALIPSO is highly relevant to the NASA SMD Science Plan and the 2017 Decadal Survey, and directly contributes to five 'most important' and three 'very important' objectives in the Decadal Survey. CALIPSO exited the A-Train and descended to its disposal orbit at 688 km in September 2018 to resume matched lidar/radar cloud profile measurements with CloudSat. All spacecraft subsystems continue to operate nominally in this new orbit. CALIPSO is now slowly drifting to later local ascending node crossing times, but data quality is insensitive to changes in crossing times. The backup laser of the CALIOP (which has been in use since March 2009 after the primary laser was stopped) will reach the end of its useful lifetime sometime within the next 6-12 months. At that time, the mission team will restart the primary laser. If this is successful, science operations will continue until September 2023, when CALIPSO is expected to be terminated due to insufficient power.

The Senior Review Science Panel unanimously finds that extending the CALIPSO mission through 2023 will have tremendous benefits. This includes maintaining critical synergies with CloudSat to provide co-located observations of clouds, aerosols, and precipitation, and allowing further development of important data synergies with other space-based sensors such as SAGE III-ISS, OMPS, VIIRS, and ICESat-2. CALIPSO provides unique monitoring capabilities that inform environmental health and human safety interests, including providing near-real time aerosol information to NOAA to improve air quality forecasts; validating passive sensor retrievals (e.g., after exiting the A-Train, the CALIPSO orbit precesses eastward across the MODIS swath, allowing long-sought validation of MODIS aerosol and cloud products as a function of MODIS view angle). Furthermore, by enabling data continuity with the space-borne lidar measurements to be acquired by EarthCARE, CALIPSO could serve as a unifying bridge to a future Aerosol-Clouds-Convection-Precipitation (A-CCP) mission. The Senior Review Science Panel supports the extension of CALIPSO FY 2021-2023 with over-guide budget, and the proposed over-guide budget for mission closure activities in FY 2024-2026.

CloudSat

The CloudSat mission, launched in 2006, carries the Cloud Profiling Radar operating at 94 GHz, which is currently the only space borne radar capable of simultaneously observing both clouds and light precipitation, albeit over a narrow swath. After its departure from the A-Train in 2017 due to a loss of a reaction wheel, it recently joined CALIPSO in its lowered disposal orbit in the C-Train. CloudSat will continue to fly in formation with CALIPSO as its mean local crossing time drifts until CALIPSO is decommissioned. CloudSat data are widely used by many other mission science teams to improve cloud and precipitation retrievals from other sensors in the PoR. They provide benchmarks for improving GPM light precipitation and snow products, and they have been used by MODIS, VIIRS, and GOES Advanced Baseline Imager (ABI) teams for validating and improving cloud property retrievals. CloudSat data are used in operational applications to quantify model errors and improve NWP models. Recent collaborations with the European Center for Medium-Range Weather Forecasts (ECMWF) have demonstrated improvements in NWP predictive skills through direct assimilation of CloudSat data. Thus, the CloudSat mission is highly relevant to the NASA SMD Science Plan, 2017 Decadal Survey objectives, and the PoR. Until the anticipated launch of EarthCARE in FY 2022, CloudSat profile

measurements of cloud water and ice and precipitation water and snow have unique characteristics in the PoR, and mission extension would assure cross-calibration of the two missions. Other benefits of extending CloudSat include maintaining continued synergy with CALIPSO in the new C-Train orbit to provide co-located observations of clouds, precipitation, and aerosols. The extension of the data record to enable further research toward an understanding of cloud and precipitation processes in the context of climate variability.

The Senior Review Science Panel unanimously finds in support of CloudSat extension[1] in FY 2021-2023 with the over-guide budget. Panelists agreed that overlap with EarthCARE for cross-calibration efforts and extension of unique precipitation and snow products were important in FY 2024-2026, but they could not agree whether continuation should be at the requested level given the maturity of the algorithms.

CYGNSS

The Cyclone Global Navigation Satellite System (CYGNSS) was initially proposed as an Earth Venture (EV) mission and is undergoing its first Senior Review in 2020. CYGNSS consists of a constellation of low-cost GNSS sensors on eight micro-satellites that measures the forward scattering of GPS satellite signals from the surface. Each satellite records the delay Doppler maps (DDMs) from each of the intersections with the GPS constellation. As such, the measurements have a unique sampling geometry, and the deployment of the sensors is such that a given region may experience several retrievals in a short period for studying rapidly-evolving phenomena (such as tropical cyclone rapid intensification). The current health of the constellation of instruments is good, especially considering the low-cost nature of the sensors. The team has been agile in dealing with unexpected GPS signal variability, and the level of engineering automation of the handling of instrument anomalies is state-of-the-art. The team continues to develop new versions of algorithms that reduce uncertainties in the ocean wind products. The current proposal expands retrievals of land surface characteristics, and the team is to be commended for the plan for validating these new measurements with new in situ measurements of soil moisture and land surface coherence properties.

The Senior Review Science Panel unanimously finds in support of CYGNSS extension in FY 2021-2023 and FY 2024-2026 with the over-guide budget.

DSCOVR

Launched on 11 February 2015, the Deep Space Climate Observatory (DSCOVR) now flies on the Lissajous orbit about 1.5M km from Earth at the Sun-Earth first Lagrange (L1) point. As a joint mission between NOAA, NASA, and the U.S. Air Force, DSCOVR carries two NASA Earth science instruments: the Earth Polychromatic Imaging Camera (EPIC) and the NIST Advanced Radiometer (NISTAR). Since beginning operations on 15 June 2015, the data stream from EPIC and NISTAR has been stable and nearly continuous except from late June of 2019 to

[1] While in the final stages of publishing the present report, CloudSat suffered possible failure of one of the reaction wheels and is operating in safe mode. The possibility of this significant anomaly was highlighted in the technical risk panel report (Appendix B) and in the Science Panel's assessment (Appendix D). The CloudSat team is investigating the possibility of operating with the two remaining reaction wheels

early March of 2020 because of a DSCOVR pointing hardware issue, now resolved. EPIC, NISTAR, and DSCOVR will be in nominal function for the next six years. Being parked at the L1 point, DSCOVR provides a new and unique vantage point for observing the full, sunlit disk of Earth multiple times a day, at a nearly constant back-scattering angular perspective (e.g., viewing from a scattering angle of 165° - 178° relative to the direct sunbeam). EPIC measures back-scattered radiation at ten wavelengths ranging from ultraviolet (UV) to solar near-infrared, enabling the retrieval of diurnal variations of O_3 amount, clouds, aerosols, volcanic SO_2 plumes, vegetation/land surface phenology, and surface UV radiation over the sunlit portion of Earth every 1-2 hours. NISTAR measures the radiances from the Earth in four spectral ranges (shortwave, longwave, near-infrared, and all spectrums), thereby recording the Earth's radiative energy balance over time at hourly resolution. These data provide new temporally continuous global information that supplements the existing climate data record primarily from satellites in low earth orbit (LEO) orbit. Research in the past five years has revealed critical merit and potential of these data for scientific discoveries and applications in areas such as atmospheric composition, climate, ecosystems, and ecology. With observations at multiple local times from sunrise to sunset, EPIC's color images have also been extremely popular, providing an unprecedented view of Earth for the public and an outreach opportunity to emphasize the fragility of our planet. The EPIC Level-1 and Level-2 data have reached maturity, and NISTAR data is on the right trajectory to achieve its expected precision.

The Senior Review Science Panel unanimously finds in support of DSCOVR extension with in-guide budget for the FY 2021-23 and FY 2024-26 periods.

ECOSTRESS

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) makes multispectral thermal infrared (TIR) measurements from the International Space Station (ISS) from 52°N to 52°S at high spatiotemporal resolution (38 × 69 m), every few days at different times of the day. ECOSTRESS products include land surface temperature (LST), and model derived evapotranspiration (ET), evaporative stress factor, and water use efficiency (WUE). ECOSTRESS is the first mission to sample the diurnal cycle of estimated ET at fine spatial resolutions, albeit over several sequential days; it potentially can play a crucial role in understanding carbon cycle feedbacks to water cycle variability and societal applications, including drought monitoring, agriculture, urban heat islands, fire management, disease transmission, and ecosystem habitat. Currently, these analyses have been applied to selected regions. However, they will be applied to the entire global land surface between 52° N and 52° S. ECOSTRESS also provides critical pathfinding data for the future Surface Biology and Geology (SBG) Designated Observables (DO) recommended by the 2017 Decadal Survey. ECOSTRESS is undergoing its first Senior Review and is expected to continue collecting data for the next 3+ years. It has expanded data collection capability over the entire land surface, coastal regions, and some open ocean areas within 52°N to 52°S and is acquiring 2.5 times as many scenes per day as originally planned. Currently, only three of the five TIR spectral bands are downlinked, but this will be resolved with a new firmware update.

The Senior Review Science Panel unanimously finds in support of ECOSTRESS extension with over-guide budget, which sustains operations for the FY 2021-23 and FY 2024-26 periods.

GPM

Launched in 2014, the Global Precipitation Measurement (GPM) mission produces a suite of unique precipitation measurements that are widely used in research, operations, and broader applications. The GPM Core Observatory (GPM-CO) satellite carries the only precipitation radar (Dual-frequency Precipitation Radar) that can measure heavy precipitation and the best calibrated conically-scanning microwave radiometer (GPM Microwave Imager) in space. GPM-CO is an advanced successor to the Tropical Rainfall Measurement Mission (TRMM), providing improved detection of light precipitation (rain and falling snow) and having a greater latitudinal coverage (65°N to 65°S). The GPM-CO provides the reference standard to unify microwave radiometer data from a constellation of 11 partner satellites (including international partner missions) to generate global precipitation estimates with high temporal (30 minutes) and spatial (10 km) resolution. These data have been back-processed to the year 2000 using TRMM measurements, providing a 20-year, high-quality precipitation data record, which will continue forward with an extended mission. GPM has achieved <1 hour latency for near-real-time applications, including weather forecasting, agricultural forecasting, and resource management. With an extended mission, Version 07 data products will be developed through GPM Ground Validation efforts and extensive modeling studies. Additionally, GPM science enabled by extended operations includes research on precipitation microphysical properties, global precipitation patterns, the water cycle, water resources, precipitation extremes, weather, and climate. The GPM-CO and its instruments are in excellent shape, and the satellite has enough fuel to last until ~2034. Overall, GPM is an unparalleled effort that provides tremendous value to science and society and is well justified for the requested mission extension.

The Senior Review Panel unanimously finds in support of GPM extension for FY 2021-2023 and FY 2024-2026 with the over-guide budget. The augmented budget request will fund the replacement of the ground-based Precipitation Processing System, which is required hardware for processing and distributing the GPM products, and whose failures would cause unacceptable delays in data delivery to operational partners.

LIS on ISS

The Lightning Imaging Sensor (LIS) is a total (i.e., intra-cloud and cloud-to-ground) lightning detection instrument that was launched to the ISS on 19 February 2017 and has collected 3+ years of lightning data. LIS is the identical spare instrument that was built as a backup for the TRMM satellite (1997-2014). LIS heritage comes from the Optical Transient Detector (OTD), aboard the MicroLab-1 satellite (1995-2000), the prototype design for the LIS concept. All three missions together, OTD, TRMM LIS and LIS on ISS, have provided global-scale lightning detection for over 24 years now. The combined data set of these missions is unique because it is the only long-term and global-scale total lightning data with steady and verified detection efficiency. This arrangement is in contrast to ground-based networks that detect globally only cloud-to-ground lightning with extremely variable detection efficiency (because of instrument technology improvements and an increasing number of sensors deployed over the years). This assured quality of the data makes LIS on ISS the reference instrument for validation and cross-calibration of the new geostationary lightning detector instruments, especially GOES-16 and 17

Geostationary Lightning Mapper (GLM). The LIS instrument is in excellent health. With an extended mission, in combination with OTD and TRMM, LIS on ISS will approach the 30-year mark for data record suitable for climate change studies and will continue with its outstanding contribution with the Cal/Val activities of GOES-R series satellites. It will also continue to contribute with international partners, such as the extensive use of LIS on ISS data to create useful proxy data to optimize the design and development of the European Meteosat Third Generation (MTG) Lightning Imager (LI).

The Senior Review Science Panel finds in support of LIS on ISS with over-guide budget, which sustains operations in FY 2021-2023 and FY 2024-2026.

OCO-2

The Orbiting Carbon Observatory-2 (OCO-2) operates a moderate-resolution spectrometer to measure the spectra of scattered solar radiation in three bands in the near-infrared and infrared since its launch in July 2014. CO_2 column abundance (XCO_2) and solar-induced chlorophyll fluorescence (SIF) are the main products. Absorption by molecular oxygen at 0.765 μm and CO_2 in weak and strong absorption bands at 1.61 μm and 2.06 μm enables the detection of the CO_2 column abundance (XCO_2). Measurements are made along a ~10km wide track in 8 contiguous footprints that have areas of < 3 km^2, with two soundings per second. SIF is quantified in the O_2 A-band channel. Measurements are made in a 1:30 pm sun-synchronous orbit in a 16-day repeat cycle. The OCO-2 mission is continuing to provide the highest precision and highest accuracy atmospheric CO_2 mole fraction observations of any space-based mission currently in orbit. Updates to the retrieval algorithm (currently in V10) are continuing to improve the quality of available data. The scientific impact of the available observations is continuing to increase as the data maturity and the period of record increase. The instrument continues to function effectively and is likely to do so for the next several years.

The Senior Review Science Panel finds in support of the OCO-2 extension with the requested budget (over-guide in FY 2021-20123 and in-guide in FY 2024-2026). The augmented budget for the FY 2021-2023 period will allow for further refinement of the data products through an update of the instrument calibration, the gas absorption coefficients, and the retrieval algorithm, thereby further increasing the scientific utility of the data.

SAGE III

The Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument on ISS draws on the several decades-long heritage of previous SAGE (I, and II and III/Meteor) solar occultation measurements. As a result, it provides an extension of long-term data records, particularly for stratospheric ozone and aerosol extinction. The team has conducted a comprehensive error characterization of SAGE III products specific to operations on ISS necessary to improve the science readiness of SAGE III data. As the data become stable and data usage increases, they will contribute not only to the advancement of knowledge of atmospheric chemistry and dynamics but also to important statutory (Clean Air Act) and scientific (World Meteorological Organization quadrennial ozone assessment) activities that inform domestic and international policy. Future application of SAGE III data can potentially include the study of wildfire and volcanic eruption

emissions to the upper troposphere and lower stratosphere, where their effects on climate are understood poorly. The SAGE III instrument is healthy and anticipated to continue returning high-quality science data, despite occasional ISS mission interruptions, from its location on the International Space Station for the next several years.

The Senior Review Science Panel finds in support of SAGE III extension with the in-guide budget for the FY 2021-23 and FY 2024-26 periods.

SMAP

The Soil Moisture Active/Passive (SMAP) mission was launched in early 2015 with two instruments onboard: a radar and an L-Band radiometer. The radar stopped operating in the same year, and the radiometer has been operating alone since then. The loss of the radar affected the spatial resolution of SMAP products. Otherwise, soil moisture, vegetation optical depth, and freeze-thaw products (all unique to the PoR) are available globally. These data sets have been used to advance water-cycle and coupled water-carbon cycles science and for many societal applications. In particular, SMAP soil moisture products are used operationally at the National Drought Mitigation Center, and the US Air Force Weather Agency is working toward data assimilation of SMAP soil moisture information into their operational weather forecasts. The Senior Review proposal includes the development of new sea surface salinity products and new soil moisture products with enhanced spatial resolution through a partnership with the planned NISAR mission. Further, SMAP extension enhances the possibility of continuous L-band radiometric observations of the Earth's land surface for more than 20 years, taking into account previous observations made by the European Space Agency's Soil Moisture Ocean Salinity (SMOS) mission since 2010 and potentially by observations from the ESA's Conical Imaging Microwave Radiometer (CIMR) high-priority candidate mission.

The Senior Review Science Panel finds in support of SMAP extension with over-guide budgets for FY 2021-2023 and FY 2024-2026. The over-guide augmentation request is to update the Science Data System (SDS) to prevent possible data delays, and to incorporate SMAP near-real-time observations into NASA's Land Atmosphere Near real-time Capability for EOS (LANCE) system, so they are more readily available to other users.

Terra

Terra has performed for more than 20 years as the flagship of the EOS era with a suite of five complementary sensors that have each generated vital and outstanding records of observations and multiple, well-documented data products used widely by the scientific community worldwide and in diverse applications and operational settings by multiple governmental agencies. Terra’s data sets are unique contributions to PoR, given the unique morning descending orbit. Terra's orbit will change in 2022 as it will begin adjusting toward its disposal orbit; MLT crossings will drift from 10:30 AM to 9 AM by 2025. These orbit changes will require modifying the retrieval algorithms and will cause uncertainties to increase to varying degrees in MODIS and CERES products. However, observations at different times of day will also provide opportunities for new science.

The Senior Review Science Panel finds that the benefits of mission extension through 2022 and possible extension through 2025 are manifold. Terra's many products have no ready substitute for most of the applied and operational uses on which agencies currently rely, specifically MODIS products, and for the PoR. Given the good health of the Terra spacecraft and its instruments, the confidence is high that quality data will continue to be produced until orbit lowering begins in 2022. The Senior Review Science Panel unanimously supports Terra's extension in FY 2021-2023 and FY 2024-2026 with the proposed over-guide budget. Close monitoring of data quality and utility is warranted as the MLT crossings drift beyond 15 minutes, as discussed in the Overall Comments Section.

APPENDIX 1

Report of the 2020 National Interests Sub-panel of the NASA Senior Review

Chair: John Haynes
NASA Applied Sciences Program

Introduction
The 2020 National Interests Panel assessed the contributions of the core data products of the 13 missions under review to national objectives by assigning a utility value to each product or group of products.

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

The following organizations were represented on the panel: the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS); NOAA/National Ocean Service (NOS) ; the Federal Aviation Administration (FAA); the US Department of Agriculture (USDA); the US Army Corps of Engineers (USACE); the Environmental Protection Agency (EPA); the Department of the Interior/US Geological Survey (USGS); the Department of the Interior/National Park Service (NPS); the National Geospatial-Intelligence Agency (NGA); the Centers for Disease Control and Prevention (CDC); the Institute for Global Environmental Strategies (IGES); Microsoft; and Conservation International (CI).

The panel met for preliminary deliberations on April 28, 2020, and then convened for final deliberations on July 6-7, 2020. Both meetings were held virtually.

Pre-panel Activities
Each organization represented on the panel pre-assessed three primary factors and one overall rating for each mission during March/April 2020. The assessed factors included:

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

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

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

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

At preliminary deliberations on April 28, the panel determined any questions to forward to mission teams via the Science Panel. Each mission team answered these questions during the full Science Panel in July 2020.

Panel Activities
Following the pre-assessments, the organization representatives met in a formal panel session over two days in July 2020. During this panel, 30 minutes of discussion time were allocated for each mission; however, 60 minutes were allocated for the flagship missions of Terra, Aqua, and Aura.

At the start of each discussion, an assigned Primary Reviewer introduced the mission and his/her organization's ratings. All organizations' pre-panel assessments and ratings were available for review by the panel. A round-table panel discussion then commenced. By the end of each discussion, the panel reached agreement on an overall utility rating for the mission and/or sensor.

Following discussions of all the missions, each organization separately ranked each mission quantitatively according to its post-panel view of national interests. Each representative was asked to assign 13 points to the mission of highest priority and one point to the mission of lowest priority.

The Primary Reviewers then prepared panel summaries for each mission.

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

NASA 2020 Earth Science Senior Review *National Interests Panel*		
Rating	**Definition**	**Missions**
Very High Utility	These missions have one or more very relevant and highly valued data products which are routinely used by one or more of the participating organizations for important activities. Loss of the data product(s) would have a significant negative impact on national on national agencies and organizations.	***Aqua, Terra***
High Utility	These missions have one or more data products which are routinely used by one or more of the participating organizations for their activities. Loss of the data product(s) would have a measurable negative impact on national agencies and organizations.	***Aura, CALIPSO, CYGNSS, ECOSTRESS, GPM, SAGE III, SMAP***
Some Utility	These missions have one or more data products which are used by one or more of the participating organizations. Loss of the data product(s) would have a small but measurable negative impact on national agencies and organizations.	***CloudSat, DSCOVR, LIS on ISS, OCO-2***
Not Applicable (aka, Minor / Negligible)	These missions had no identified or significant applied or operational utility to the participating organizations. Loss of the data product(s) would have no or negligible negative impact on national agencies and organizations.	***None***

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

Mission	Civil Agencies								Military / Intelligence Community		NGO			Overall Score
	A	B	C	D	E	F	G	H	J	K	L	M	N	
	NOAA NWS	NOAA NOS	FAA	USDA	USGS	CDC	EPA	NPS	USACE	NGA	CI	Microsoft	IGES	
DSCOVR ES Instruments	4	1	4	1	8	3	1	5	1	2	4	3	1	38
SAGE III	2	2	1	2	2	1	3	10	3	4	2	1	5	38
OCO-2	1	4	3	8	3	4	2	8	2	5	7	5	4	56
LIS on ISS	8	3	8	3	1	7	7	7	5	1	8	4	3	65
CloudSat	6	5	10	5	4	6	5	6	7	3	5	7	2	71
CALIPSO	7	8	9	6	9	8	11	1	6	8	1	8	6	88
CYGNSS	5	7	5	9	7	5	9	2	9	11	6	6	7	88
ECOSTRESS	3	6	2	10	11	2	4	9	8	6	10	9	8	88
Aura	11	11	6	4	10	11	10	4	10	10	3	2	10	102
GPM	10	10	13	7	5	9	6	3	4	9	11	10	11	108
SMAP	9	9	7	11	6	10	8	11	11	7	9	11	9	118
Aqua	13	13	12	12	12	12	12	13	12	12	12	13	12	160
Terra	12	12	11	13	13	13	13	12	13	13	13	12	13	163

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

Mission / Sensor	Overall Rating	Civil Agencies								Military / Intelligence Community		NGO		
		NOAA NWS	NOAA NOS	FAA	USDA	USGS	CDC	EPA	NPS	USACE	NGA	CI	Microsoft	IGES
Aqua	**Very High Utility**	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility
AIRS	**High Utility**	Very High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility
CERES	**Some Utility**	Not Applicable	Very High Utility	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility
MODIS	**Very High Utility**	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility
Aura	**High Utility**	Very High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	High Utility	Not Applicable	Very High Utility	High Utility	Not Applicable	Not Applicable	High Utility
MLS	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Not Here	Some Utility	Not Applicable	Not Applicable	Not Applicable
OMI	**Very High Utility**	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Very High Utility	High Utility	Not Applicable	Not Here	Very High Utility	Not Applicable	Not Applicable	High Utility
CALIPSO	**High Utility**	Some Utility	Not Applicable	High Utility	Not Applicable	High Utility	Some Utility	High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	High Utility	High Utility
CloudSat	**Some Utility**	Some Utility	Not Applicable	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Some Utility	Not Applicable	High Utility	Some Utility
CYGNSS	**High Utility**	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Very High Utility	Not Applicable	High Utility	High Utility
DSCOVR	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable
EPIC	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable
NISTAR	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable
ECOSTRESS	**High Utility**	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	Not Applicable	Not Applicable	Some Utility	Very High Utility	High Utility	Some Utility	Very High Utility	Very High Utility
GPM	**High Utility**	High Utility	Very High Utility	Very High Utility	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	High Utility	Very High Utility	High Utility
LIS on ISS	**Some Utility**	Some Utility	Not Applicable	Some Utility	Not Applicable	Some Utility	Some Utility	Some Utility	Not Applicable	Not Applicable	Some Utility	Some Utility	Some Utility	Some Utility
OCO-2	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	High Utility	Not Applicable	Some Utility	Some Utility
SAGE III	**High Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Very High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	High Utility
SMAP	**High Utility**	High Utility	High Utility	Some Utility	Very High Utility	High Utility	Some Utility	Not Applicable	High Utility	Very High Utility	High Utility	Some Utility	Very High Utility	High Utility
Terra	**Very High Utility**	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility
ASTER	**High Utility**	Not Applicable	Not Applicable	Some Utility	High Utility	Very High Utility	Some Utility	Not Applicable	Some Utility	Very High Utility	Very High Utility	Some Utility	Not Applicable	High Utility
CERES	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Some Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility
MISR	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility
MODIS	**Very High Utility**	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility
MOPITT	**Some Utility**	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Some Utility

PANEL SUMMARIES OF EACH MISSION

Terra (Very High Utility)

The panel easily reached a consensus rating of very high utility, primarily due to the great practical utility of Moderate Resolution Imaging Spectroradiometer (MODIS) for a wide range of applications. The value of other sensors, particularly the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), added to utility rating. Uses included:

1) USACE uses ASTER data to validate MODIS derived land cover and fire. The USGS Mineral Resources Program uses ASTER data to map altered minerals and volcanic hazards. NGA uses ASTER data for mineral analyses.

2) CDC noted that Multi-angle Imaging Spectroradiometer (MISR) data provide a large database of wildfire smoke and aerosol plume heights, which are useful in determining the spatial extent of aerosol emissions.

3) Clouds and the Earth s Radiant Energy System (CERES) value was noted for general climate applications and assimilation in global weather forecast models, similar to Aqua.

4) MODIS supports diverse atmospheric, oceanic, and terrestrial applications. EPA uses MODIS for aerosols (as does CDC) and change detection algorithms, including production of daily surfaces of nationwide Particulate Matter (PM) 2.5 (AirNow). NOAA/NOS and NWS state that MODIS is the primary data source for sea ice analysis. USDA uses MODIS in monitoring fire growth, hot spots, and new fire detection. MODIS data is also used to support numerous decision support tools, such as Smartfire. NGA uses MODIS data to address environmental and agricultural issues, commonly through Normalized Difference Vegetation Index (NDVI) products.

5) CDC uses Measurement Of Pollution In The Troposphere (MOPITT) data for carbon monoxide (CO) profiles in major cities and long-term CO trends. NGA is using MOPITT data to observe changes in CO profiles due to coronavirus disease 2019 (COVID-19) mitigation efforts.

Aqua (Very High Utility)

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

1) The importance and utility of Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU) data was widely noted. Profiles are assimilated in NOAA numerical weather prediction (NWP) models and AIRS data are considered one of their most critical NASA data sets. CDC noted use of key trace atmospheric constituent data in environmental health applications.

2) MODIS supports diverse atmospheric, oceanic, and terrestrial applications. NDVI products are used by USGS in the Famine Early Warning Systems Network (FEWS NET) to monitor drought conditions. MODIS data remain the most widely and broadly used data set in NOAA. MODIS images have become one of the primary data sources for their ice analyses. NGA uses MODIS Snow Cover products, supplied by the US Air Force, in support of military operations in Central Command's (CENTCOM's) Areas of Responsibility (AR). USDA uses MODIS products to monitor global croplands for food security, cropland water use assessments, drought studies, and other natural resources assessments.

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

SMAP (High Utility)

Soil Moisture Active/Passive (SMAP) serves the community well in forecasting flash floods in agricultural watersheds, parameterizing the strength of the relationship between surface soil moisture and evapotranspiration with land surface models, monitoring the extent and severity of global agricultural drought, closing the terrestrial water balance over medium-scale agricultural

basins, and effectively monitoring cropland evapotranspiration. The mission was rated very positively, despite the limiting factor of losing the Active part of the mission. Uses included:

1) NOAA National Environmental Satellite, Data and Information Service (NESDIS) ingests SMAP radiometer data into the Soil Moisture Operational Product System (SMOPS) to provide the best available satellite global soil moisture data products for NWS NWP and other uses. The NOAA Climate Prediction Center (CPC) uses SMAP data operationally to determine where drought areas exist, and where drought conditions are improving or getting worse.

2) USDA noted that SMAP data are assimilated into a soil water balance model to improve ability to globally-track soil water availability and anomalies within the root-zone. These root-zone assessments are then provided to regional crop assessment analysts who include them in regional crop yield models worldwide. SMAP data products are assimilated to improve the National Agricultural Statistics Service's (NASS) operational weekly Crop Progress and Condition Report, which has over 13,000 weekly subscribers.

3) Microsoft uses SMAP data in soil moisture prediction modeling, particularly in data sparse regions. Data has been used successfully for crop yield prediction and harvest timing.

The panel praised the SMAP Early Adopter program as an effective model for operational agencies to dedicate resources to prepare earlier for missions that potentially benefit their monitoring programs. The Early Adopter program focused Agency mission activities and resources to prepare for the operational three-year mission, thereby creating mission awareness, preparedness, and enabling research and monitoring actions at an earlier than normal rate. Private sector organizations echoed the value of this program.

GPM (High Utility)

Global Precipitation Measurement (GPM) is the advanced successor to the Tropical Rainfall Measuring Mission (TRMM), with higher frequency channels added to both the Dual-frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), providing capabilities to sense light rain and falling snow. The mission unifies the data from a constellation of 10 partner sensors to generate the global next-generation merged precipitation estimates. There are widespread applications in precipitation structure and intensity; tropical cyclone observations; hazard assessment for floods, landslides, and droughts; inputs to improve weather and climate models; and insights into agricultural productivity, famine, and public health. Uses included:

1) NGA uses GPM data for baseline mapping for predictive hydrologic analyses, including food security risk assessments.

2) NOAA uses GPM data for operational tropical cyclone analysis and forecast applications, including center location and identification and structural analysis, as well as the identification of eyewall formation and eyewall replacement cycles.

3) FAA noted GPM as its most important NASA mission. Research partners use the dual-band radar as an independent data set in a comparison of ground-based radar mosaics, in the evaluation of a radar-like diagnostics, and as a truth set for evaluations of global convective forecast products. Data are also being evaluated for turbulence case studies.

4) CI uses GPM data in their FireCast Program (daily products reporting fires and fire risk trends) and in their Freshwater Health Index, where data are used to drive hydrological models and provide background information for target watersheds.

Aura (High Utility)

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

1) NOAA is using OMI in a near real time (NRT) mode to calculate total column ozone, which is currently assimilated into the National Centers for Environmental Prediction (NCEP) Global Forecast System.

2) The USGS Volcano Hazards programs uses OMI NRT data for eruption detection, forecasting, and eruption modeling.

3) CDC has partnered with researchers at Emory University and the University of Nebraska to conduct a health study exploring associations between UV exposures (derived from OMI) and melanoma. County-level ultraviolet (UV) data from OMI are now available on the CDC Environmental Public Health Tracking Network (EPHTN) for environmental health end users and researchers.

4) OMI NRT SO_2 and Aerosol Index (AI) data are integrated into the decision support system at the NOAA NESDIS Washington Volcanic Ash Advisory Center (VAAC).

5) EPA uses OMI data for assessment of pollutants and the input is assimilated into other climate models. OMI NO_2 and SO_2 data have been highlighted in the EPA annual Air Quality Trends Report. OMI HCHO data are also used by EPA to estimate and map cancer risks from formaldehyde.

6) NGA uses Microwave Limb Sounder (MLS) to monitor atmospheric conditions that may impact image acquisition. Other parameters (e.g., CO and N_2O) can be used as proxies of industrial and urban activity.

ECOSTRESS (High Utility)

ECOSTRESS was delivered to the International Space Station (ISS) in 2018 as a one-year mission with targeted terrestrial land mapping areas. Currently, it is the only sensor that provides

thermal infrared (TIR) data of sufficient spatial, temporal and spectral resolution to reliably estimate evapotranspiration (ET) at local to global scales over the diurnal cycle. The panel found the pathfinder mission to be of high utility and high interest, particularly notable for a young mission. Some of the applications reported by the panel include monitoring of agriculture, water, snow and mineral resources, and mapping of land surface temperature and emissivity. Uses included:

1) Microsoft uses the data in agricultural applications, including crop harvest prediction/modeling, especially when combined with other observed data such as soil moisture, air temperature, and precipitation.

2) USACE uses ECOSTRESS data for supplementary land cover and ecosystem information related to military planning, mapping, and modeling.

3) USDA uses the data for evapotranspiration, drought stress in Ponderosa pine conifers, tree plot estimation, water resources, and in algorithm development work towards the next Landsat mission.

4) USGS noted that ECOSTRESS data are specifically used in the mineral mapping, land surface temperature, land cover, hydrological modeling, glaciology, fire, volcanic science and operation programs, as well as in Landsat Next sensor algorithm development tasks.

The panel encouraged that the firmware update be completed as soon as possible in order to enable downlink of all five TIR bands.

CYGNSS (High Utility)

Cyclone Global Navigation Satellite System (CYGNSS) is the first mission to routinely take GNSS-Reflectometry (GNSS-R) measurements over the global tropics, the first NASA mission to employ a constellation of small (micro) satellites, and the first mission to use differential drag maneuvers to maintain constellation spacing. CYGNSS fills a critical need for observations of ocean surface winds over global tropical oceans with revisit frequency high enough to observe the tropical cyclone (TC) rapid intensification process. The panel rated CYGNSS as high utility, primarily based on novel applications of the data, including for soil moisture retrievals and ionospheric modeling.

1) NGA is using the data in maturing ionospheric modeling capabilities for improved Over the Horizon Radar performance as a possible source of geospatial intelligence.

2) For USACE, CYGNSS provides a signal of opportunity soil moisture downscaling verification signal that provides much higher resolution soil moisture nodules. CYGNSS fills in the missing critical function of validating high resolution soil moisture algorithms via remote sensing, a function which is unable to be performed in denied areas. It is a critical part of the soil moisture system of sensors when calculating mobility models from observation, as opposed to modeling.

3) CYGNSS data are used within USDA for the purposes of providing water quantity (soil moisture) estimates at the near surface and are being developed and integrated into large scale monitoring estimates including the National Soil Moisture Network. The data are currently in development for a soil moisture product which would be on par with Advanced Microwave Scanning Radiometer 2 (AMSR2), AMSR-E, or Soil Moisture and Ocean Salinity (SMOS).

CALIPSO (High Utility)

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data products are produced routinely, archived, and made available to researchers worldwide through data centers in the United States and France. Several agencies ranked CALIPSO as high utility, while others said it had only some utility for their community. Many organizations are using CALIPSO data for operational and verification purposes. The overall rating of high utility is given due to the importance of the aerosol data in operations and verification. Uses included:

1) FAA stated that CALIPSO data are one of the primary sources used for evaluating the quality of icing forecast products. When combined with CloudSat profiles, the resulting data have provided accurate retrievals of column aerosol optical depth and cloud ice-water content. Additionally, the data are important for volcanic ash plume detection and plume dispersion prediction.

2) EPA has integrated CALIPSO data into the Community Multi-scale Air Quality (CMAQ), a key component of EPA's decision support system in managing air quality domestically and also in meeting US international obligations.

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

4) NOAA utilizes data for cloud top height, cloud typing, and volcanic ash detection. It is also used for NWP model validation.

SAGE III (High Utility)

Stratospheric Aerosol and Gas Experiment III (SAGE III) was delivered to the ISS to extend the collection of observations of the vertical structure of aerosols and trace gases in the stratosphere and upper troposphere for development of high precision and high-resolution data products supporting climate research. While only four organizations noted use of SAGE III data, the importance of the data to climate applications and continuity of the data record led the panel to concur on high utility. Uses included:

1) NPS noted that SAGE III data are critical to the agency's Interdisciplinary Science Group on climate change.

2) USGS highlighted the utility of SAGE III for volcanic research and monitoring programs.

3) NGA noted value in monitoring of industry at regional scales.

4) IGES stated the importance to partners of SAGE III for continuity in the data record.

CloudSat (Some Utility)
CloudSat is the only source for combined vertical profiles of global cloud liquid content/ice. Operationally, it is used as an independent source in model verification of clouds and cloud structures and is an uninterrupted source for aviation and weather prediction applications. Outside of these applications, limited utility was noted. Uses included:

1) CloudSat supports over 100 programs within USGS via direct and indirect means. Programs utilizing CloudSat indirectly range from climate and land use change; glacier research; contaminant biology environmental impact assessments; drought assessments and groundwater studies; snow cover modeling; and volcano hazards.

2) FAA utilizes CloudSat data in conjunction with CALIPSO as part of icing forecasts by identifying cloud layers in regions where temperatures support the presence of supercooled water. CloudSat data are used to verify nowcasting products and to forecast high ice water content clouds. Recent experimental applications of the data are being incorporated with the commercial aviation sector, as well as civil and defense weather.

3) NOAA notes that CloudSat data are being investigated to improve Geostationary Operational Environmental Satellite-R (GOES-R) algorithms. CloudSat data are used by NOAA/Global Systems Laboratory to evaluate the quality of icing forecast products.

The panel stated that a clearer pathway to operations and additional outreach could alleviate some of the low and not applicable (N/A) ratings by multiple agencies.

LIS on ISS (Some Utility)
Lightning Imaging Sensor (LIS) is deployed on the ISS for lightning detection and is the sibling sensor of TRMM LIS. LIS provides total lightning measurements in NRT between +/- 48 degrees latitude, which covers a geographic range that includes nearly all global lightning. The panel found some utility for these measurements, although acknowledged that the data have been superseded in many instances with Geostationary Lightning Mapper (GLM) on GOES. Uses included:

1) Some NOAA NWS field offices are evaluating LIS on ISS data as part of their operations through a project with NASA Short-term Prediction Research and Transition Center (SPoRT). The National Hurricane Center (NHC) is currently developing a rapid intensification tool that uses lightning input, and intends to utilize LIS on ISS.

2) Microsoft stated that their defense and intelligence industry partners indicate some utility in detection of false alerts for nuclear detonation.

3) FAA is investigating using the data in upcoming turbulence case studies.

4) USGS is investigating LIS on ISS data to monitor lightning events for wildfire risk.

OCO-2 (Some Utility)
Orbiting Carbon Observatory-2 (OCO-2) monitors CO_2 with enough precision to identify sources and sinks at a regional scale. OCO-2 is also capable of monitoring solar-induced chlorophyll florescence, a measure of early plant stress. OCO-2 currently provides limited value for a few agencies; however, this mission has the potential to positively impact additional agency programs. The panel anticipated expanded uses to be documented in future National Interest Panels. Uses included:

1) USGS uses OCO-2 data in their hydrology and climate change and land carbon estimation programs.

2) IGES noted increased use of and interest in OCO-2 data among partners in the private sector concerning carbon emissions.

3) NGA utilizes the raw and calibrated radiance to provide an increased understanding and accuracy of estimates concerning food, water, and environmental issues. The CO_2 products provide trends in urban and industrial areas in support of addressing economic national security issues.

The panel stressed the need for improved communication and educational opportunities with potential users at other agencies and, particularly, the private sector. The panel stated that there were likely other organizations who could benefit in applying OCO-2 products to their missions, but lack of awareness has hampered broader adoption.

DSCOVR (Some Utility)
Deep Space Climate Observatory (DSCOVR) provides a unique Earth Observation data set from the Lagrange 1 (L1) vantage point. There are two Earth observation instruments: the Earth Polychromatic Imaging Camera (EPIC) and the National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR). Two agencies currently found utility in observations from DSCOVR; however, others remarked that their organizations were unaware of the mission and its capabilities, so lack of communication/outreach is an issue. The coarse resolution of the data products may also prevent certain applications from using the data. These issues led to a rating of some utility by the panel. Uses included:

1) USGS noted that the Landsat Science Team is investigating DSCOVR data for supplemental atmospheric characterization.

2) NGA stated that EPIC's continuous observation of the Earth allows for the examination of influence of bidirectional reflectance factors on intelligence matters; however, the spatial resolution of EPIC limits these to general trends. Also, the format of the data is very different than other missions, limiting utility.

The panel encouraged better communication of DSCOVR products to the applications community, possibly through workshops, webinars, conference sessions, etc. The absence of DSCOVR data from June 2019 to March 2020 was also noted.

APPENDIX 2

Report of the 2020 Technical Sub-panel of the NASA Senior Review

Chair: T. Duncan Fairlie
NASA Science Office for Mission Assessments

Introduction

NASA's Science Mission Directorate (SMD)/Earth Science Division (ESD) periodically conducts comparative reviews of on-orbit missions in extended operations to maximize the scientific return of the Earth Science mission fleet within finite resources, a process called the Senior Review for Extension of Operating Missions. NASA uses the findings from these comparative reviews to define an implementation strategy and give programmatic direction and budgetary guidelines to the missions and projects concerned for the next 6 fiscal years (matching the Federal government's budget planning cycle). This periodic NASA comparative review for missions in extended operations is known as the "Senior Review."

The following thirteen missions (in alphabetical order) were invited to propose to the 2020 Senior Review: Aqua, Aura, CALIPSO, CloudSat, CYGNSS, DSCOVR Earth Science Instruments, ECOSTRESS, GPM, LIS on ISS, OCO-2, SAGE III, SMAP, and Terra. Performance factors are to include quality and demonstrated scientific utility of the mission datasets, contributions to national objectives, technical status and budget efficiency. The period for the 2020 review covers Fiscal Years (FY)2021 through FY26.

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

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

The National Interests Panel assesses the utility and applicability of the mission's data products to satisfy national objectives through non-research use for applied and operational purposes by non-NASA organizations. The National Interests Panel is drawn from federal, local government, non-profit and commercial users of NASA research data.

The Senior Review Panel considers the results from the National Interest Panel and the Technical Sub-panel in their final review findings and ratings.

The NASA Science Office for Mission Assessments (SOMA) performs a Technical Review that partially mirrors the Technical, Management, and Cost (TMC) evaluations that NASA SOMA performs on Pre-Phase A mission concepts. As the Senior Review proposals are for extensions on

the Operations and Sustainment phase (extended Phase E), the Technical Review emphasizes the hardware status and performance, life expectancy, and mission operations plans for health, safety, and data collection. Figure 1, below, shows the role of the technical sub-panel in the Senior Review flow.

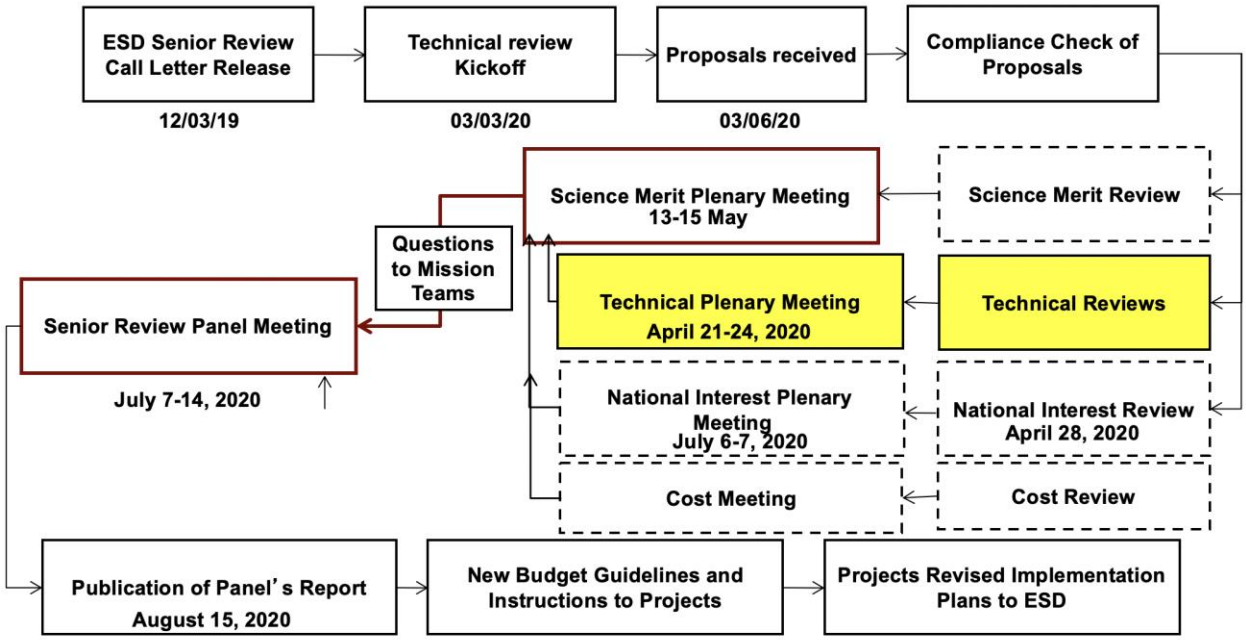


Fig. 1. Senior Review Flow

Proposers were instructed in the "Call for Proposals – Senior Review 2020 for Extension of Earth Science Operating Missions" to:

> *"Discuss the overall technical status of the elements of the mission, and the team's approach to managing operations to optimize health and vitality of the elements. Include the spacecraft, instruments, and ground systems including spacecraft control center and science center(s). Summarize actions taken to improve the effectiveness of the mission operations tasks and describe what improvements have been accomplished. Summarize the health of the elements and point out limitations as a result of degradation, aging, use of consumables, obsolescence, failures, orbit changes, etc. Hosted instruments, especially those on the International Space Station, should address accommodation issues such as cleanliness or duty cycles, that may affect the dataset. Include an estimate and rationale of mission life expectancy, including an estimate of post-mission lifetime (assuming the initial 3-year extension) and an updated estimate of the reliability to accomplish your planned end-of-mission passivation procedure (also assuming the 3-year extension). Provide supporting data in the form of engineering data tables and figures in Appendix E."*

Technical Review

Technical Review Criteria

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

The Technical Sub-panel is assigned the task to assess each mission's performance and reliability projections for the satellite and instrument(s), the mission operations implementation plan, and the likelihood of accomplishment within the proposed cost. The technical experts will consider factors including the status of consumables and predicted utilization; spacecraft and instrument status, performance degradation, and failure risk; the proposed mission operations approach for the effective and safe management of an aging satellite; and mission and data management. The Technical Review results in narrative text as well as a Risk Rating for the feasibility of the extended mission implementation.

Technical Review Principles

The basic assumption is that each mission will be extended unless significant technical weaknesses are evident that raise concerns about the proposed mission extension. The proposer is regarded as the expert on his/her proposal, and is therefore accorded limited benefit of the doubt.

The proposer's task is to provide evidence of the viability of the mission extension. During the review the Technical Sub-panel's task is to try to validate the proposer's assertion of risk.

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

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

Technical Risk Ratings

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

Technical Risk Ratings are defined as

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

Technical Review: Definitions of Findings

Each finding is identified as a

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

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

Technical Review Process

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

The Technical Sub-panel develops individual comments, followed by findings for each proposal that reflect the general agreement of the entire sub-panel. Comments form the basis of findings as follows: "above expectations" translate into "strengths", "below expectations" translate into

"weaknesses", and "as expected" do not result in findings. Sub-panel teleconferences are held for each proposal to discuss comments and findings. During the discussions, individual comments are kept, merged with other similar individual findings, or dismissed where appropriate.

A Technical Sub-panel Meeting is held to refine and finalize the Technical Forms and determine the Risk Rating for each proposed mission extension. Findings are refined, merged with other similar findings, or dismissed. Each Form is reviewed 3 times and polling is held to determine the Risk Rating.

Technical Review Product

The Technical Review of the 2020 Senior Review results in a Technical Review Form for each proposal. This form is labeled with the appropriate Mission name and Principal Investigator; it contains the Risk Rating and a rationale paragraph explaining the rating; and it enumerates the Major Strengths, the Major Weaknesses, the Minor Strengths, the Minor Weaknesses, and any questions sent to the proposing mission team. This form is the product of the Technical Review process described above and for each proposal it is regarded as the report from the Technical Sub-panel to the Senior Review Panel.

Technical Review Summary Results

Table 1 shows the Risk Ratings for each proposed mission extension. Including the Technical Review Form for each proposal in this report would be very cumbersome therefore only the risk rating and rationale are presented. If more detail on the results of the Technical Sub-panel is required, the Technical Review Forms are available from the NASA SOMA archive. The rationales are organized alphabetically.

Table 1. Summary results of the Technical Review for the 2020 Senior Review

Mission \ Risk	Low	Medium-Low	Medium	Medium – High	High
CALIPSO			X		
ECOSTRESS			X		
GPM			X		
SMAP			X		
Aura		X			
CloudSat		X			
CYGNSS		X			
Aqua	X				
DSCOVR	X				
ISS-LIS	X				
OCO-2	X				
SAGE III	X				
Terra	X				

Rationale statements

Aqua

The Aqua proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified four Major Strengths and no Major Weaknesses. The Atmospheric Infrared Sounder (AIRS) instrument is expected to continue to perform well throughout the extended mission. The Clouds and the Earth's Radiant Energy System (CERES) instruments (FM-3 and FM-4) performance is unchanged since 2017, and nearly all instrument components appear to be in excellent condition and are expected to perform well for the anticipated life of the spacecraft. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument continues to operate very well, and is expected to continue to perform well throughout the extended mission. All spacecraft subsystems remain configured through their primary-side hardware, providing resilience to anomalies that may occur during the remaining years of the mission.

Aura

The Aura proposed mission extension is rated as **Medium-Low Risk**. The Senior Review Technical evaluation has identified one Major Strength and no Major Weaknesses. The Microwave Limb Sounder (MLS) is in very good condition after 15 years of successful operation in orbit and should operate successfully through 2024. Minor Strengths include: The Ozone Monitoring Instrument (OMI) is currently operating at reduced efficiency … but is still producing useful scientific data and should continue to operate well through the extended mission; the Aura spacecraft bus continues to perform adequately, having never experienced safe or a survival mode event. Minor weaknesses associated with the Flight Systems were noted by the panel.

CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) proposed extension is rated as **Medium Risk**. The Senior Review Technical evaluation has identified three Major Strengths and one Major Weakness. The three-band Infrared Imaging Radiometer (IIR) has performed well within specification with the exception of the low voltage power supply, and can be expected to continue to work well for several years. The Wide Field of View Camera (WFC) is performing well and is expected to do so throughout the extended mission*. The CALIPSO spacecraft bus continues to perform well, and all of its subsystem redundancies remain in place. However, the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) backup laser is near the end of its useful life due to a steadily increasing frequency of low energy laser pulses, and it is uncertain whether a re-start of the primary laser will be successful.

*The panel notes that the WFC is currently powered off, but is assured that "the temporary loss of the WFC data is not considered a significant impact to the mission" (CALIPSO mission report of 20200423).

CloudSat

The CloudSat proposed mission extension is rated as **Medium-Low Risk**. The Senior Review Technical evaluation has identified one Major Strength and no Major Weaknesses. The Cloud Profiling Radar (CPR) can be expected to perform within specification well beyond the extended mission with a likely switch to the backup Extended Interaction Klystron (EIK) within about a year. Minor Strengths include: The CloudSat spacecraft bus continues to perform adequately and

is expected to fully support the continued operations through 2026. Some subsystems have experienced degradation and lost redundancy, but are not expected to impact continued operations.

CYGNSS

The Cyclone Global Navigation Satellite System (CYGNSS) proposed mission extension is rated as **Medium-Low Risk**. The Senior Review Technical evaluation has identified two Major Strengths and no Major Weaknesses. Since science operations began on 18 March 2017, the doppler delay mapping instrument has been performing very well, returning data with close to 100% duty cycle, and this performance is expected to continue through the extended mission. Nearly all of each Observatory's subsystems are operating well, no major, ongoing degradation of any components has been observed, and trending indicates that all eight CYGNSS observatories are likely to continue nominal science operations through the proposed extended mission.

DSCOVR

The Deep Space Climate Observatory (DSCOVR) proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified three Major Strengths and no Major Weaknesses. The Earth Polychromatic Imaging Camera (EPIC), a Cassegrain-based system featuring 10 narrow bands and a Charge Coupled Device (CCD) for ultraviolet (UV) – visible (VIS) – near infrared (NIR) imaging, is performing well and is expected to continue to do so throughout the extended mission. The NIST Advanced Radiometer (NISTAR), a three-cavity electrical substitution radiometer (ESR), is operating as expected, has not had any issues, and can be expected to perform stably for many years. The majority of the spacecraft subsystems are operating well and are expected to be able to support the proposed mission extension.

ECOSTRESS

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) proposed mission extension is rated as **Medium Risk**. The Senior Review Technical evaluation has identified one Major Strength and no Major Weaknesses. ECOSTRESS, a thermal infrared cross-track scanning radiometer, is currently collecting data in three of five spectral bands within the 8 to 12.5 micrometer region, and exhibits good instrument health that is expected to continue throughout the extended mission. While all minor strengths and weaknesses were also considered in the risk assessment, one significant Minor Weakness was identified, as follows: ECOSTRESS's proposed plan to continue science operations for the full duration of the proposed extension is not supported by the current International Space Station (ISS) manifest planning.

GPM

The Global Precipitation Measurement (GPM) proposed mission extension is rated as **Medium Risk**. The Senior Review Technical evaluation has identified two Major Strengths and one Major Weakness. The GPM Core Observatory (GPM-CO) instruments, the Dual-frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), have been stable and have performed very well since launch in 2014. Most of the GPM bus subsystems are expected to continue to operate well throughout the proposed mission extension. However, the majority of the Precipitation Processing System (PPS), a very important component of the ground system for the GPM mission, has either exceeded its operational life or is very close to doing so, and there are insufficient resources to provide urgently needed maintenance and updates to the hardware. While all minor strengths and weaknesses were also considered in the risk assessment, one significant Minor

Weakness was identified, as follows: Given the recent malfunction with Reaction Wheel Assembly (RWA) #5, and the 2019 failure of RWA #2, there is an increased concern that an additional RWA will fail within the extended mission period, and that the remaining control authority may not be sufficient to support nominal operations.

ISS-LIS

The ISS-LIS proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified one Major Strength and no Major Weaknesses. The Lightning Imaging Sensor (LIS) on the ISS, based on an Optical Transient Detector (OTD) design, has had radiation and operational issues, but these appear to have been resolved and LIS can be expected to perform predictably for several years.

OCO-2

The OCO-2 proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified two Major Strengths and no Major Weaknesses. The single instrument on OCO-2, a three-channel imaging spectrometer, can be expected to continue to perform for many years with minor optical and detector degradation, and no significant issues remaining to be addressed. The OCO-2 spacecraft is in excellent health and is expected to support the continued operations without issue.

SAGE III on ISS

The SAGE III/ISS proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified one Major Strength and no Major Weaknesses. The SAGE III instrument, a grating spectrometer measuring UV, visible, and NIR energy using solar/lunar occultation techniques, has performed reliably and can be expected to continue its performance with only very minor issues.

SMAP

The SMAP proposed mission extension is rated as **Medium Risk**. The Senior Review Technical evaluation has identified two Major Strengths and one Major Weakness. The SMAP L-band RADiometer (RAD) is healthy and likely to operate successfully for several years. The SMAP spacecraft is in excellent health and should support the mission extension without major issues. However, the Science Data System (SDS) hardware is currently past its design life, has suffered failures that impacted science operations, and is nearing storage capacity; without additional data storage, storage limits will be reached early in the extended mission.

The SMAP mission technical risk for the 2023-2026 operations extension period is expected to be higher due to the lack of a budget for the SDS hardware maintenance or additional science data storage and due to the ongoing spacecraft Non-Volatile Memory (NVM) degradation.

Terra

The Terra proposed mission extension is rated as **Low Risk**. The Senior Review Technical evaluation has identified six Major Strengths and no Major Weaknesses. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument, which scans along-track in the visible and near infrared, and across-track in the thermal infrared, and with the exception of the shortwave infrared (SWIR) channel, has performed as predicted since launch and

is expected to continue to do so for several more years. The two Clouds and the Earth's Radiant Energy System (CERES) broadband radiometer instruments have performed stably for the duration of the mission and should continue to do so for several years. The Multi-Angle Imaging SpectroRadiometer (MISR), with nine along-track Visible/Near InfraRed cameras, has performed stably and reliably throughout its lifetime, with combined radiometric performance at the 3% uncertainty level. The MODerate-resolution Imaging Spectroradiometer (MODIS), a visible to longwave cross-track scanner, has had minor issues, but can be expected to perform within requirements for several years. The Measurements of Pollution in the Troposphere (MOPITT), an 8-channel gas correlation spectrometer, is expected to operate predictably over the mission lifetime with 4 of 8 channels active. The majority of the spacecraft bus subsystems continue to perform well, with most of the redundancies in place.

The Terra mission technical risk for the 2023-2026 operations extension period is expected to be higher due to several failures experienced by the Electrical Power Subsystem. Operational impacts will likely occur starting in 2025, forcing mission termination in 2026.

APPENDIX 3

Report of the 2020 Cost Sub-panel of the NASA Senior Review

Chair: Richard Law
NASA Langley Research Center, Earth System Science Pathfinder Program Office. Richard Law was assisted by Mark Jacobs, Sherill Platt, and Takenya Roberts.

INTRODUCTION

The cost team conducted their analyses from February-July 2020. The cost team conducted one-on-one meetings with each the Senior Review Lead Reviewers, one for each of the reviewed projects, in July 2020 and met with the full Science Panel in July 2020 to discuss their analysis method, rating criteria, and discussed any required clarifications. The final meeting in July 2020 included presentations from each of the mission project teams including responses to the review panel's questions.

The cost analysis process followed was derived from the approach used to evaluate Announcement of Opportunity proposals, with necessary adjustments to incorporate unique aspects of the Senior Review. This process, represented by the "pyramid" (shown in the Figure 3-1), relies on detailed analysis of many items within each proposal to form the foundation of the analysis.

Findings from the proposal cost review and inputs from the full review panel are used to identify risk items, assess viability of risk mitigation plans, and define threats that could lead to cost growth. Given these missions are beyond the end of their primary mission, reserves are generally limited, and operating missions tend to rely on un-costed carryover from the prior year as reserve.

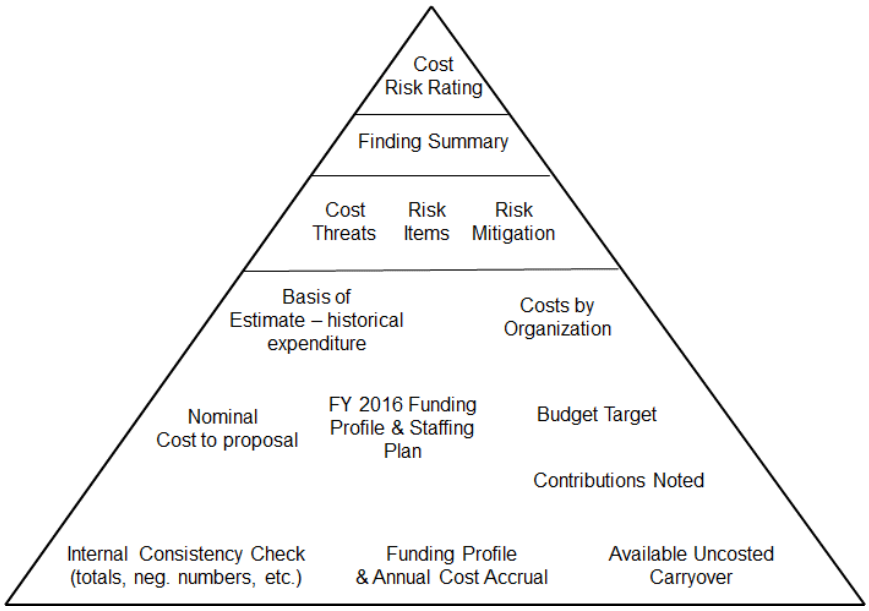


Fig. 3-1 Cost Analysis Process

The overall risks, mitigation plans, and cost threats all contribute to the overall cost risk rating. Five categories were used and definitions for each are provided in Figure 3-2. This cost risk rating is based on the proposed costs and plans during the period of performance. As secondary rating, the cost evaluation then looked at project request and compared to the funding target as provided as part of the 2020 Senior Review call letter. This portion of assessment considered prior years, fiscal year (FY) 2018 to FY2020, project's expenditures or cost accruals and compared it to the funding requested value as well as the available uncosted carryover.

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

Fig. 3-2 Risk Categories

HIGH-LEVEL COMPARISONS

Comparisons of the proposed funding levels for combined mission operations and data analysis (MO&DA), mission operations, and the science team are summarized in Figure 3-3. Most of the projects are near or below primary mission funding levels except CloudSat and Soil Moisture Active/Passive (SMAP), which are only slightly above 100%. The plot on the right shows the ratio of science team funding to mission operations. Projects with higher mission operations costs (above the dashed line) may be trading science data product efforts to support mission operations to maintain science data collection (with some deferred science analysis).

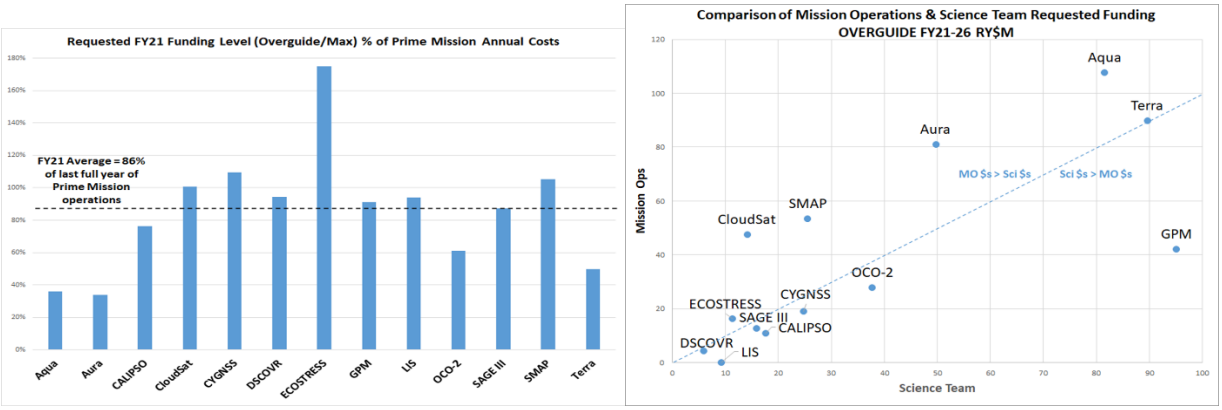


Fig. 3-3 Mission FY18 costs compared to previous expenditures (left), and ratio of mission to science dollars (right).

SUMMARY COST RATINGS

The final cost risk ratings are shown in Figure 3-4. Details for each project are provided in the next section of this report.

Mission	Cost Risk Rating	Rationale
CALIPSO	Med Risk	Efforts to revive primary laser may not succeed
CYGNSS	Low Risk	Requested funding appears conservative
Aqua	Low Risk	Reasonable request with well supported BoE
Aura	Low Risk	Request appears reasonable & HW is in good condition
DSCOVR	Low Risk	Request appears reasonable
GPM	Med/Low Risk	Request appears reasonable although concerns about RWAs
Terra	Low Risk	Request appears reasonable and HW in ok condition
LIS	Low Risk	Request appears reasonable; Overguide options based on likely delay to replace with CPF on ISS
CloudSat	Med Risk	S/C health beyond 2023 likely to have issues
ECOSTRESS	Med/Low Risk	Based on reasonable likelihood to experience HW issues operating out to 2026
SMAP	Med Risk	High level BoE; Unclear BoE for SAR "jump start" effort
OCO-2	Med/Low Risk	Not clear if Overguide funding is sufficient
SAGE III	Low Risk	Request appears reasonable

Fig. 3-4 Mission extension cost risk assessments for each mission as well as the high level rationale

INDIVIDUAL PROJECT COST ANALYSIS SUMMARIES

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

- Project-specific cost assessment summary.
- *Findings:* Includes significant items that may affect cost performance. These are based on details from the cost assessments covering various aspects of each proposal.
- *Evaluation Criteria Assessment*: Summarizes lower-level findings regarding evaluation criteria derived from the Call for Proposals.
- *Project Cost/Expenditure History and Request:* Shows funding and workforce by fiscal year for FY 2017 / 2019 through the proposed operating time. Data includes funding guidelines and uncosted carryover.
- *Cost Analysis Comparisons:* This analysis compares costs to the nominal operations level, MOS vs. Science, and costs by organization.
- *In-Kind Support/Funding:* This area covers all significant contributions toward each project's Mission Operations (MO) and Science Data Analysis (DA) requirements.

Additional supporting details covering all cost analysis areas were provided to the panel and are covered in a separate presentation ("2020 Senior Review - Cost Analysis Final Assessment Rating (4.30.17).ppt").

CALIPSO

CALIPSO Summary: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) received a Cost Risk Rating of Medium. The project's proposal is above their budget target to allow for extended operations through FY23. The CALIPSO primary laser has been non-operational (since February 2009) and the backup laser has a pressure leak. Expected life is 6-12 months. The team is planning to attempt restarting the primary laser. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

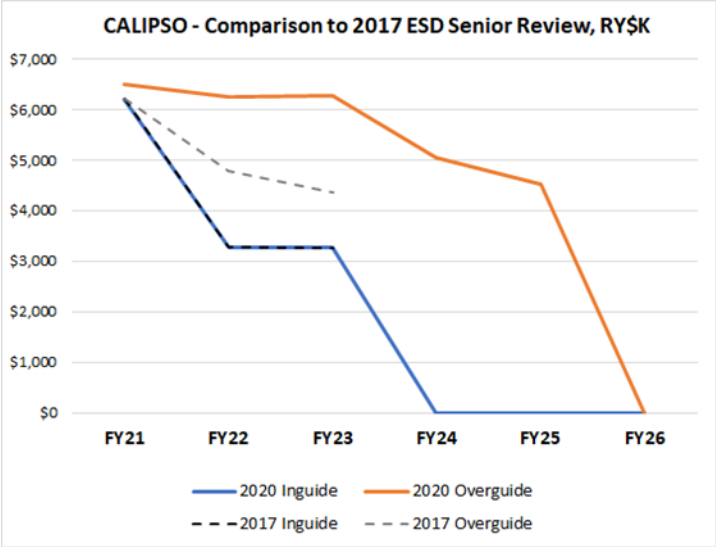
CALIPSO Findings:

- The Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) Secondary Laser expected end of life (EOL) is in 6-12 months
- Switchback to Primary Laser expected in 2021
- 2020 Overguide request is significantly higher than 2017 Overguide
- Driven by laser efforts and additional science
- Operation of beyond 2023 appears uncertain due to CALIOP performance and spacecraft (S/C) power; power margins are expected to go negative in September 2023.
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Assessment supports the proposed budget

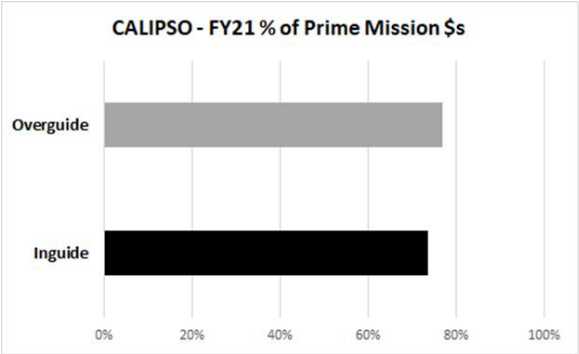
CALIPSO Evaluation Criteria Assessment:

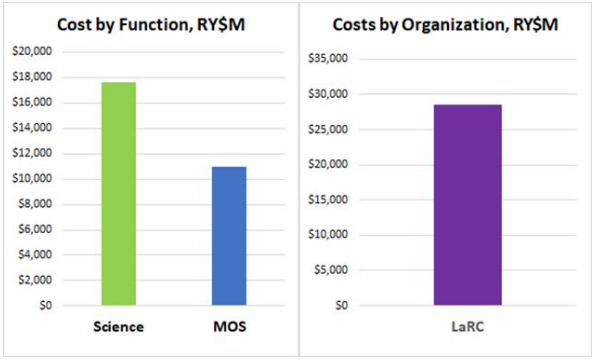
	Rating	Notes
Cost Risk Rating	Med Risk	Efforts to revive primary laser may not succeed
Technical Risk		
HW Status/Perf/Lifetime	Med/Hi Risk	In 688km disposal orbit since Sep'18; Switchback to primary laser in 2021
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		CALIOP low energy laser pulses
Overguide Request?	Yes	Pending successful restart of Primary Laser; Maintains joint CALIPSO-CloudSat science
Contributions? (*beyond ROSES*)	Yes	NISN LaRC/GSFC/CNES network support

CALIPSO Cost History and Request:



CALIPSO Cost Analysis Comparisons:





CALIPSO In-Kind Support/Funding Summary:

- Research Opportunities in Space and Earth Science (ROSES)
- NASA Integrated Services Network (NISN) Langley Research Center (LaRC)/Goddard Space Flight Center (GSFC)/Centre National D'Études Spatiales (CNES) network support

CYGNSS

CYGNSS Summary: Cyclone Global Navigation Satellite System (CYGNSS) received a Cost Risk Rating of Low and proposed an over target budget to extend full operations through FY26. The CYGNSS project has been performing well. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

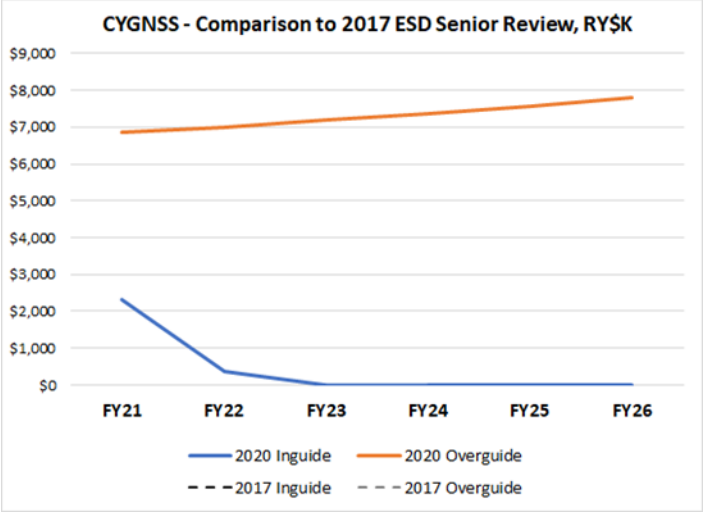
CYGNSS Findings:

- Overguide request appears to cover additional science than included with the Primary Mission
  - Additional budget appears reasonable for the added science
  - Inguide request covers Phase F
- All 8 microsats and payloads appear to be in reasonable health
- Proposed cost and proposed workforce numbers are well correlated with each other
- Assessment supports the proposed budget

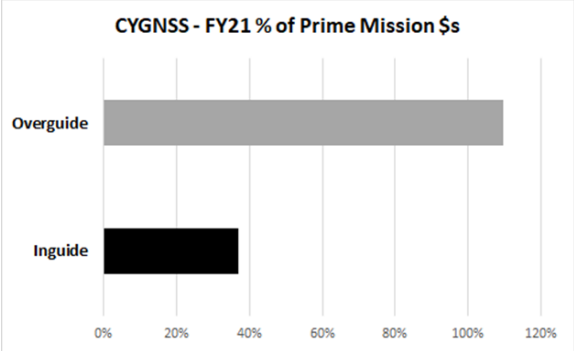
CYGNSS Evaluation Criteria Assessment:

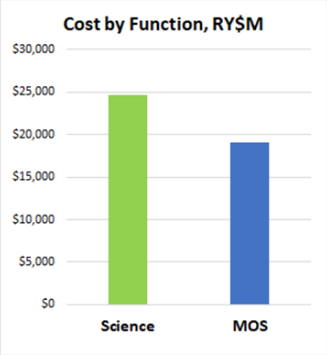
	Rating	Notes
Cost Risk Rating	Low Risk	Requested funding appears conservative
Technical Risk		
HW Status/Perf/Lifetime		
Mission Ops Plans	Low Risk	Sign reduction of safings/yr over past 3yrs
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Covers more ops time and add'l effort for new soil moisture data products
Contributions? (*beyond ROSES*)	No	

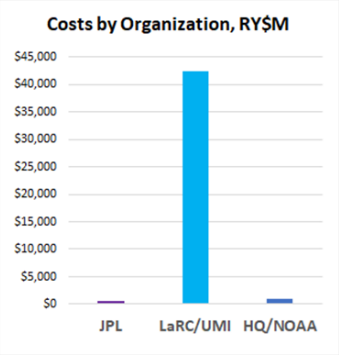
CYGNSS Cost History and Request:



CYGNSS Cost Analysis Comparisons:







CYGNSS In-Kind Support/Funding Summary:

- None

Aqua

Aqua Summary: Aqua received a Cost Risk Rating of Low and requested an Overguide to extend full operations through FY25 and support algorithm maintenance. The Aqua project has been performing well, although the Humidity Sounder for Brazil (HSB) and the Advanced Microwave Scanning Radiometer (AMSR) instruments are not operating. Depleted fuel is driving an exit from the A-Train targeted for January 2022. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

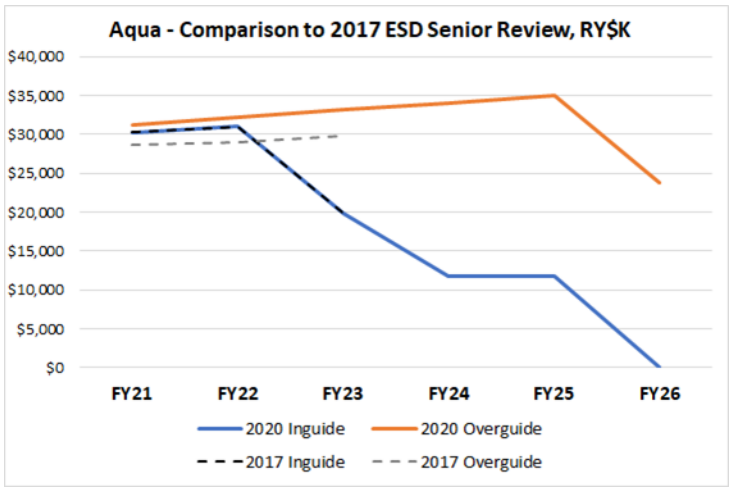
Aqua Findings:

- Proposal contained well supported Basis of Estimates (BOE)
- Proposed cost and proposed workforce numbers are well correlated with each other
- Funding level for FY23 through FY25 includes appropriate inflation
- Assessment supports the proposed budget

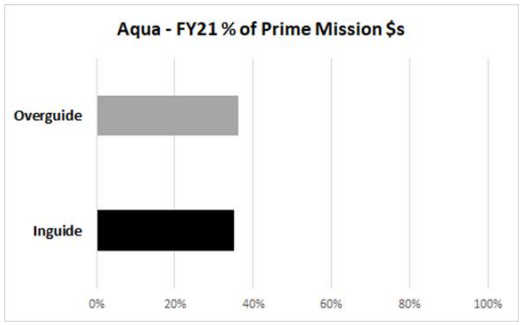
Aqua Evaluation Criteria Assessment:

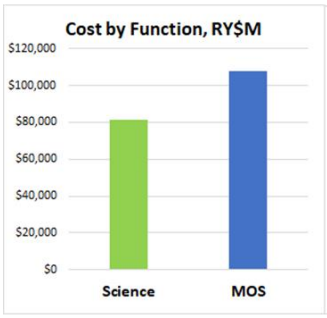
	Rating	Notes
Cost Risk Rating	Low Risk	Reasonable request with well supported BoE
Technical Risk		
HW Status/Perf/Lifetime		
Mission Ops Plans		Will exit A-Train Jan'22 (multiple options for post-exit ops)
Cost Performance		
Cost Realism		
Potential Cost Risks	Low $ Impact	Some instrument degradation & mitigation should be expected
Overguide Request?	Yes	Covers add'l 2.4yrs ops; Adds $9.4M for algorithm maintenance; Planned Phase F continuation in FY27
Contributions? (*beyond ROSES*)	Yes	NASA GSFC ESDIS; ESMO ground systems; CERES funded separately

Aqua Cost History and Request:



Aqua Cost Analysis Comparisons:





Aqua In-Kind Support/Funding Summary:

- NASA GSFC Earth Science Data and Information System (ESDIS)
- ESMO ground systems
- Clouds and the Earth's Radiant Energy System (CERES) funded separately

Aura

Aura Summary: Aura received a Cost Risk Rating of Low. The Aura project has been performing well. They requested an Overguide to extend full operations through FY25. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

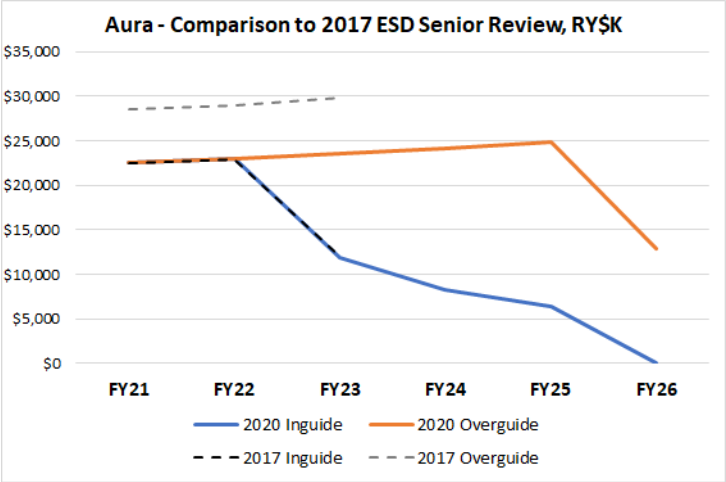
Aura Findings:

- No significant changes since 2017 Senior Review
- Inguide decommissioning in July 2022, data collection ends November 2022, and passivated in March 2023
- The S/C, Microwave Limb Sounder (MLS), and Ozone Monitoring Instrument (OMI) all appear to be reasonably healthy, although fuel limitations will require exiting the A-Train around November 2022
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Request appears reasonable, consistent with historical expenditure and about the same funding level as similar/like operating missions, Terra and Aqua
- Assessment supports the proposed budget

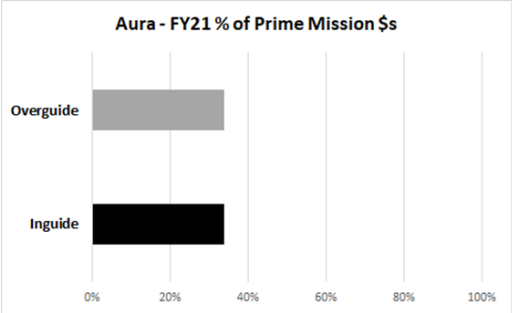
Aura Evaluation Criteria Assessment:

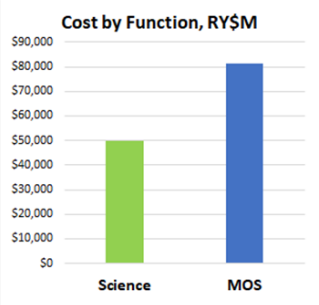
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable & HW is in good condition
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	S/C, MLS, and OMI appear to be operating well
Mission Ops Plans		OMI flight ops will be transferred from KMNI to ESMO by end of 2020; New MLS/OMI data products since SR17
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Extends ops from early 2023 thru 2025 (after exiting A-Train)
Contributions? (*beyond ROSES*)	Yes	OMI (Netherlands/Finland); ESMO mission ops

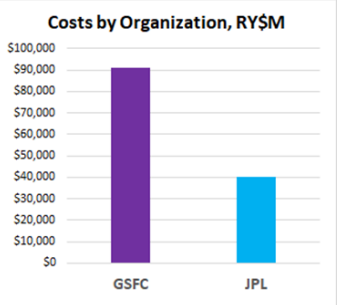
Aura Cost History and Request:



Aura Cost Analysis Comparisons:







Aura In-Kind Support/Funding Summary:

- ROSES
- OMI (Netherlands/Finland)
- ESMO Mission Ops

DSCOVR

DSCOVR Summary: Deep Space Climate Observatory (DSCOVR) received a Cost Risk Rating of Low and their proposal meets target baseline. The DSCOVR project has been performing well. Associated risks appear to be within the project's ability to cover within its available funding until the next Senior Review.

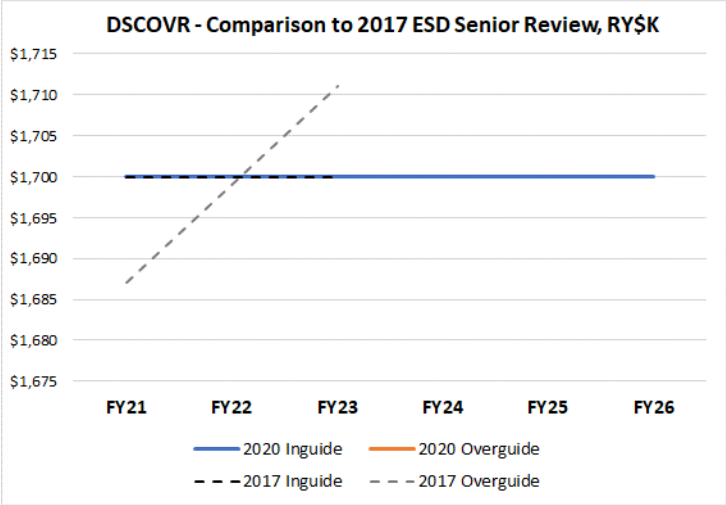
DSCOVR Findings:

- Spacecraft and payload appear to be operating nominally
- Requested funding appears reasonable
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Request appears reasonable
- Assessment supports the proposed budget

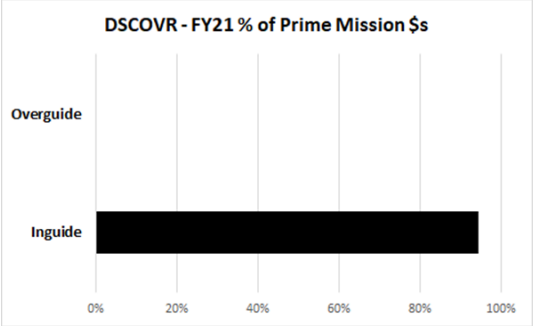
DSCOVR Evaluation Criteria Assessment:

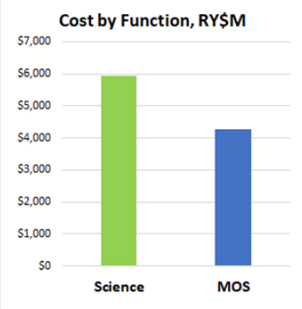
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetime		S/C & payload operating nominally
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	NOAA (Mission/spacecraft MOC)

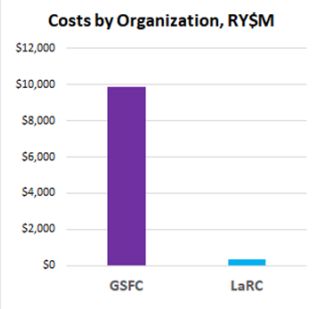
DSCOVR Cost History and Request:



DSCOVR Cost Analysis Comparisons:







DSCOVR In-Kind Support/Funding Summary:

- ROSES
- National Oceanic and Atmospheric Administration (NOAA) for S/C, Mission Operations Center (MOC), and Ground System

GPM

GPM Summary: Global Precipitation Measurement (GPM) received a Cost Risk Rating of Medium/Low driven by concerns with the reaction wheel assemblies (RWAs). They requested an over-baseline to address ground systems hardware (HW) refresh in FY23/24. The GPM project has been performing well. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

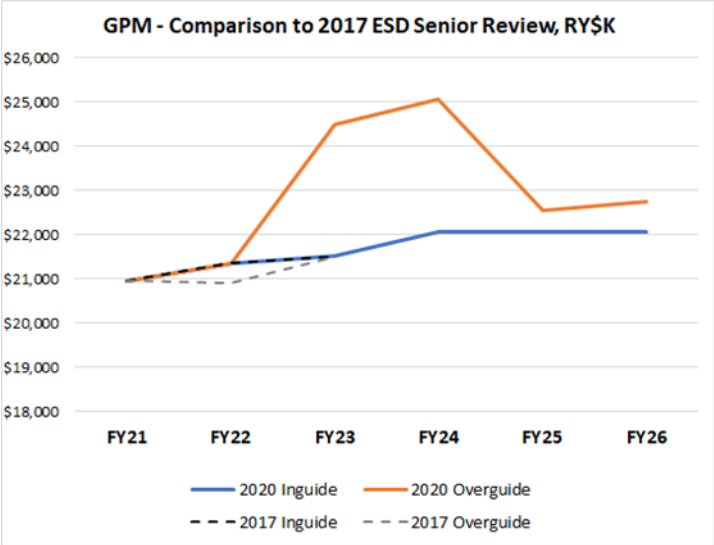
GPM Findings:

- S/C and instruments appear to be operating well
    - Inguide includes multiple science data enhancements
- Overguide request covers 2023 HW refresh
    - Enables ops beyond 2026
    - Includes costs for Information Technology (IT) security with new ground hardware
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Request appears reasonable
- Assessment supports the proposed budget

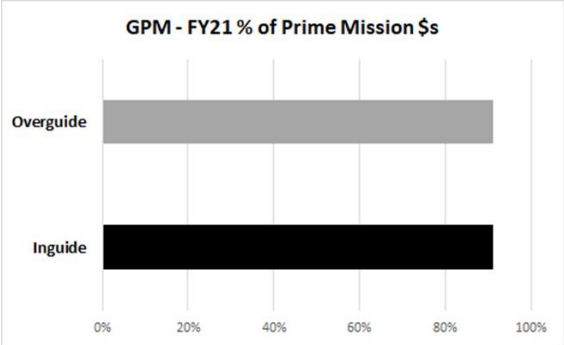
GPM Evaluation Criteria Assessment:

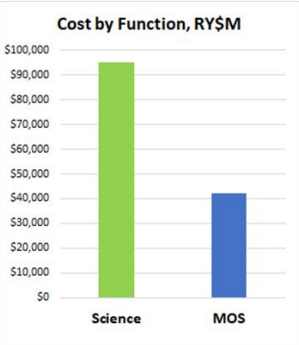
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Request appears reasonable although concerns about RWAs
Technical Risk		
HW Status/Perf/Lifetime		
Mission Ops Plans		MOC refresh currently in progress
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Ground system 2023 HW refresh
Contributions? (*beyond ROSES*)	Yes	DPR (JAXA)

GPM Cost History and Request:



GPM Cost Analysis Comparisons:





GPM In-Kind Support/Funding Summary:

- ROSES funding for all US developed products
- Japan Aerospace Exploration Agency (JAXA) for the Dual-frequency Precipitation Radar (DPR)

Terra

Terra Summary: Terra received a Cost Risk Rating of Low. The project's request is over their budget target driven by extending full operations through FY25. The Terra project has been performing well. Associated risks appear to be within the project's ability to cover within its available funding until the next Senior Review.

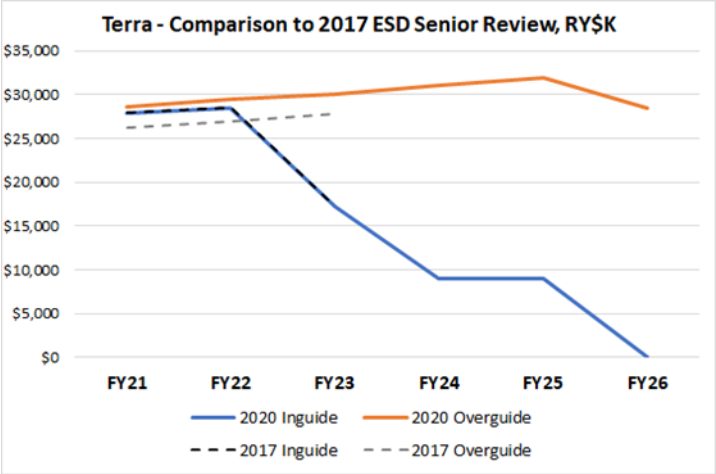
Terra Findings:

- Inguide request assumes passivation in 2022
  - FY23-26 covers Phase F/closeout
- Overguide request covers continued ops through 2026
  - S/C and instruments in good operating condition
  - Covers reallocation of algorithm maintenance between Terra and Aqua
- Proposal above budget target ~$14M FY21-23
- Proposed cost and workforce number correlate with each other as well as to other operating missions
- Assessment supports the proposed budget

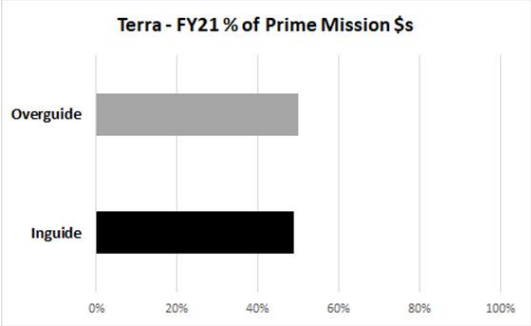
Terra Evaluation Criteria Assessment:

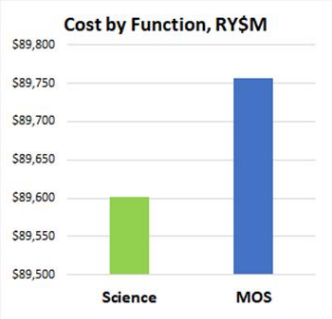
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable and HW in ok condition
Technical Risk		
HW Status/Perf/Lifetime		Fuel can support ops to Oct'22
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Inguide has passivation in 2022; Overguide covers ops thru 2026
Contributions? (*beyond ROSES*)	Yes	ESMO ground systems

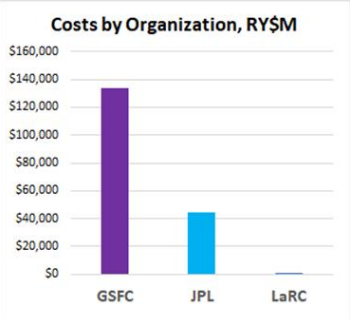
Terra Cost History and Request:



Terra Cost Analysis Comparisons:







Terra In-Kind Support/Funding Summary:

- ESMO ground systems
- Cost sharing between Aqua and Terra for the Moderate Resolution Imaging Spectroradiometer (MODIS) and CERES processing facilities
- CERES funded separately

LIS

LIS Summary: Lightning Imaging Sensor (LIS) received a Cost Risk Rating of Low. The project's proposal is above their target budget to allow for extended operations through FY24, driven by likely delay to replace it with the CLARREO Pathfinder (CPF) on the International Space Station (ISS). Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

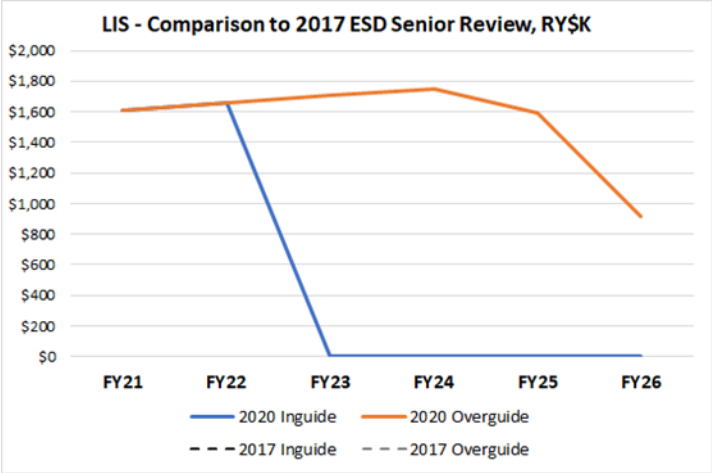
LIS Findings:

- Inguide request covers ops through FY22; Overguide continues ops through FY23 or FY24 (2 options) with Phase F continuing into FY26
- Instrument appears to be operating nominally
- Two Overguide options:
    - Option A assumes CPF arrives at ISS in March 2023 (EOM in FY23)
    - Option B assumes CPF arrives in January 2024 (EOM in FY24)
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Proposal above budget target ~$2M FY21-23
- Assessment supports the proposed budget

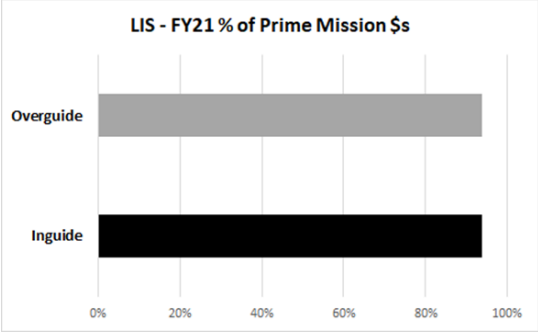
LIS Evaluation Criteria Assessment:

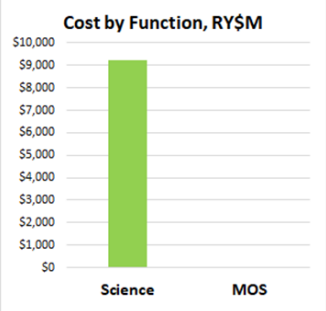
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable; Overguide options based on likely delay to replace with CPF on ISS
Technical Risk		
HW Status/Perf/Lifetime		Reasonable health
Mission Ops Plans		Apr'21 planned move from ELC-1 Site 8 to ELC-1 Site 3; May need to be moved again for CPF
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Covers late delivery of CPF to ISS (Inguide assumes CPF replaces LIS in FY22)
Contributions? (*beyond ROSES*)	Yes	ISS (attached payload)

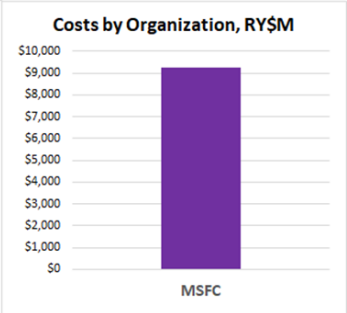
LIS Cost History and Request:



LIS Cost Analysis Comparisons:







LIS In-Kind Support/Funding Summary:

- ROSES
- ISS attached payload

CloudSat

CloudSat Summary: CloudSat received a Cost Risk Rating of Medium driven by concerns over the future S/C health. They requested an over target budget to extend operations through at least FY26. The CloudSat project departed the A-Train in early 2018 due to RWA failure. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

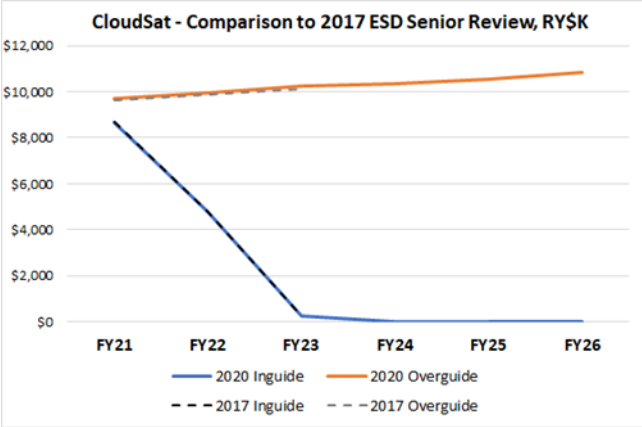
CloudSat Findings:

- Inguide request assumes decommissioning Fall 2020
    - FY21-23 covers Phase F/closeout
- Overguide request covers continued ops through 2026
    - Formation-flying with CALIPSO to end of 2023
    - FY24-26 to cover ops while drag reduces altitude
- S/C health seems good for ops through 2023 but not much later
    - Degradation of propulsion, power, and communications elements
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Over-guide request is ~$16M FY21-23
- Assessment supports the proposed budget

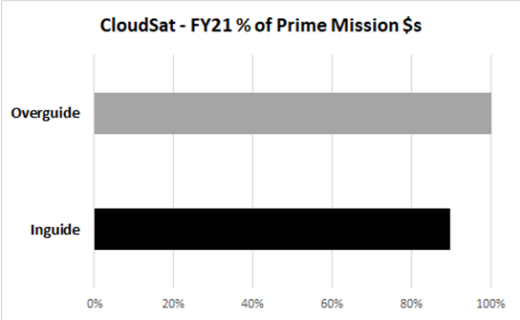
CloudSat Evaluation Criteria Assessment:

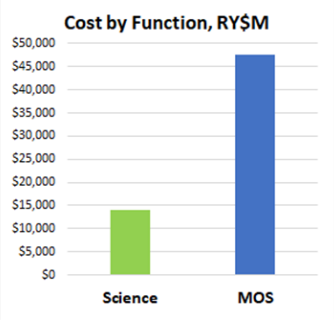
	Rating	Notes
Cost Risk Rating	Med Risk	S/C health beyond 2023 likely to have issues
Technical Risk		
HW Status/Perf/Lifetime	Med Risk	Exited A-Train in early 2018 due to RW failure
Mission Ops Plans		Operating in DO-Op mode since 2011
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Formation-flying w/ CALIPSO to end of 2023; Continued ops to 2026 at lower altitudes
Contributions? (*beyond ROSES*)	No	

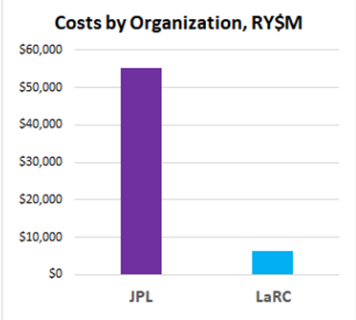
CloudSat Cost History and Request:



CloudSat Cost Analysis Comparisons:







CloudSat In-Kind Support/Funding Summary:

- ROSES

ECOSTRESS

ECOSTRESS Summary: ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) received a Cost Risk Rating of Medium/Low driven by concerns over potential future hardware issues. They submitted an over target budget proposal for extended operations through FY26. The ECOSTRESS project has been performing well. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

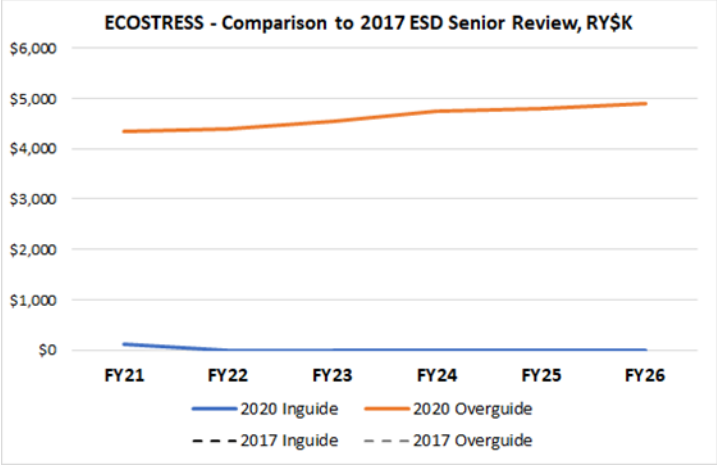
ECOSTRESS Findings:

- Inguide request assumes decommissioning in FY20
    - FY21 covers Phase F/closeout
- Overguide request covers continued ops through 2026
- Instrument health appears ok, but there are some issues that have come up
    - Carbon Cycle and Ecosystems (CCE) and Mass Storage Unit (MSU) anomalies, 5 safeholds since launch Inguide/Overguide requests to cover ops through 2026
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Over-guide request is ~$13M FY21-23
- Assessment supports the proposed budget

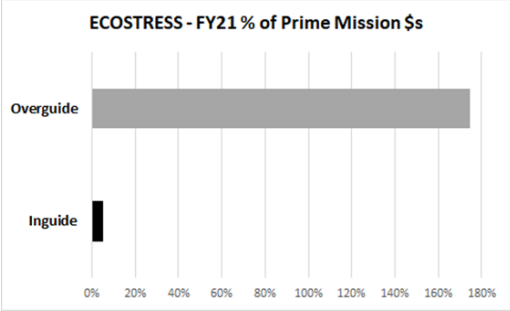
ECOSTRESS Evaluation Criteria Assessment:

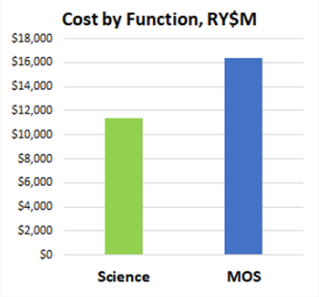
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Based on reasonable likelihood to experience HW issues operating out to 2026
Technical Risk		
HW Status/Perf/Lifetime	Med/Low Risk	Reasonable health but some anomalies
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	Covers ops thru 2026 (Inguide assumes FY20 decomissioning)
Contributions? (*beyond ROSES*)	Yes	ISS (attached payload, JEM EFU#10)

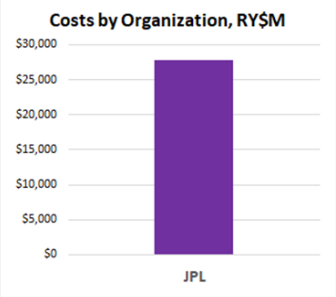
ECOSTRESS Cost History and Request:



ECOSTRESS Cost Analysis Comparisons:







ECOSTRESS In-Kind Support/Funding Summary:

- ISS attached payload (Japanese Experiment Module [JEM] Exposed Facility Unit [EFU] #10)

SMAP

SMAP Summary: SMAP received a Cost Risk Rating of Medium driven by risk associated with the synthetic aperature radar (SAR) "jumpstart" effort. They requested an Overguide to cover near real-time (NRT) system support. The SMAP SAR failed in July 2015, but the RADiometer (RAD) instrument is operating. Associated risks appear to be within the project's ability to cover within its requested funding until the next Senior Review.

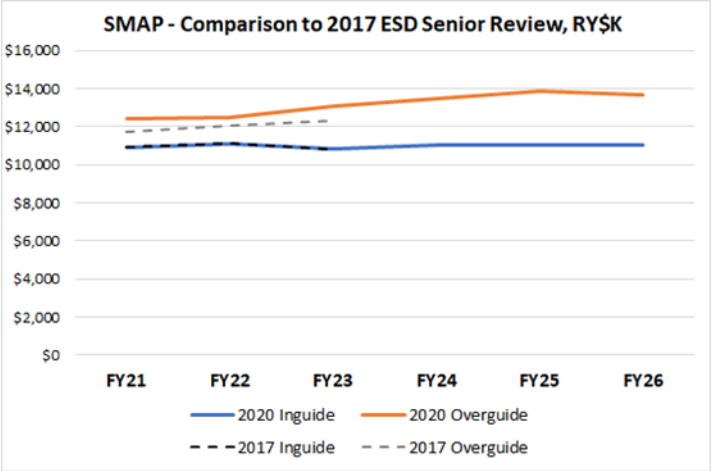
SMAP Findings:

- Inguide/Overguide requests cover ops through 2026
- Overguide request adds a SAR "jump start" effort to bypass the failed the high power amplifier (HPA) and enhancements to NRT system support
- Basis of Estimate for requested funding is high-level
    - Costs for the SAR "jump start" effort not explicitly shown or described
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Overguide is for ~$5M FY21-23
- Assessment supports the proposed budget

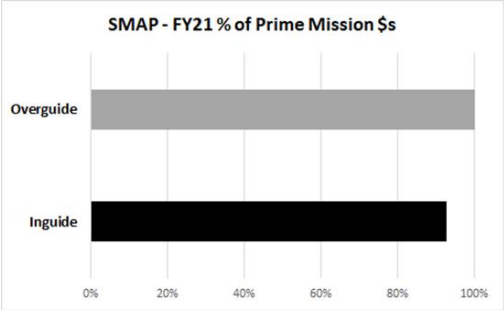
SMAP Evaluation Criteria Assessment:

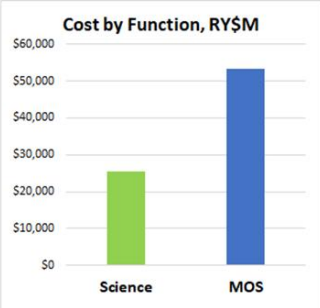
	Rating	Notes
Cost Risk Rating	Med Risk	High level BoE; Unclear BoE for SAR "jump start" effort
Technical Risk		
HW Status/Perf/Lifetime		Orbit lifetime to 2025
Mission Ops Plans		
Cost Performance		
Cost Realism		Very high-level BoE provided
Potential Cost Risks		
Overguide Request?	Yes	Covers NRT system support & more
Contributions? (*beyond ROSES*)	No	

SMAP Cost History and Request:



SMAP Cost Analysis Comparisons:





SMAP In-Kind Support/Funding Summary:

- ROSES

OCO-2

OCO-2 Summary: Orbiting Carbon Observatory-2 (OCO-2) received a Cost Risk Rating of Medium/Low driven by concerns over sufficient Overguide funding. They requested an Overguide for enhancements to science data processing and algorithm development. The OCO-2 project has been performing well, though some degradation to A-band has been seen. Associated risks may challenge the project's ability to cover within its requested funding before the next Senior Review.

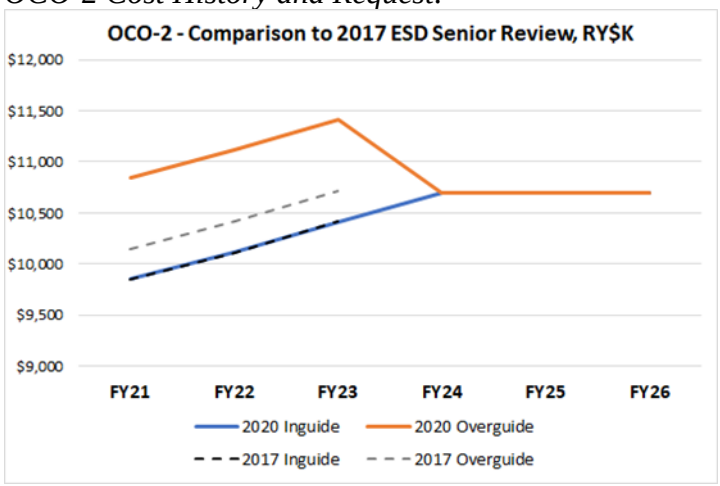
OCO-2 Findings:

- Inguide/Overguide requests cover ops through 2026
- Overguide request improves the XCO2 and solar induced chlorophyll fluorescence (SIF) products and includes
    - Improved instrument calibration
    - Updated gas absorption cross-sections
    - Level 2 Algorithm modifications to reduce anomalous carbon dioxide (CO2) profile errors
- Additional Overguide $s seem somewhat low
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Over-guide request is $1M/year (FY21-23)
- Assessment supports the proposed budget

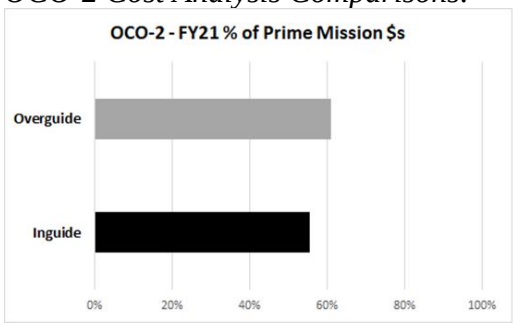
OCO-2 Evaluation Criteria Assessment:

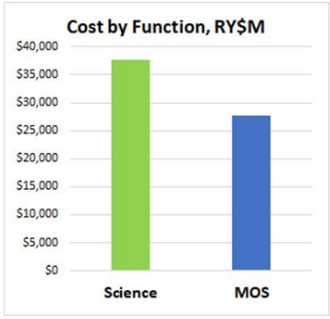
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Not clear if Overguide funding is sufficient
Technical Risk		
HW Status/Perf/Lifetime		
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	Yes	For science data processing and algorithm dev enhancements
Contributions? (*beyond ROSES*)	No	

OCO-2 Cost History and Request:



OCO-2 Cost Analysis Comparisons:





OCO-2 In-Kind Support/Funding Summary:

- ROSES

SAGE III

SAGE III Summary: Stratospheric Aerosol and Gas Experiment III (SAGE III) received a Cost Risk Rating of Low. The proposal is aligned with their budget target. The SAGE III project is operating nominally. Associated risks appear to be within the project's ability to cover within its available funding until the next Senior Review.

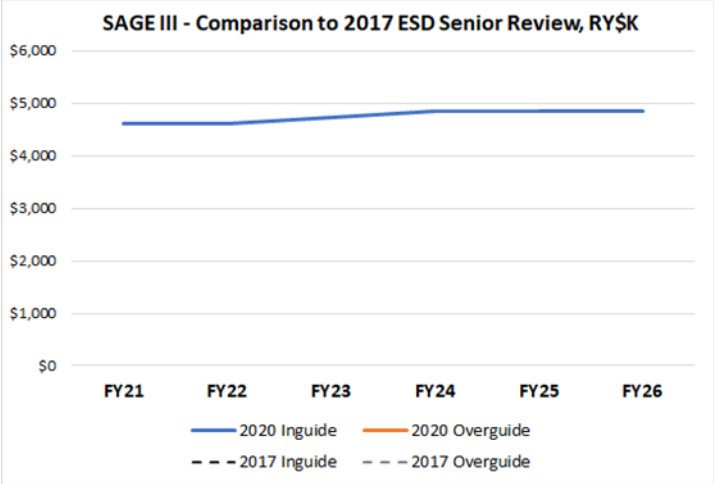
SAGE III Findings:

- Request covers ops through 2026
- Instrument appears to be operating nominally
- Annual staffing seems to be the same from FY21-26 (25.5 full-time equivalents [FTEs]/year)
- Cost estimate and workforce numbers are well correlated to each other as well as to other similar operating missions
- Assessment supports the proposed budget

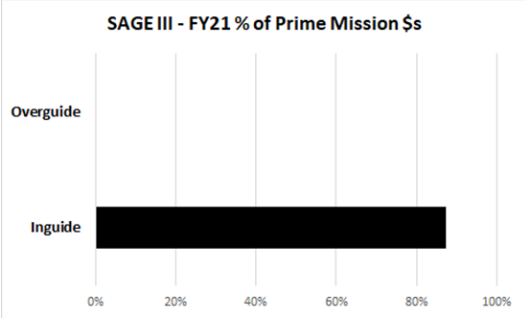
SAGE III Evaluation Criteria Assessment:

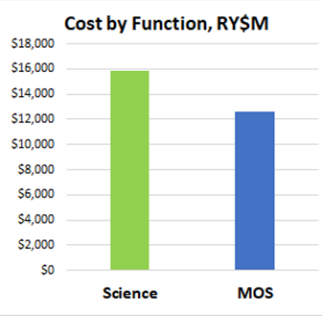
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetime		Reasonable health
Mission Ops Plans		
Cost Performance		
Cost Realism		
Potential Cost Risks		
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	ISS (attached payload, ELC-4/FRAM-3); ESA, NIWA (New Zealand)

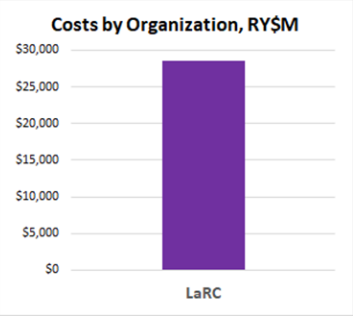
SAGE III Cost History and Request:



SAGE III Cost Analysis Comparisons:







SAGE III In-Kind Support/Funding Summary:

- ISS attached payload (ELC-4/ Flight Releasable Attachment Mechanism [FRAM]-3)
- European Space Agency (ESA), National Institute of Water and Atmospheric Research (NIWA) of New Zealand

APPENDIX 4

Detailed Science Reviews

A4.1 Aqua

A4.2 Aura

A4.3 CALIPSO

A4.4 CloudSat

A4.5 CYGNSS

A4.6 DSCOVR

A4.7 ECOSTRESS

A4.8 GPM

A4.9 LIS on ISS

A4.10 OCO-2

A4.11 SAGE III

A4.12 SMAP

A4.13 Terra

Detailed Science Reviews

A4.1 Mission: Aqua

Mission Extension Conclusion:

FY 2021-2023	FY 2024-2026
Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*	Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*

Overview

Aqua is one of NASA's flagship missions. The satellite was launched on 4 May 2002 and was the first in the A-Train constellation. Aqua is an international mission, based on a partnership between the United States, Japan, and Brazil. The spacecraft bus is still in excellent condition and four working instruments (AIRS, AMSU, CERES and MODIS) are still healthy, except that some channels have been degraded but do not have significant impact on data quantity and quality. The data quality and algorithm maturity are very high. Aqua-collected data are highly relevant to the NASA SMD Science Plan, the Program of Record, and the 2017 Decadal Survey priorities for observables. Aqua data has been used to answer four of NASA's key science questions and has provided seven of fourteen priority targeted observables and one of three targeted observables not allowed to flight programs. Moreover, the CERES instrument on Aqua, together with other CERES instruments on Terra, Suomi NPP and NOAA-20, has contributed to the important Earth Radiation Budget (ERB) climate data record. Due to fuel limitations, Aqua will lower its orbit and exit from the A-Train in January 2022. At that time, Aqua's mean local time (MLT) will start drifting to later in the afternoon. The in-guide (baseline) budget will support Aqua's operation until April 2023, while the over-guide budget requests an additional 2.4-year operational time until September 2025.

Aqua has provided a long history and an enormous quantity of observations, which cover nearly all areas of the Earth System sciences. In addition to advancing our fundamental understanding of Earth System sciences, Aqua's data have played a critical role in weather forecasts, climate modeling, air and water quality monitoring, and disaster monitoring. As a member of the A-Train constellation, Aqua has provided near-coincident information to assist with other A-Train satellites' data retrievals. With such wide swaths for a majority of the data, Aqua has also provided data for retrieval products of other non-A-Train satellites.

Since the previous senior science review, the project team has continued improving data quality, synergizing Aqua data with other satellite data, and producing new products (e.g., MODIS land surface temperature). Aqua data have also continued to advance sciences. For example, recent research has shown that AIRS' long, stable, high-precision data can reliably monitor our changing climate, such as finding changes in the surface temperature, cloud properties, atmospheric composition and extreme weather.

In the next 3 years, Aqua will continue the observations at 1:30 AM/PM local time until it exits the A-Train in January 2022. After that, the changes of MLTs and solar zenith angles might have an impact on some Aqua data products. In particular, a lower zenith angle could cause a minor to moderate degradation in the quality of the cloud mask and surface energy flux-related products, and different MLTs might have an impact on the continuity of some climate data records. Modifications to some algorithms and look-up tables are to be expected and are one of the main focuses in several algorithm/data product maintenance proposals. However, the change of MLTs will have minimal, if any, impact on AMSU and AIRS radiances, which are critical to weather forecasts in both national and international operational centers. This is because both AIRS and AMSU have their own internal blackbody calibrators.

Although after Aqua exits the A-Train, a small set of data products might be degraded, and some data might not be suitable for climate data records due to the MLT change, the benefit of continually receiving Aqua data is still enormous. Given a reasonable level of effort, the majority of the data products will remain at the same or a similar quality level, and these data will continue contributing to the NASA SMD Science Plan, the Program of Record, and the 2017 Decadal Survey priorities for observables; advancing Earth System science research; and calibrating other satellite data. Most critically, these data will continue supporting weather forecasts, hazardous-event monitoring and other national interests. Thus, the senior review panel highly suggests the extension of the Aqua mission with the over-guide budget for both 2021-2023 and 2024-2026.

Scientific merits: Excellent

Strengths

Aqua was launched in 2002 and more than 18 years of data have been collected. Four (originally six) very distinct instruments (MODIS, AIRS, CERES and AMSU) onboard Aqua have provided a long record and an enormous quantity of observations across a vast array of areas of the Earth System sciences, such as the water cycle, the radiative energy budget, moisture and temperature profiles, aerosols, vegetation, fire, ice cover, ocean color, polar winds, surface temperatures, etc. Aqua data have advanced our understanding of physical processes, land-surface interaction, global water and energy cycles, and climate change. The datasets have been used substantially for scientific research, as evidenced by the number of associated publications, which has steadily increased over the years. Furthermore, AIRS and AMSU radiances have been shown to greatly contribute to the reduction of weather forecast errors. As a member of the A-Train constellation, Aqua has provided near-coincident information to assist other A-Train satellites' data retrievals. In addition, Aqua provides data to calibrate and improve retrievals of other data products for non-A-Train satellites.

Since the last senior science review, in addition to performing instrument maintenance and operations, data calibration and algorithm maintenance and integration, the mission and science teams have upgraded existing products and produced new data products. Several examples are given here. The AIRS project (a) released the AIRS IR radiance spectra product L1C (V6.7), which aims to facilitate cross-comparison with other instrument data, and a newer version (V7) of L1C data (V7) will become available in 2021, which will include noise flagging, co-registration correlation, and channel replacement; (b) produced climate radiance data by integrating data from AIRS, CrIS, and IASI; (c) released new L2 and L3 V7 data, which reduces errors of temperature

and moisture within the boundary layer over subtropical oceans; and (d) is currently integrating and validating Aqua-CLIMCAPS, which provides a common algorithm for AIRS, CrIS, and IASI and is well suited to generate long-term multi-sensor/multi-platform climate data records. The MODIS team fully reprocessed MODIS-derived cloud optical properties using the Collection 6.1 algorithm, produced new Aqua MODIS land surface temperature (LST) and emissivity data, and created a heat vulnerability index using the LST data.

Recent research studies have shown that AIRS' long, stable, high-quality dataset can reliably monitor climate changes, such as changes in the surface temperature, cloud properties, atmospheric composition and extreme weather. The high-precision CERES data from Aqua and Terra have recorded the decline of the Earth's reflected shortwave radiation in recent years, which is due to the decreased coverage of low-level clouds. CERES data, along with other CERES data onboard Terra, Suomi NPP and NOAA-20, provides an important ERB climate data record. CERES has been used to verify sea surface temperature and sea ice boundary conditions in climate model simulations.

Weaknesses

MODIS AOD retrievals remain discontinuous over the boundary between the ocean and barren land where the dark-target algorithm data and deep-blue algorithm data meet. This is a long-standing problem, which will be further investigated in one of the algorithm/data product maintenance proposals.

Value of data record with the additional 3-6 years of data, and overall data continuity

Continuing the Aqua mission is very important because of its great scientific merit, high relevance to NASA programs and decadal survey, and the very-high national interest. However, Aqua will exit the A-Train in January 2022 and the mean local time (MLT) will start drifting to later in the afternoon. This will provide Aqua with some new scientific opportunities, such as sampling data closer to the typical time of peak thunderstorm activity in many locations, including the U.S.

After exiting the A-Train, the AIRS and AMSU instruments will continue to provide data products of almost the same quality, with a relatively minor effort in data calibration and product algorithm development, thanks to the internal blackbody calibrators contained in both instruments. Both AIRS and AMSU radiance data have been shown to effectively reduce forecast error, in particular over cloudy areas where AMSU data are available. As neither data set is influenced by the change of MLTs, the continuity associated with providing AIRS and AMSU data in near real time to operational centers for weather forecasting is critical in order to maintain and potentially continue improving forecast skill. MODIS data have provided helpful information to monitor hazardous weather and disaster events. Although some data products related to cloud mask and aerosol will be degraded due to the change of MLTs (i.e., lower zenith angles), they can still provide useful qualitative information. Thus, in addition to providing value to scientific research, the MODIS data remains of high national interest. The CERES instrument on Aqua can continue providing the ERB data for climate data records and reduce data gaps. CERES instruments are available on Aqua, Terra, Suomi NPP and NOAA-20. The risk of a data gap is 27% if both Aqua and Terra are given in-guide budgets and reduces to 1.5% if over-guide budgets are granted for both satellites. The risk in 2024 is 6.5% if only Aqua or Terra is granted an over-guide budget. Beside CERES ERB data, it would be a challenge to match new data collected at different MLTs with the preceding data streams (e.g., climate datasets) and the new data might no longer have near-

coincident measurements with other satellites in the A-Train. The interpretation of the observations taken after Aqua exits the A-Train is not necessarily straightforward for climate use due to different MLTs.

Standard mission data product quality: **Excellent**

The quality and maturity of Aqua data products are rated as excellent. This is because 1) the satellite has taken observations for 18 years, during which time the data calibration, validation, and algorithms have continued, 2) Aqua carries two instruments, MODIS and CERES, which are identical to those carried by Terra and the sharing of the data processing experiences between two mission teams has highly advanced data maturity and quality, and 3) Aqua data have been broadly used by different communities, which have helped test and further improve data quality. The level of science support required to maintain the quality of these standard data products has been greatly reduced compared to the prime mission period. This is because 1) product algorithms are highly mature, 2) the Aqua and Terra mission teams split the effort on MODIS algorithm maintenance and development, and 3) CERES data has been separated from the Aqua mission, except for algorithm maintenance, but combined with observations from CERES instruments onboard Terra, Suomi NPP and NOAA-20.

Aqua AIRS L1 radiance is unique since it is the longest hyperspectral IR global climate data record with very high quality. AIRS radiances, along with AMSU radiances, have greatly improved weather forecasts. Joint AIRS and MODIS retrieval algorithms can produce improved moisture and temperature profiles in meteorologically complex scenes.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

Aqua's data are highly relevant to the 2020-2024 SMD Science Plan, including priorities 1, 3 and 4. For priority 1 (exploration and scientific discovery), Aqua produces data in five out of six earth-science focus areas listed in the SMD Science plan. For priority 3 (interconnectivity and partnerships), the Aqua mission team has worked with several NASA centers, two international partners (Japan and Brazil), other federal agencies, and many research institutes. For priority 4 (inspiration), Aqua has a great diversity team itself and has strong engagement with the public. The Aqua mission has greatly contributed to the Program of Record and to the 2017 Decadal Survey priorities for observables. Aqua data has been used to answer four of NASA's key science questions: 1) How is the global Earth system changing? 2) What causes these changes in the Earth system? 3) How will the Earth system change in the future? 4) How can the Earth system science provide societal benefit? Aqua provides seven of fourteen priority targeted observables (PTOs) (aerosols; cloud, convection and precipitation; surface biology and geology; greenhouse gases; ozone and trace gases; atmospheric winds; and planetary boundary layer) and one of three targeted observables not allowed to flight programs (NAFPs) (aquatic-coastal biogeochemistry and ocean ecosystem structure). In addition to seven PTOs and one NAFP, Aqua CERES, together with other CERESs onboard Terra, Aqua, Suomi NPP, and NOAA-20, contributes to the important ERB data for the climate data record.

Weaknesses

None.

Technical and Cost

The Senior Review Science Panel in general concurs with sub-panel assessments. The technical and cost risks are low. The four working instruments on Aqua are still healthy, except some channels in AIRS, AMSU and MODIS instruments have degraded. Fortunately, the channel degradation has a minor impact on data quality and quantity.

National Interests

There is no question that the national needs for Aqua data are rated very high. In particular, AIRS and AMSU on Aqua have been providing high-quality, near-real-time radiances to national and international operational centers for weather forecasts. MODIS data has been used to monitor air and water quality and disasters.

Other Comments

During the interview, the mission team provided detailed information about the impact of MLT changes on a) the level of effort required to calibrate the L1 data and update product algorithms, b) data quality, and c) long-term climate datasets for each instrument after Aqua exits the A-Train. This information was very helpful to the senior review panel in making their final evaluations.

Detailed Science Reviews
A4.2 Mission: Aura

Mission Extension Conclusion:

FY 2021-2023	FY 2024-2026
Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*	Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*

Overview

The operating Aura instruments have several benefits for continuing the mission. Atmospheric composition and dynamics are changing on scales from urban to global, and Aura measurements are making key contributions to understanding those changes.

With its long-term record of high-quality measurements, the Microwave Limb Sounder (MLS) has become the gold standard for vertical profiles of atmospheric gases (including H_2O, O_3, ClO, HCl, HNO_3, CO, SO_2, and N_2O), cloud ice water content, and temperature from the upper troposphere to the upper stratosphere. No other satellite instrument in the POR (program of record) or to be deployed has the capability to make the many discoveries that MLS has made and continues to make. Continuing MLS through 2025 will enable MLS to extend its long-term record of unique and excellent science, including studying the recently discovered apparent shift in stratospheric dynamics and, in 2020, the observed Arctic ozone hole, smaller than, but as deep as an Antarctic ozone hole.

The Ozone Monitoring Instrument (OMI) has used its nadir-looking, wide-view, UV-Vis hyperspectral imaging capability to give long-term daily global coverage for column amounts of several gases (including O_3, NO_2, SO_2, BrO, HCHO), aerosol types (smoke, dust, sulfates), and cloud-top pressure. Its long-term, stable solar irradiance measurements, widely recognized as the gold standard by which other solar irradiance measurements are evaluated, will be available until 2024 when Aura must leave its orbit and descend. As attested by the increasing number of high-quality publications, OMI's measurements of atmospheric reactive gases are finding an increasingly wider use in science, air quality management, health studies, and economic analysis, including the economic impacts of COVID-19. Continued operation will also give OMI more time to provide the long-term, high-accuracy, and stable gas measurements to test and to help improve the measurements of its successor, TROPOMI, and the emerging constellation of geostationary trace gas monitoring instruments.

Scientific merits: Excellent

Strengths
Data from both instruments are highly and widely used, as a quick look at recent publications shows, with more than 2000 publications (600 since the 2017 Senior Review).

MLS measurement capabilities are unique among satellite instruments that retrieve vertical profiles above the upper troposphere in terms of its long-term record, the number of chemical species measured, and the measurement quality. MLS measurements have been widely used to understand the behavior of polar ozone and to study stratospheric dynamics and their changes over that record.

OMI measurements are being used for studies of a wide variety of issues involving atmospheric chemistry and its changes. The OMI science team's ability to determine tropospheric column amounts and vertical profiles has provided exceptional value for these studies. One of the most important is the measurement of near-surface NO_2, which is a strong indicator of air quality. The long-term record of tropospheric NO_2 has provided a context in which changes in NO_2 can be assessed. For instance, the recently observed reduced urban and regional NO_2 provides an indication of the drop in transportation and economic activity due to COVID-19.

Both instruments have worked well since 2004 and thus provide an unprecedented long-term view of global atmospheric composition. In addition, the mission teams have been clever in expanding the number of data products and the usefulness of their data for more science and applications.

Weaknesses
There are no major weaknesses for either OMI or MLS.

Both measurement methods have well-known inherent limitations. For MLS, it is the lower limit of the limb measurement, which is different for different gases. For OMI, it is the relatively low horizontal resolution, or footprint, of 12 km x 25 km and inability to see all the way to the ground for O_3 due to increased scattering.

For the minor technical weaknesses that affect the science return, both teams have found work-arounds that mostly maintain data quality and record continuity. For MLS, there is the loss of some detection channels, resulting in the loss of stratospheric / mesospheric OH measurements, while both N_2O and HCl are being measured in their secondary bands. The most serious is the drift in the water vapor channel, which can affect the important study of the long-term water vapor trend in the northern midlatitude stratosphere. For OMI, 60 rows in the spatial dimension were affected in June 2007, causing a reduction in spatial coverage so that it now takes two days for total global coverage. The number of radiation-damaged pixels is increasing, but at an expected rate. There are remaining questions on how this row anomaly will affect spatial coverage once Aura leaves the A-Train and enters a lower orbit.

Value of data record and overall data continuity
Maintaining the OMI and MLS data records for another 3-5 years and continuing the long data record is important. There is no satellite instrument in the POR or in planning stages that has MLS's measurement quality, continuity, or number of trace gases measurements. TROPOMI, OMI's likely successor, has been data for only 2+ years, so extending OMI's mission provides a critical overlap with TROPOMI and the emerging constellation of geostationary satellites for North American, Europe, and East Asia.

Standard mission data product quality: Excellent

Both MLS and OMI are extensively tested against other satellites, ground-based networks (for OMI), and aircraft/ rocket/ balloon campaigns. Aura scientists have been heavily involved in defining the best way to do these intercomparisons. Both instruments, with one exception in the water vapor channel for MLS, have been quite stable.

Both MLS and OMI data algorithms and datasets are mature. The MLS team will continue to evaluate the current v5 data set and work to improve known issues for a final v6 data set, such as the unexpected behavior of the 190-GHz N_2O product. For OMI, KNMI has handed GSFC the responsibility for OMI flight operations and L1B processing, which will be based on the newer TROPOMI code. This transition will require updating of current L2 algorithms and other changes, such as transitioning to NetCDF compliant outputs for easier use with widely used data analysis systems. The goal is to make the combined OMI-TROPOMI data record more seamless.

The Aura team has a strong plan for reducing science support costs by combining operational and administrative needs for Aura, Aqua, and Terra into GSFC Earth Science Mission Operations (ESMO) and by using ROSES grants for supporting a substantial amount of the Aura science. The downside of not extending the mission of Aqua or Terra means additional ESMO costs for Aura.

The levels of science support required to maintain the quality of these core data products is reasonable. The quality is not just being maintained, it is being improved for both MLS and OMI.

This proposal clearly discusses all other satellites that have overlapping measurement capabilities with MLS and OMI. POR satellites that complement OMI include TROPOMI (improved spatial footprint, similar spectral resolution, addition of channels for CO and CH_4) and NOAA-20 OMPS (similar surface footprint; lower spectral resolution and range; noisier data; poorer capability for surface NO_2; no solar spectral irradiance). TROPOMI is the logical successor to OMI.

In February 2020, the first of a constellation of three geostationary satellites, South Korea's GEMS, will cover Asia in the Northern Hemisphere, while TEMPO, scheduled for launch in 2022, will cover the US and Sentinel-4 will cover Europe. These will measure in the UV/Vis similar to OMI, but hourly, with ~5 km / 5 km resolution. None will cover the tropics or Southern Hemisphere, so the need for OMI / TROPOMI remains.

POR satellite instruments that complement MLS are OMPS-LP for O_3 profiles (although not in the dark, and apparently drifting) and the Swedish Odin/SMR instrument (5 chemical species; noisier). MLS data are better than these others in terms of both number of chemical species measured and data quality, although European SIW (launch 2023) and Altius (2024) may come closer. The MLS ability to measure through aerosol is another unique strength.

What is really impressive about the MLS and OMI teams is not only do they maintain the high quality of existing products, but they are also getting the most benefit out of their spectral radiance data by continually developing and testing new measurement capabilities. The team is also forward thinking in preparing the algorithms to deal with possible complications (such as larger solar zenith

angles) for the future when Aura leaves the A-Train for a lower orbit and its equator crossing time starts to drift to later in the afternoon.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

Table 2 in the proposal lists the 2017 Decadal Survey priority science and application targeted observables for "Ozone and Trace Gases". There is one "Most Important", 2 "Very Important', and 9 "Important" questions. The most important one is "(W-5) What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?" OMI measurements are being used to examine and provide applications for this question. MLS contributes to the Very Important question "(C-2g) Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of $0.05 W/m^2$ over the course of the decade." By monitoring these changes in water vapor and temperature in the UT/LS region, there are also several Important questions that MLS or OMI can address directly.

Weaknesses

There are no serious weaknesses for either MLS or OMI in terms of relevance to NASA Science Goals. Each continues to play a unique role in the NASA measurements strategy, although TROPOMI, with its better measurement capability, will soon replace OMI for trace gas column measurements but not for high-accuracy solar irradiance measurements.

Technical and Cost

We concur with the sub-panels' analyses.

Parallel funding sources, such as ROSES, have been frequently used for both MLS and OMI science, operational applications, and outreach. This external science and applications support is critical for the advancement of Aura measurement science and applications.

National Interests

We concur with the National Interests Panel's conclusions. Their ranking of Aura as "high" is appropriate.

Other Comments

The Aura proposal is excellent, albeit at times a little overwhelming in details and breadth. The proposal rightly focuses on the science and applications from the past three years, but the total body of science including the recent work is even more impressive.

Detailed Science Reviews
A4.3 Mission: CALIPSO

Mission Extension Conclusion*:

FY 2021-2023	FY 2024-2026
Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations through FY2023*	Not Applicable (Extension not requested) but *following the proposed optimal/over-guide budget to complete mission data processing*

*CALIPSO in-guide budget supports the satellite mission through FY21. The over-guide budget will support:

- Extending the satellite mission through FY23 (it is expected to be terminated in 09/2023)
- Restarting primary laser
- Science algorithm enhancements including implementing new approaches for lidar signal noise suppression and improved feature detection
- Developing and implementing techniques to mitigate impact of low-energy shots to full suite of CALIPSO products
- EOM activities (FY24-25) (no budget is required for FY26).
- The panel notices the importance of the proposed efforts under the overguide budget during FY24-25 to complete and release V5 L2 data (V4.5 data, to be released during FY21-23, will not include the mitigation of the impact of low-energy shots).

Overview

The CALIPSO mission, launched in April 2006, is entering its 15th year of successful operation, providing unique observations of global aerosol and cloud vertical profiles. The CALIPSO instruments include a two-wavelength polarization-sensitive lidar (CALIOP), a three-channel infrared imaging radiometer (IIR), and a single-channel wide field-of-view camera (WFC). Data have been collected continuously since 2006 and the CALIPSO project routinely produces both standard and expedited data products that are widely used by both scientific and operational communities. Observationally-based estimates of all-sky aerosol direct radiative effect are made possible by CALIOP's unique ability to measure aerosols in cloudy skies. CALIOP directly observes cloud altitude and phase, providing key insights in understanding the cloud feedbacks in the climate system. CALIPSO's vertical profile measurements of clouds and aerosols provide an unprecedented resource for evaluating and improving weather and climate and air quality models, and models used to forecast the dispersion of volcanic and fire plumes. CALIPSO is highly relevant to the NASA SMD Science Plan and the 2017 Decadal Survey, and directly contributes to 5 most important (MI) and 3 very important (VI) objectives in the Decadal Survey.

CALIPSO exited the A-Train and descended to its disposal orbit at 688 km in September 2018 to resume matched lidar/radar cloud profile measurements with CloudSat. All spacecraft subsystems continue to operate nominally in this new orbit. CALIPSO is now slowly drifting to later local ascending node crossing times. CALIPSO data quality is insensitive to changes in crossing times. Both CALIOP and IIR have operated well so far, and so had the WFC until 04/11/2020 when WFC

anomaly occurred and it was turned off. The backup laser of the CALIOP (which has been in use since March 2009 after the primary laser was switched off) is expected to reach the end of its useful lifetime sometime within the next 6-12 months. At that time the primary laser will be restarted. If this is successful, science operations will continue until September 2023 when CALIPSO is expected to be terminated due to insufficient power.

The panel submits that extending the CALIPSO mission through 2023 will have tremendous benefits that include

- maintaining critical synergies with CloudSat to provide co-located observations of clouds, aerosols, and precipitation and thus significantly enhancing our ability to characterize the processes that control the seasonal and interannual variability of clouds and aerosols and rapid climate change on both regional and global scales;
- allowing further development of important data synergies with other space-based sensors such as SAGE III-ISS, OMPS, VIIRS, and ICESat-2;
- Enabling data continuity with the spaceborne lidar measurements to be acquired by EarthCARE, which in turn could serve as a unifying bridge to a future A-CCP mission;
- maintaining unique monitoring capabilities that inform environmental health and human safety interests including providing near-real time aerosol information to NOAA to improve air quality forecasts;
- validating passive sensor retrievals (e.g., after exiting the A-Train, the CALIPSO orbit precesses eastward across the MODIS swath, allowing long-sought validation of MODIS aerosol and cloud products as a function of MODIS view angle).

Scientific merits: Excellent

Strengths

CALIPSO's lidar (CALIOP) measurements fill a crucial, well recognized need for vertically-resolved aerosol and cloud profiles, and are proving essential in reducing the uncertainties that limit our understanding of aerosol and cloud effects in the global climate system. The science objectives of the CALIPSO mission together with other satellite observations are to provide 1) estimates of aerosol direct radiative forcing; 2) assessment of the aerosol indirect radiative forcing; 3) improved estimates of radiative fluxes; and 4) assessment of cloud-radiation feedbacks. The science achievements since the last Senior Review aligned with these mission objectives are significant. Specifically, observationally-based estimates of all-sky aerosol direct radiative effect were made possible and improved by CALIOP's unprecedented ability to observe aerosols beneath optically thin clouds and above low clouds and bright surfaces. By using co-located observations from CALIOP and the IIR, global ice crystal number concentration distributions were retrieved, showing a dependence of homogeneous ice nucleation in cirrus clouds on topography and latitude. Greatly improved observational estimates of the surface and atmospheric radiation budgets were obtained by using CALIPSO-CloudSat cloud profiles combined with passive sensor MODIS data. A new method was developed to quantify the cloud LW feedback from CALIOP observations, which was used to evaluate the model simulations. Beyond these original science objectives, CALIPSO observations have been used to extensively evaluate aerosol and clouds in climate and weather and air-quality models and to also evaluate passive satellite retrievals (e.g. MODIS aerosol and cloud products). CALIPSO expedited data products, with a latency of 24 hours or less, are providing valuable information to operational forecast centers for time-sensitive applications.

CALIPSO observations and data products contribute to five most important (MI) and 3 very important (VI) objectives in the Decadal Survey, spanning topics from reducing cloud feedback and aerosol forcing uncertainties, quantifying aerosol emissions and indirect effects, and air quality applications. The great impact of the CALIPSO mission on the scientific community is reflected by the publications: CALIPSO data have been used in more than 1060 peer-reviewed publications since the last Senior Review.

Weaknesses
WFC anomaly occurred on April 11, 2020 and the instrument is powered off. The panel concurs with CALIPSO team's assessment that loss of the WFC does not significantly impact the remainder of the CALIPSO mission.

Value of data record with the additional 3-6 years of data, and overall data continuity
The CALIPSO lidar (CALIOP) data represent a unique sampling of the vertical profile of aerosol and clouds at very high resolution. Widespread use and adoption of these data across the scientific and operational communities suggests that continuing these data would provide many benefits. The great value of CALIOP data in cloud and aerosol and climate investigations will continue by a continued operation with CloudSat and Aqua and other satellites. The 2017 Earth Sciences Decadal Survey (National Academies, 2018) identified a significant upcoming observational gap due to the lack of a follow-on to CALIOP: Until the launch of the EarthCARE satellite (anticipated in 2022), CALIPSO is the only mission addressing the priorities for cloud and aerosol lidar observations identified in the Decadal Survey report. Additional two years of the CALIOP data would enable data continuity with the spaceborne lidar measurements to be acquired by EarthCARE, which in turn could serve as a unifying bridge to a future A-CCP mission. The value of continuing the CALIPSO data can also be seen from their operational applications. Letter from NOAA (June 15, 2020) provides a tangible example for how CALIPSO data products are used by NOAA in support of the NWS's mission, which stated that "NOAA would very much like the CALIPSO/CALIOP data to continue, as it is our only source of data for validation. […] We would be at a great disadvantage if space-based aerosol vertical profile and aerosol typing information becomes unavailable". Furthermore CALIPSO's eastward drift across the MODIS swath will provide a unique data set for validating both MODIS and AIRS retrievals as a function of MODIS/AIRS view angle.

Standard mission data product quality: Excellent

The CALIPSO project routinely produces and archives a comprehensive catalog of standard and expedited data products that are distributed worldwide. The expedited products are designed to meet the near-real-time data delivery requirements of field campaigns and operational forecast centers and are generated immediately upon receipt of the downlinked data. The standard products are produced later, using temporally matched meteorological reanalysis data. To date there have been four comprehensive releases of the standard data products, with each new release offering substantial improvements in retrieval accuracies and uncertainty characterization. Since 2017, the CALIPSO project released a new lidar level 1.5 (L1.5) product, a new lidar level 2 (L2) blowing snow product, four new lidar level 3 (L3) products, updates to the established lidar L2 and L3 data products, a new version of the IIR level 1 (L1) data products, and a new IIR level 2 (L2) product. The CALIPSO standard mission data product accuracy has been assessed and the uncertainties in

the product are well established via independent measurements. Quality of the CALIPSO data production is high and sustained, and similar data are not available anywhere else. The CALIPSO data have been embraced throughout the science community, as evidenced by the publication of over 2900 studies in peer-reviewed journals.

The project will continue generating and distributing the full suite of current data products. New CALIOP algorithm and data product development during the 2020–2023 time frame will focus on (1) final code development and quality assurance testing of the CALIOP L2 V4.5 data product; (2) identifying and implementing new strategies for ameliorating the effects of low energy laser pulses on the CALIOP L2 data products; and (3) generating a V5.0 release of the CALIOP L1B data that minimizes known instrument artifacts and incorporates enhanced ancillary data sets. Development of the CALIOP V5.0 L2 products with several scientifically significant improvements would start immediately following the release of CALIOP V5.0 L1 data (The panel notices the importance of the proposed efforts under the overguide budget during FY24-25 to complete and release V5 L2 data). CALIPSO will maintain its mission-long record of validation underflights conducted by the LaRC HSRL. Airborne coincident measurements are critically important for validating space-based lidars and will provide essential characterization during the laser switch period and as CALIPSO adapts its calibration algorithms to accommodate intermittent low-to-no energy laser pulses.

The ground-based Raman lidar observations at the DOE ARM sites have been shown to be extremely valuable to evaluate and validate the CALIPSO aerosol and cloud products. The panel encourages the CALIPSO team to actively seek the use of these ground-based observations in the validation of the new Lidar Version 5 data products.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

The CALIPSO mission directly contributes to NASA ESD research objectives by addressing the questions in four of NASA SMD's six interdisciplinary Earth Science Focus Areas: atmospheric composition, climate variability and change, water and energy cycle, and weather.

CALIPSO is responsive to the four major priorities identified in the SMD Science 2020-2024 Vision for Science Excellence plan. For the Exploration and Science Discoveries (Priority 1), CALIPSO is highlighted in 2017 NAS Earth Sciences Decadal Survey Report as a transformative capability for determining global aerosol and cloud vertical profiles; CALIPSO has helped advance understanding of the identified key areas: coupling water and energy cycles, reducing climate uncertainty, and improving weather and air quality forecasts; CALIPSO has provided tangible improvements to NWP model parameterizations, satellite weather cloud detection and retrievals, and validation for air quality models. For the Innovation (Priority 2), CALIPSO provides leadership in remote sensing science with pioneering developments in retrieval algorithms of cloud and aerosol properties. For the Interconnectivity and Partnerships (Priority 3), CALIPSO is a highly successful international partnership between NASA and CNES; Measurement synergies enabled by CALIPSO with the A-Train have helped facilitate productive collaborations among NASA Centers, other government agencies, and academia. For the

Inspiration (Priority 4), CALIPSO has helped to inspire the next generation of scientists as witnessed by >204 Ph.D. dissertations and 94 Master theses based on CALIPSO data.

The CALIPSO mission is highly relevant and has greatly contributed to the Program of Record and the science priorities called out in the 2017 Decadal Survey for Earth Science, including C-2a (reduce uncertainty in low and high cloud feedback by a factor of 2) (MI), C-2h (reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2) (MI), C-2g (quantify the contribution of the upper troposphere and stratosphere to climate feedbacks and change) (VI), C-5a (improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints) (VI); C-5c (quantify the effect that aerosol has on cloud formation, cloud height, and cloud properties including semi-direct effects) (VI); W-1a (determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts) (MI); W-2a (improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability, e.g. MJO, ENSO) (MI); W-5a (improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems) (MI).

Weaknesses
None were identified.

Technical and Cost

We concur with the technical and cost sub-panels. It is worth pointing out that the cost risk rating for CALIPSO is largely driven by the technical concerns instead of the "likelihood of accomplishing proposed task within proposed cost".

National Interests

We concur with the National Interests sub-panel assessment.

Detailed Science Reviews
A4.4 Mission: CloudSat

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline to sustain operations	Continuation with augmentations to the current baseline to sustain operations but reduced from the requested optimal funding, given the maturity of the algorithms

Overview

The CloudSat mission, launched in 2006, carries the Cloud Profiling Radar operating at 94 GHz, which is currently the only spaceborne radar capable of simultaneously observing both clouds and precipitation. After its departure from the A-Train in 2017 due to a loss of a reaction wheel, it recently joined CALIPSO in its lowered disposal orbit in the C-Train. CloudSat will continue to fly in formation with CALIPSO as its mean local crossing time drifts until CALIPSO is decommissioned. Until the launch of EarthCARE in FY22, CloudSat remains the only source for vertical profiles of cloud and precipitation properties (including cloud water and ice and precipitation water and snow). The panel rated the CloudSat mission as excellent in science, relevance, and data quality. The panel unanimously agreed that extension of the CloudSat mission for FY21-23 with the requested augmentations to the baseline is a priority. Without augmentation, CloudSat mission termination would begin in FY21 leaving a gap in critical vertical cloud and precipitation profile measurements until the planned launch of EarthCARE in FY22. The CloudSat mission is highly relevant to the NASA SMD Science Plan, 2017 Decadal Survey objectives, and the program of record. The benefits of extending CloudSat through the requested budget augmentations include:

- Maintaining continued synergy with CALIPSO in the new C-Train orbit to provide co-located observations of clouds, precipitation, and aerosols
- Extension of the data record enabling understanding of cloud and precipitation processes in the context of important modes of climate variability
- Facilitating overlap and intercalibration between CloudSat and EarthCARE, which serves as a bridge to the future ACCP mission
- Continued collaborations and new opportunities that exploit the existing program of record.
- The panel also deemed that continuation of CloudSat for FY24-26 was important, but was split on the conclusion for funding level for this period. Panelists agreed that overlap with EarthCARE for cross-calibration efforts and extension of unique precipitation and snow products were important, but were split on whether continuation should be at the requested levels or at reduced levels for FY24-26 given the maturity of the algorithms.

Overall, the CloudSat mission has demonstrated important progress in improving physical understanding of cloud and precipitation processes and translating these into model improvements and better understanding of cloud feedback mechanisms. The team has continued validation of existing products, contributed to improvements of products from other missions, and developed

new products, such as the constant sensitivity product that will be particularly important for understanding and interpreting variability in the long record.

In addition to the aforementioned science contributions, CloudSat data are widely used by many other mission science teams to improve cloud and precipitation retrievals from other sensors in the program of record. CloudSat data products provide benchmarks for improving GPM light precipitation and snow products. They have also been used by MODIS, VIIRS, and GOES ABI teams for improving cloud property retrievals. CloudSat data are also used in operational applications to quantify model errors and improve NWP models. Recent collaborations with ECMWF have also demonstrated improvements in NWP predictive skill through direct assimilation of CloudSat data.

The probability of technical success is high provided continued operation of the remaining three reaction wheels. A switch to the backup Extended Interaction Klystron is expected within the next year to maintain mission science requirements.

Scientific merits: Excellent

Strengths

The CloudSat mission carries only the Cloud Profiling Radar (CPR), which is currently the only spaceborne radar capable of simultaneously observing both clouds and precipitation. After its departure from the A-Train in 2017 due to a loss of a reaction wheel, it recently joined CALIPSO in its lowered disposal orbit in the C-Train. CloudSat will continue to fly in formation with CALIPSO as its mean local crossing time drifts until CALIPSO is decommissioned. CloudSat provides a unique set of observations of vertical profiles of cloud and precipitation properties, as well as derived information about the vertical profiles of atmospheric radiative fluxes and heating rate profiles. The panel felt that the CloudSat team has been especially successful in exploiting the synergies with CALIPSO and other A-Train sensors to produce value-added joint products. The extended mission proposes 4 science goals:

1. use the extended data record to examine cloud processes in the context of climate variability at interseasonal to decadal timescales
2. apply understanding from 1. to improve model representation of cloud and precipitation processes
3. use the extended data record to evaluate existing cloud and precipitation climatologies
4. open new research areas and product opportunities that exploit the existing program of record, including GPM and new geostationary imagers.

The panel commends the CloudSat team for a number of recent accomplishments that span a wide range of applications across the globe. The now relatively mature cloud and precipitation products have been used to evaluate representation of cloud and precipitation processes in models and improve global scale precipitation climatologies, like GPCP, and cloud retrievals from MODIS and GOES ABI. Recent work using CloudSat observations to understand the warm rain process has shed light on missing aerosol-cloud interactions and led to model parameterization improvements with significant implications for effective radiative forcing in climate models. CloudSat products have also exposed a number of shortcomings in light precipitation and snow

regimes in both existing climatologies and models. The team has also further developed their snowfall product, which serves as a reference for other precipitation missions (like GPM) and reanalyses and is being used to better understand high latitude snow climatologies and ice sheet mass balance. CloudSat data has also been applied to better understand tropical high cloud feedback mechanisms and has exposed unaccounted-for shortwave cloud feedback mechanisms and microphysics changes correlated with warming. The proposed extended data record is expected to continue providing important data that can be used to further understanding of cloud and precipitation processes in the context of climate variability.

Weaknesses

One weakness of extension beyond FY23 is the loss of joint radar-lidar retrieval products when CALIPSO is decommissioned in 2023. In addition, some panelists felt that the requested science team funding for FY23-26 at the same level of the prime mission may not be justified given the relative maturity of the algorithms and that EarthCARE intercalibration procedures should be fully developed in FY21-23.

Value of data record with the additional 3-6 years of data, and overall data continuity

CloudSat mission extension for FY21-23 should be considered high priority given its unique vertical profile observations and measurements below sensitivity limits of other sensors in the program of record. The unique observations also contribute to improving and constraining retrievals from other active and passive platforms in the program of record. Extension will also allow continued production of joint CloudSat-CALIPSO products in the new C-Train orbit and will overlap with EarthCARE, enabling intercalibration, data continuity, and development of a merged dataset that spans a long enough period to detect climate trends. The panel suggests:

- continued development of the constant sensitivity 2B-GEOPROF product, as well as a stream of retrieved products that use this constant sensitivity product as input
- continued collaborations with other missions like GPM and GOES-ABI to improve cloud and precipitation retrievals from other sensors in the program of record
- development of the new optimally-merged hydrometeor profile 2C-HYDRO product
- development of CloudSat-EarthCARE CPR intercalibration procedures
- expansion of efforts to use CloudSat data to improve forecast skill of operational NWP models both domestically and abroad.

Extension beyond FY23 will continue the long record of vertical reflectivity profile observations and cloud and precipitation retrievals. The continuation beyond FY23 is especially important to prevent data gaps if EarthCARE launch is delayed, for intercalibration efforts, and for continued unique rain/snow precipitation products that may not be planned by the EarthCARE team. However, the panel notes that the value of CloudSat observations in FY23-26 decreases after the loss of CALIPSO and once EarthCARE is successful.

Standard mission data product quality: Excellent

The core mission products are mature and on the 5th release. Regular calibration is performed using ocean surface reflectance and corrections are included in product releases. There are ongoing validation efforts that leverage both systematic observations and campaign opportunities to

improve products. The team validates the physics of the algorithm, performs intercomparison with similar products from other sensors, and compares with ground truth measurements. The proposal highlights recent efforts at validating light precipitation with shipborne radars, snow product estimates with measurements collected at high elevation stations and GHCN observations, and derived radiation products with CERES data.

The mission has been especially successful at leveraging A-Train synergies and incorporates CALIPSO, MODIS, and OCO-2 data to improve retrievals and create new products. The joint CloudSat-CALIPSO products should be continued as long as possible in the new C-Train. The team also produces a number of matched, subset products from a variety of platforms including not only the aforementioned A-Train products, but also AMSR-E, CERES, SSM/I, TRMM, GPM, AMSU, MHS, HIRS, and a combined tropical cyclone product. These ancillary or special products are useful for not only the CloudSat algorithm development team, but also for development and validation for other missions and to facilitate multi-sensor investigations by the science community. Product distribution has increased 67% since the previous senior review.

For FY21-23, the team proposes continued development in 3 important areas: continued development of the constant sensitivity radar reflectivity product and data stream, a combined CloudSat-CALIPSO-OCO2 product, and development of an optimally-merged hydrometeor profile product. The constant sensitivity product will be important for removing instrument sensitivity artifacts in trend analyses for climate applications. The combined OCO-2 product will mitigate current CloudSat-CALIPSO limitations in marine boundary layer clouds and improve estimates of cloud thickness, optical depth, and particle size which will be important for aerosol-cloud-precipitation studies. The panel thinks that the team should prioritize the proposed "best estimate" optimally-merged 2C-HYDRO product. The current products contain a number of independent estimates of the same retrieved geophysical parameters that use different input datastreams or different sets of (sometimes inconsistent) assumptions. These products will be especially important for reducing user confusion among members of the broader science community who may not be as familiar with the underlying retrieval assumptions and sensitivities to the input products.

One weakness the panel noted is that, with the exception of proposed new products, there is a lack of detail on science support needed for maintaining core products and the mission's targets for continued algorithm development/improvement efforts especially beyond FY23. Given the maturity of CloudSat products and that intercalibration procedures with EarthCare are expected to occur during the FY21-23 budget period, some reviewers felt that the requested flat funding levels for FY23-26 may not be justified.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

The CloudSat mission contributes to Strategies 1.1, Strategy 2.2, and 3.2 Science Leadership Priorities of the NASA 2020-24 Vision for Scientific Excellence. Strategy 1.1 recognizes the importance of the Decadal Survey recommendations, of which CloudSat addresses 9 of the most important (MI) Decadal Survey objectives. These MI objectives span the range from high latitude

hydrology and climate, improved understanding of a variety of important water and energy cycle components, weather applications in both deep and shallow cloud regimes, and reducing climate and cloud feedback uncertainties. In addition, CloudSat extended mission goals map onto multiple Aerosol, Cloud, Convection, and Precipitation (ACCP) designated observables. The CloudSat team has demonstrated their commitment to Strategy 2.2 through the demonstration of formation flying, their multisensor approach to retrieved data products, and collaboration with other missions in the program of record. These collaborations also contribute to Strategy 3.2. CloudSat has developed a number of partnerships within the A-Train community, and with other NASA partners, like GPM, with the US Air Force, operational forecast and major modeling centers, and international partnerships with EarthCARE.

Weaknesses
None were identified.

Technical and Cost

The science panel concurs with technical panel who rated the mission extension as a medium-low risk. The transition to the backup Extended Interaction Klystron (EIK) is expected within the next year once the radar sensitivity on the primary EIK drops below minimum science requirements. Spacecraft subsystems have a high probability of success. CloudSat is down to three reaction wheels, but no degradation in the remaining wheels has been observed. Loss of another reaction wheel would require decommissioning, which can be performed safely without the reaction wheels.

National Interests

The national interests panel gives CloudSat a "Some Utility" rating. CloudSat is primarily used for hydrologic applications, icing forecasts, and in constraining GOES operational cloud products. We note that the previous Senior Review rated CloudSat as "High Utility", so we concur with the national interest panel that better research-to-operations pathways and additional outreach could improve low or N/A ratings by some agencies.

Other Comments

The panel felt that the proposal was of high quality and sufficient for review.

Detailed Science Reviews
A4.5 Mission: CYGNSS

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline; over-guide as proposed to sustain operations	Continuation with augmentations to the current baseline; over-guide as proposed to sustain operations

Overview

CYGNSS was initially proposed as an Earth Venture mission and is undertaking its first senior review in 2020. This proposal covers mission operation costs as well as a science team that focuses on retrievals, data assimilation of oceanic wind measurements, and development of land validation products.

CYGNSS consists of a constellation of low-cost GNSS sensors on eight micro-satellites that measures the forward scattering of GPS satellite signals from the surface. Each satellite records the delay Doppler maps (DDMs) from each of the intersections with the GPS constellation. As such, the measurements have a sampling geometry that is unique, and the deployment of the sensors is such that a given region may experience several retrievals in a short time period for studying rapidly-evolving phenomena (such as tropical cyclone rapid intensification).

The DDMs were originally proposed to be used to retrieve the ocean surface wind speed (not direction), and the team has met mission level 1 requirements across most values of wind speed. The L-Band frequency of CYGNSS can penetrate through clouds and precipitation to retrieve ocean wind speeds in all-weather conditions, which is unique in the current satellite fleet that relies on scatterometer measurements at lower frequencies that suffer from degraded measurements in heavy rain and high wind conditions above ~30 m/s. This allows the sensor to potentially measure very high wind speed conditions in tropical cyclones with benefits for studying such high impact weather. These measurements have value, particularly in data sparse regions where tropical cyclones form. The wind speed measurements can also be used in estimating surface heat fluxes from the ocean (alongside MERRA-2 reanalysis), a key parameter coupled with regional weather which has large uncertainties in models.

After launch, it became apparent that the DDM measurements had applications for studying land surface conditions in addition to oceanic measurements. This includes measurements of soil moisture through vegetation that may meet the accuracy thresholds of "mainline" soil moisture missions such as SMAP, but with the potential for more frequent revisit times in particular regions. In addition, the DDM can determine the coherence of the forward scattered signals which can be used to determine characteristics of the surface, for example, if it is inundated with water. These measurements are unique and offer advantages to other measurements of flooded area that are obscured by overlying vegetation.

The data from this mission offers opportunities to advance the science of high impact weather prediction through studies of oceanic weather phenomena such as tropical cyclones, convective cold pools, the Madden-Julian Oscillation, and longer term coupled ocean-atmospheric climate variability. Land-atmosphere interaction studies are also enabled, allowing additional retrievals of land surface properties such as soil moisture, vegetation cover, and flooding extent. Current latency of the data limit real-time applications, limited by downlink capability, in fields such as weather forecasting and real-time data assimilation of ocean and land products with agencies such as NOAA, however the measurements from CYGNSS are useful for the research arms of government agencies such as NASA, NOAA, USGS, the university and private sector communities to perform algorithm development, hindcasts and process studies.

The current health of the constellation of instruments is good, especially considering the low-cost nature of the sensors. The team has been agile dealing with unexpected GPS signal variability and the level of engineering automation of the handling of instrument anomalies is state-of-the-art. The team continues to develop new versions of algorithms that reduce uncertainties in the ocean wind products. The current proposal expands retrievals of land surface characteristics and describes a plan for validating these new measurements with new in situ measurements of soil moisture and land surface coherence properties.

Scientific merits: Excellent

Strengths

During the past three years, the CYGNSS mission successfully deployed and coordinated the constellation of 8 micro-satellite orbital platforms and sensors which comprise the observing system. This was a tremendous feat given the low-cost nature of the systems which were built to "off-the-shelf" engineering specifications. The satellites were successfully configured into the pre-designed orbital configuration, using modulation of the satellite's on-orbit drag to control altitude and thus velocity, allowing for the use of differential drag to implement the designed configuration. The ultimate planned configuration allows for rapid update measurements in the same sampling region within the "swarm". The sensors performed to specifications upon deployment and have so far stood the test of space's harmful environment allowing for measurements to mostly meet mission requirements.

The CYGNSS science team was initially focused during the EVM period on the development and validation of ocean wind products. They implemented Day 0 algorithms after launch and made improvements to handle unexpected variations in GPS signal that were caused by anti-jamming techniques used by the GPS satellites. These anomalies were successfully accounted for and new versions of the mission retrievals and products took these variations into account to produce retrievals of ocean surface winds that met L1 requirements. These measurements were validated using ocean surface wind measurements from NOAA Hurricane Hunter ocean surface wind measurements for L2 requirement validation, as well as comparisons with the wind fields from the operational NOAA HWRF tropical cyclone prediction model. A new level 4 tropical cyclone wind radius product has been published and offers opportunities for reanalyzing the wind field in past tropical cyclone analyses, including widely-used reanalysis products. Hindcasts of tropical cyclone case studies assimilating CYGNSS wind products showed modest improvements in skill, particularly early in the tropical cyclone life cycle where other observations were sparse.

Retrievals of latent heat flux have been implemented using the observed wind speed and reanalysis products. These products have been used by the science team to understand the roles of ocean surface fluxes in the Madden Julian Oscillation. Ocean waves, ocean altimetry, and ocean plastics products have also been developed, and validation activities are planned in the mission extension.

During the past 3 years, the team recognized the opportunity for CYGNSS measurements to enable retrievals of land surface products, and in the proposal and subsequent discussion there was much attention paid to this new opportunity. The collection of these GNSS-reflectometry measurements may enable new science outside of what is proposed, and should be commended. The proposal outlined the potential and some initial work developing these land surface retrievals in several areas. These included the demonstration of a GNSS soil moisture retrieval that may have the potential for meeting the sensitivity requirements of other missions that were designed to observe soil moisture. In addition, a land type classification scheme and land inundation retrieval were demonstrated. Along with these new products, a calibration/validation effort was initiated recognizing the dearth of such measurements, particularly in regions within CYGNSS coverage that experienced freeze/thaw cycles.

Weaknesses

The panel noted that while the measurements of ocean wind speed met L1 requirements, the retrievals of surface wind speed suffer compared with validation measurements in high winds, which the mission was purported to excel at. This could be due to the lack of quality of in situ validation data at the scale of the CYGNSS footprint for comparison, the relatively coarse data resolution, or any additional shortcomings in the retrievals themselves. The panel suggests continued work on validating wind speeds in these conditions with further coordination with NOAA and the scatterometer wind community (for example, the international NASA Ocean Vector Winds Science Team).

The panel commends the CYGNSS science team in using their products in data assimilation efforts to try to quantitatively assess the impact of CYGNSS ocean wind retrievals in hindcasts of tropical cyclone track and intensity forecasts. However, relatively few studies have used CYGNSS measurements directly to "improve understanding of tropical cyclone processes". The panel suggests partnering with tropical cyclone dynamicists in the government and university communities to expand how CYGNSS measurements could improve the understanding and predictability of tropical cyclones.

The panel noted that the shift of the mission to land surface products may have come at the expense of further development, refinement, and validation of ocean products. The panel felt that this may lead to less use of the products in the long run, and hopes that these products are continually improved and the use of the products is disseminated to relevant communities.

Value of data record with the additional 3-6 years of data, and overall data continuity

Overall, the panel felt that the operations of the satellites are likely to continue into the future, with a low-medium risk of technical issues. This provides for a good opportunity to increase the statistical sample of intercepts with high-impact weather systems such as intense tropical cyclones, more cycles of tropical oscillations such as the Madden Julian Oscillation, and continued

development and collection of new ocean and land surface products, algorithm development, and validation. The continuity of the products will enable both new science looking at long term climate variability as well as increasing the sample size of extreme events. This will enhance our Period of Record for ocean wind products under several Decadal Survey-related objectives, particularly in high wind and heavily precipitating conditions where other sensors have shortcomings or in other data sparse regions.

The panel noted that the engineering challenges of CYGNSS and its low-cost microsatellites present a valuable opportunity and technology demonstration for the extension of mission operations. As the sensors experience issues due to the changing GPS constellation and the degradation of the low-cost satellite hardware itself, this will present challenges to the team and lessons learned will guide the deployment of future low-cost satellite missions that are planned and to be proposed under the Earth Venture program.

Standard mission data product quality: Very Good

The standard ocean products from CYGNSS meet L1 requirements for accuracy and coverage. This is after the team accounting for correction of products due to the variable GPS transmit power noted above, providing the increase of the mission's data by a significant amount. This correction, and new retrieval assumptions, will yield improvements in accuracy and coverage in the version 3.0 ocean products due out soon. During the next 3 years, a new sequential algorithm will be enabled near tropical cyclones, further reducing algorithm uncertainties. The level of support for these operational products is adequate, although cooperation with the NASA OVWST not noted in the proposal could be beneficial for the CYGNSS science team as there are overlapping objectives and science applications.

Operational land products are to be developed in the forthcoming cycle, and validation efforts will be developed and performed. Given that these are new products that will require significant effort, the panel commends the team, consisting of expansive expertise, for their initiative and plans for rolling out these new products to the community. The panel felt that cooperation with the SMAP science team could benefit some of their algorithm development and validation efforts.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

CYGNSS provides measurements of surface winds and soil moisture that contribute to the following 2017 Decadal Survey Targeted Observables: Atmospheric Winds (TO-4), Ocean Surface Winds and Currents (TO-11), and Soil Moisture (TO-17). In addition, the program of record, as defined in the National Academy of Sciences Earth Science and Applications from Space Decadal Survey, includes CYGNSS as one of the operating missions with a design life of 2 years (consistent with the prime mission) and expected end of life beyond 2019. In addition, each panel participating in the ESAS DS specified measurements that may be obtained from the program of record. CYGNSS measurements are specifically called out in the following: Climate Variability and Change (C-4a, Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture) and other Gases), and Climate Variability and Change (C-4d, Evaluate the effect of surface CO_2 gas exchange, oceanic storage, and impact on ecosystems). In addition,

the CYGNSS proposal highlighted relevance to multiple areas covered in the 2017 Decadal Survey: 1) Global Hydrologic and Water Resources areas H-2a (Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling), H-3b (Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers), and the response to extreme events); 2) Weather and Air Quality areas W-2a (Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months), and W-3a (Determine how spatial variability in surface characteristics modifies regional cycles of energy, water and momentum (stress)); 3) Marine and Terrestrial Ecosystems area E-1d (Quantify moisture status of soils); and 4) Climate Variability and Change areas C-4c (Improve bulk flux parameterizations, particularly in extreme conditions and high- latitude regions), C-7d (Quantify the linkage between the dynamical and thermodynamic state of the ocean upon atmospheric weather patterns on decadal time scales), and C-8i (Quantify how increased fetch, sea-level rise and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify).

CYGNSS is responsive to the 2020 NASA SMD Science Plan elements Strategy 1.1 “Execute a balanced science program based on discipline-specific guidance from the National Academies of Sciences, Engineering, and Medicine, Administration priorities, and direction from Congress”, Strategy 1.3 “Advance discovery in emerging fields by identifying and exploiting cross-disciplinary opportunities between traditional science disciplines”. In addition, it is relevant to Strategy 2.1 “Foster a culture that encourages innovation and entrepreneurship across all elements of the SMD portfolio”, Strategy 2.3, through its innovative use of microsats to “Enhance our focus on high intellectual risk/high impact research investments” and through the use of off the shelf commercial technology, Strategy 2.4 “Drive innovation in focused technology areas to capitalize on the rapid evolution of commercial capabilities”, as well as Strategy 3.4, by being based at the University of Michigan, “to provide increasing opportunities for research institutions, including academia and non-profits, to contribute to SMD’s mission.”

Weaknesses
None were identified.

Technical and Cost

The panel defers to the technical and cost panel evaluations. A CYGNSS ROSES call for enhancing science use of the data is noted.

National Interests

We defer to the National Interest Panel evaluation.

Other Comments
None

Detailed Science Reviews
A4.6 Mission: DSCOVR Earth Science Instruments

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation as currently baselined;	Continuation as currently baselined;

Overview

Launched into space on 11 February 2015, DSCOVR now flies on the Lissajous orbit about 1.5M km away at the Sun-Earth first Lagrange (L1) point. As a joint mission between NOAA, NASA and the U.S. Air Force, DSCOVR carries two Earth science instruments that NASA operates: the Earth Polychromatic Imaging Camera (EPIC) and the NIST Advanced Radiometer (NISTAR). Since its operation on 15 June 2015, except from late June of 2019 to early March of 2020 (because of the DSCOVR pointing hardware issue), the data stream from EPIC and NISTAR has been stable and nearly continuous. As far as hardware, power, and fuel are concerned, it is expected that the EPIC, NISTAR, and DSCOVR can be in nominal function for the next 6 years. Being parked at L1 point, DSCOVR provides a new and unique vantage point for observing the full, sunlit disk of Earth multiple times a day, at a nearly constant back-scattering angular perspective (e.g., viewing from a scattering angle of 165° - 178° with respect to the direct sun beam). EPIC measures back-scattered radiation at 10 wavelengths ranging from ultraviolet (UV) to solar near infrared, enabling the retrieval of diurnal variations of O_3 amount, clouds, aerosols, volcanic SO_2 plumes, vegetation/surface phenology, and surface UV radiation over the sunlit portion of Earth every 1-2 hours. NISTAR measures the radiances from the Earth in four spectral ranges (shortwave, longwave, near infrared, and all spectrums), thereby recording the Earth's radiative energy balance over time at hourly resolution. These data provide new temporally continuous global information that supplements the existing climate data record primarily from satellites in LEO orbit. Research in the past 5 years has revealed critical merit and potential of these data for scientific discoveries and applications in areas such as atmospheric composition, climate, ecosystems and ecology. With observations at multiple local times from sunrise to sunset, EPIC's color images have also been extremely popular, providing an unprecedented view of Earth for the public and outreach opportunity to emphasize the fragility of our planet. The EPIC level-1 and level-2 data have reached its maturity, and NISTAR data is on the right trajectory to achieve its expected precision. The panel suggests that the mission should be extended as currently baselined (extend/in-guide) for the FY 2021-23 and FY 2024-26 periods.

Scientific merits: Excellent (median score: 5.0)

Strengths

Since DSCOVR started its operation only about five years ago, extensive on-orbit adjustments and calibrations were performed that included geo-locating EPIC data for each filter (band), correcting for irregularities (flat-fielding) of the camera, correcting for stray light effects, and

establishing calibration factors to convert counts/second to absolute radiances. Through NASA ROSES funded projects, various level-2 products were also developed, including columnar O_3 products, UV aerosol data (e.g., aerosol index, aerosol optical depth, single scattering albedo, aerosol optical depth above cloud, aerosol height), SO_2 data from volcanic eruptions, cloud products (cloud mask, cloud effective pressure, cloud optical depth, and cloud phase), and surface products such as Lambert equivalent reflectivity data, surface reflectance, leaf area index, and erythemal irradiance estimates. While EPIC has the heritage from TOMS, it is understood that EPIC is a new instrument, the first of its kind, especially considering: (a) challenges to stabilize and calibrate such instrument that is 1.5M kilometer from Earth, (b) movement of the Earth while EPIC is taking the observation sequentially band by band, (c) multiple observations per day for a fixed location from sunrise to sunset (with large change of solar zenith angles), and (d) unique measurements of the radiances within and outside both O_2 A and B bands, which enables the retrieval of aerosol height and cloud height. Hence, the progress made for developing EPIC's Level-1 and Level-2 products have been excellent. The EPIC data has reached its maturity.

Since the last senior review, progress has been made also in understanding the error characteristics of NISTAR measurements of irradiances reflected and emitted from the Earth in four spectral ranges: the total channel (0.2 -100 μm), the total solar reflected channel (0.2 to 4 μm), the near infrared solar reflected channel (0.7 to 4 μm), and the silicon-sensitive near infrared spectrum (0.2 to 1.1 μm). Various efforts have been undertaken to analyze and correct the measurement errors from signal noise, thermal stability, dark offset and background noises. NISTAR's level-2 products include the EPIC composite cloud products and daytime shortwave and longwave fluxes from NISTAR. Its algorithm has the heritage from ERBE and CERES with additional use of the cloud product from EPIC, ancillary information of surface properties and atmospheric profiles, as well as the angular dependence model (ADM) to derive shortwave and longwave fluxes. The EPIC-based SW flux product is in good agreement with CERES counterparts, and is in a good trajectory to reach its expected data quality of 1.5% precision.

Overall, since the last senior review, the DSCOVR science data products have achieved the level of calibration accuracy and stability that are needed for generating level-2 scientific data products. Indeed, several level-2 scientific products from EPIC have already been used by the scientific community and illustrated their importance to advance Earth science. Furthermore, several new endeavors have also been carried out by the scientific community, such as using DSCOVR level-1 data to study ocean color. A few highlights of DISCOVR data for scientific discovery and applications include (but not limited to): (a) diurnal variation of ozone, clouds and aerosols as well as the global diurnal courses of sunlit leaf area and fraction of photosynthetically active radiation absorbed by vegetation, (b) retrieval of absorbing aerosol plume heights and movement and their diurnal variations, (c) monitoring and estimate of volcanic SO_2 plume movement multiple times per day, (d) a new way to monitor vegetation greenness even under cloudy conditions, and (e) estimates of day-time total erythemal irradiance (with observation-based treatment of diurnal variation) that is of high interest of NOAA National Weather Service. Finally, EPIC's color images have been extremely popular, providing an unprecedented view of Earth for the public and an outreach opportunity to emphasize the fragility of our planet.

Weaknesses

Given that the DSCOVR Earth Instruments datasets, especially its EPIC level-1 and level-2 data products, have reached maturity and science-grade quality, the panel suggests that the DSCOVR

mission enhance their efforts to engage the scientific community broadly to increase the use of the DSCOVR data and demonstrate its scientific value. In addition, there are some concerns that the DSCOVR Earth Instruments are not well integrated with the cohort of NASA's science missions (which in part is reflected in the history of the mission).

Standard mission data product quality: Very Good (median score: 4)

Strengths
As documented in the peer-reviewed literature, EPIC level-1 products (e.g., georeferenced and calibrated reflectance and radiance data) have reached the level of stability, accuracy, and maturity to enable scientific research and generate level-2 product with high fidelity.

All of the DSCOVR level-2 science data products are generated by competitively selected teams under the NASA ESD ROSES opportunity. The products (except NISTAR level-2 flux data) appear to be mature and ready for scientific research.

The EPIC-based SW flux product is in good agreement with CERES counterparts, and is on the right trajectory to reach its expected data quality of 1.5% precision.

Weaknesses
While the DSCOVR team efforts in developing level-1 and level-2 products are acknowledged, several panel members expressed concerns about the NISTAR data products. Many panel members were satisfied that the 1.5% precision achieved by NISTAR shortwave products is good, especially in the context of the history of evolving values of solar constant by different measurements in the past three decades and given the uniqueness of DSCOVR data, but strong concerns are expressed by several other panel members as follows:

a) the all-wave NISTAR measurement will likely never be able to be used because there was no time to conduct careful calibration before the mission was launched. This all-wave measurement would have been unique and very interesting as it is one of the components of net radiation for Earth, the total amount of radiation emitted. This is not the fault of the DSCOVR mission, but likely it may be the result of hurrying the mission launch for other reasons.

b) the data quality is deemed as only good because DSCOVR should engage more with the scientific community to encourage the use of DSCOVR data and to demonstrate its scientific value.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent (median score 5)

Strengths
The objectives of DSCOVR are very clearly aligned with NASA science goals to understand the role of aerosols, clouds, O_3, vegetation and volcanic eruptions in the Earth System. It contributes to the exploration of atmospheric chemistry, ocean bio-productivity, vegetation properties, and global cloud and aerosol coverage studies, all of which are key parts of NASA science focus area. DSCOVR datasets contribute to NASA's program of records of aerosols and clouds.

Weaknesses
Some panel members are concerned that the DSCOVR Earth Instruments flying on a NOAA satellite are not well integrated with NASA's science missions.

Technical and Cost

The senior review panel concurs with the sub-panel forms; the cost risk is deemed to be low.

National Interests

The senior review panel concurs with the sub-panel forms; the national interest sub-panel ranked the DSCOVR Earth Science Instruments as some utility.

Other Comments

The panel thanks the DSCOVR Earth Instrument team for presenting a thorough and solid proposal, and sharing with the panel DSCOVR's uniqueness and research efforts for improving DSCOVR level-1 and level-2 products. It is suggested that the scientific discoveries with the DSCOVR datasets should be part of the research focus of DSCOVR program in the mission extended time periods.

The panel recognizes that the mission science team is exclusively dedicated to the retrieval algorithms and product development, and DSCOVR mission is dependent on external research funded by ROSES. Given that the products are now reaching maturity, the panel suggests that the mission's scientific impact should benefit greatly from reaching out to the broader community in research areas of climate, atmospheric composition, ecosystems and hydrology programs to advertise their products. For example, to shine light into the existence of DSCOVR to a broader community, perhaps a virtual booth during the AGU and AMS Fall meetings may be helpful. The overall score of DSCOVR is 4 or very good; this is the median of all the scores given by all panel members for all three categories (merit, relevance, data quality).

Detailed Science Reviews
A4.7 Mission: ECOSTRESS

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline with proposed over-guide budget to sustain operations	Continuation with augmentations to the current baseline with proposed over-guide budget to sustain operations

Overview

ECOSTRESS provides land surface temperature (LST), evapotranspiration (ET), evaporative stress factor, and water use efficiency (WUE) measurements derived from high spatiotemporal resolution (38 × 69 m from 52°N to 52°S; every few days at varying times of day), multispectral thermal infrared (TIR) measurements from the International Space Station (ISS). ET is a critical parameter to monitor vegetation response to water stress under severe drought condition and a key climate variable linking water, carbon, and energy systems. ECOSTRESS is the first mission to sample the diurnal cycle of ET at fine spatial resolutions, it will play a key role in understanding carbon cycle feedbacks to water cycle variability and extremes.

ECOSTRESS has a variety of societal applications including: water management, agriculture, urban heat, fire management, disease transmission, and ecosystem habitat. ET measures US agricultural water consumption, which enables improved drought estimation accuracy and improved water use accuracy. These analyses have currently been applied to selected regions, but will be applied to the entire global land surface between 52° N and 52° S. ECOSTRESS also provides critical pathfinding data for the future Surface Biology and Geology (SBG) Designated Observable (DO) recommended by 2017 Decadal Survey.

ECOSTRESS mission is expected to continue collecting data for the next 3+ years. It has expanded data collection capability over the entire land surface, coastal regions, and some open ocean areas within 52°N to 52°S and are acquiring 2.5 times as many scenes per day as originally planned. Currently, only three of the five TIR spectral bands are downlinked, but this will be resolved with a new firmware update.

Scientific merits: **Excellent**

Strengths

The ECOSTRESS provides land surface temperature and emissivity (LSTE) measurements and ET, evaporative stress factor, and water use efficiency (WUE) products derived from high spatiotemporal resolution (38 × 69 m from 52°N to 52°S; every few days at varying times of day), multispectral TIR radiance measurements from the International Space Station (ISS). ECOSTRESS is the only satellite sensor that provides TIR data with sufficient spatial, temporal, and spectral resolution to estimate ET at local scale over the diurnal cycle across the globe. The ability to sample these variables at different times of the day for each location (over the course of two weeks or so and under cloud free conditions) provides insight in the important diurnal

variability of these properties, particularly ET, and thus WUE. The relatively good spatial resolution (70 m) enables looking at variation even within agricultural fields.

The team focused on three objectives in the past three years: The first is to identify critical thresholds of water use and water stress in the key climate sensitive biomes. They demonstrated that they can identify distinct differences in water use efficiency (WUE) across different biomes and identify the importance of plant function types in WUE. However this WUE data product is not been adequately evaluated yet. The second objective is to detect the timing, location, and predictive factors leading to plant water uptake decline and/or cessation over the diurnal cycle. The proposal demonstrates that their ET product was able to provide the diurnal patterns of ET in different locations. The last objective is to measure agricultural water consumptive use over CONUS at spatiotemporal scales applicable to improving drought estimation accuracy. Limited comparisons with the WUE derived from Landsat data suggest that using ECOSTRESS data improved estimates of agricultural water use accuracy by up to 40%.

In the last three years, ECOSTRESS demonstrates technology feasibility of high resolution (combined spatial, temporal, spectral) spaceborne thermal measurements and innovative use of ISS in accelerating critical Earth science and applications discoveries. They have been collecting much high-quality data (planned for 74 scenes per day, but actually receiving 200+ scenes per day on average). Surface temperature and ET products are being validated. Their daily ET product has potential to monitor water stress and water use in agriculture fields in the CONUS.

Expanding the data set to the entire observable land surface is an important goal for the next three years. The firmware fix in the near future to expand data retrieval back to the full 5 TIR bands will probably improve data quality.

Weaknesses

There are many exciting potential science research topics and societal applications for the ECOSTRESS data, but relatively few quantitative results so far. This situation is likely to change once the data set has become more extensive and users have had time to learn how to integrate it into their science analyses and their water management applications. We are being asked to take a leap of faith that this explosion of ECOSTRESS data usage will occur, but considering the potential, it could be a leap worth taking.

ECOSTRESS cannot measure in the highly climate sensitive regions north of 50^{O}N and in locations and time periods with extensive cloud cover.

Clear sky ET product was evaluated against 82 eddy covariance sites around the world with general good agreement, however at ET values below ~150 W m^{-2}, ECOSTRESS ET is more than 2 times larger than surface ET. Since these low ET regions must be regions of greatest interest and nearest "tipping points", this large error somewhat larger than ECOSTRESS ET uncertainty estimates is disconcerting. No validation is available for level3-4 products yet.

Value of data record with the additional 3-6 years of data, and overall data continuity

ECOSTRESS provides unique datasets, but it is presently only two years long. With an additional 3-6 years of data, ECOSTRESS will be able to provide derived products that can track not only

how ecosystems respond to water stress, particularly through changes in diurnal water use, but how those responses change with time. These global-scale, climate-scale, ecosystem responses to a changing water cycle are critical for constraining climate model uncertainties with respect to biome sensitivity to possible tipping points into the future.

Standard mission data product quality: Very Good

ECOSTRESS data maturity, use, and testing are appropriate for such a new instrument. The product qualities are actively being assessed and the quality of the products (e.g., cloud masking) are improving. Level 1 radiance and level 2 surface temperature and emissivity products are well validated with good accuracy. Level 3 ET products were compared with eddy covariance measurements with reasonable accuracy, however, the lower range of ET seems biased high. No validation results for two level 4 products are available at this early stage.

Level 3-4 products are quite unique, but they depend heavily on other satellite or model products. It is not quite clear how the uncertainties associated with these inputs may affect the quality of ET and other higher-level products. As these products are being tested and refined, different/alternate data sources are proposed. For example, vegetation inputs from Landsat are being replaced with Sentinel-2 data for ET calculation, and high spatial resolution of BESS-modeled GPP instead of MODIS GPP products are being used for the WUE product. It is assumed that these replacements will improve the quality and robustness of ECOSTRESS products. However, rigorous validation plans for higher level products are required to ensure quality before these products are available for the science and applications communities.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

ECOSTRESS provides key measurements of high spatial and temporal surface temperature and ET products to improve our understanding how Earth's ecosystems respond to changes in the water and energy cycles, which are directly tied to NASA's SMD goals of understanding Earth's ecosystems (Carbon Cycle and Ecosystems) and water cycle (Water and Energy Cycle). ECOSTRESS detects the timing, location, and predictive factors leading to plant water uptake decline and/or cessation over the diurnal cycle. The plant-water dynamics and the functioning of terrestrial ecosystems over the diurnal cycle is encompassed within NASA's SMD Science Plan ecosystem response to changing climate. Monitor agricultural water use and water managements is directly aligned with SMD's global change and extreme hydrology goals.

ECOSTRESS by providing key measurements of high spatial and temporal surface temperature measurements for 3-6 years will bridge the gap between the current ASTER on Terra and the future SBG mission, directly contribute to NASA POR.

The need for TIR and ET measurements is highlighted as a national priority in the most recent 2017 Earth Science Decadal Survey. By measuring the temperature and ET of plants, ECOSTRESS directly addresses multiple Most Important (top priority) and Very Important (second ranked priority) Decadal Survey objectives. ECOSTRESS was identified as the program

of record (POR) for SBG Designated Observables of the Earth system identified Decadal Survey. It provides critical measurements that will help design the future SBG mission.

Weaknesses
The Science review panel did not identify any weaknesses.

Technical and Cost

We concur with the sub-panel.

NASA ROSES calls for an ECOSTRESS science team is necessary to expand the science and applications of the ECOSTRESS mission. Having a science team would enable more timely production, validation, and utilization of ECOSSTRESS data products.

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National Interests

We concur with sub-panel.

Other Comments

N/A

Detailed Science Reviews
A 4.8 Mission: Global Precipitation Measurement (GPM)

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentation to the current baseline with the proposed over-guide budget to fund replacement of the ground-based Precipitation Processing System	Continuation with augmentation to the current baseline with the proposed over-guide budget to fund replacement of the ground-based Precipitation Processing System

Overview

The Global Precipitation Measurement (GPM) mission produces a suite of unique precipitation datasets that are widely used in research, operations, and broader applications. Launched in 2014, the GPM Core Observatory (GPM-CO) satellite carries the only precipitation radar (Dual-frequency Precipitation Radar) and the best calibrated conically-scanning microwave radiometer (GPM Microwave Imager) in space. GPM-CO is an advanced successor to the Tropical Rainfall Measurement Mission (TRMM), providing improved detection of light precipitation (rain and falling snow) and having a greater latitudinal extent (65°N to 65°S). The GPM-CO provides the reference standard to unify radiometer data from a constellation of 11 partner satellites (including international partner missions) to generate global precipitation estimates with high temporal (30 minute) and spatial (10 km) resolution. These data have been back-processed to the year 2000 using TRMM measurements, providing a 20-year, high-quality precipitation data record, which will continue forward with an extended mission. GPM has achieved <1 hr latency for near-real-time applications, including weather forecasting, agricultural forecasting, and resource management. With an extended mission, Version 07 data products will be developed through GPM Ground Validation efforts and extensive modeling studies. Additionally, GPM science work enabled by extended operations includes research on precipitation microphysical properties, global precipitation patterns, the water cycle, water resources, precipitation extremes, weather, and climate. The GPM-CO and its instruments are in excellent shape, and the satellite has enough fuel to last until ~2034. The requested augmented budget will fund replacement of the ground-based Precipitation Processing System, which is required hardware for processing and distributing the GPM products. The panel found that GPM is an unparalleled effort that provides tremendous value to science and society and is well justified for the requested mission extension.

Scientific merits: Excellent

Strengths

GPM's science objectives are to: advance precipitation measurements from space, improve knowledge of precipitation systems, improve climate modeling and prediction, improve weather forecasting and reanalysis models, and improve hydrological modeling and prediction. Precipitation is a key source of freshwater, which is essential for life on Earth. Thus, knowing when, where, and how much it rains or snows around the world is important for science and society. Furthermore, precipitation is integral to the hydrological cycle and is directly linked to net

latent heating, so is important to understanding the weather and climate of our planet. The GPM mission addresses these issues by providing high quality precipitation products at high temporal and spatial resolutions from a constellation of satellites. The GPM-CO satellite, with its superior instrument suite (DPR and GMI), serves as the reference standard for calibrating observations within this constellation. The DPR is the only precipitation radar in space, directly measuring the precipitation and its vertical structure near globally. The GPM-CO is an advanced successor to the Tropical Rainfall Measurement Mission (TRMM), providing improved detection of light precipitation (rain and falling snow) and having a greater latitudinal extent (65°N to 65°S). With added high frequency channels on both sensors, the GPM-CO is capable of retrieving vertically-resolved hydrometeor size distributions and a broader range of precipitation parameters than other sensors. GPM precipitation products are made available in near-real-time (<1-2 hours after observations). With such low latency and high quality products, GPM has a wide user base (including academic, government, non-profit, and commercial users) and broad applications that span thematic areas of ecology, water and agriculture, energy, disasters, health, and weather.

The panel was impressed with the many GPM accomplishments achieved in the past three years. These include:

1. Improved Retrieval Algorithms: GPM has been able to build upon the precipitation retrievals from spaceborne radar and radiometers developed for TRMM. Such advancements have been necessary to account for the new instrument capabilities of the GPM-CO and partner satellites. GPM has improved retrieval algorithms for the DPR, GMI, combined DPR+GMI, and merged satellite precipitation estimates. Ground validation datasets and advanced modeling, along with a longer record of GPM-CO observations, have yielded updates to the a priori cloud/radiance database that allows for united retrievals across the GPM constellation radiometers and prior TRMM observations. From these updates, the most widely used precipitation estimate, the Integrated Multi-satellitE Retrievals for GPM (IMERG) product, has been reprocessed back to 2000, now providing a 20-year record of global precipitation. Another important update has been improved latent heating estimates, which is critical for better understanding of precipitation processes in tropical and extratropical systems.

2. Microphysics and Storm Structure: With the new high-frequency capabilities of the DPR and GMI, knowledge of the microphysical properties of precipitating storms has advanced. New algorithms have improved detection of snowfall, heavy ice, shallow cloud precipitation, and extreme rainfall. Novel retrievals of particle size distributions have shown significant differences between land and ocean and seasonal variations in precipitating system structures worldwide. With the GPM-CO's higher latitude coverage than TRMM, significant progress has been made in studying midlatitude storm systems. A global climatology of hail showed that some of the highest hail frequencies occur in the midlatitude regions of northern Argentina and also the central United States.

3. Weather and Climate Forecasting Models: Weather and climate models require parameterizations for convection and cloud microphysics, which often are based on GPM observations and research. The widely used NASA Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model was updated from CMIP5 with new

parameterizations. These updates led to vertical latent heating profiles in CMIP6 that were more similar to GPM-derived latent heating, which overall points to more realistic simulations and forecasts.

4. Data Assimilation: GPM data have been successfully assimilated into operational global weather models. In particular, all-sky GMI radiances were assimilated into the European Centre for Medium-Range Weather Forecasts (ECMWF) global model and resulted in reductions in the short- and medium-term forecasts of about 0.5%. Similarly, all-sky GMI radiances were also assimilated into the NASA GEOS-5 model and found significant improvements in temperature and humidity, which led to forecast improvements.

5. Hydrology: GPM data have been used to improve hydrological modeling and prediction, and also to perform hydrological validation of precipitation within the U.S. and internationally. This research primarily uses the multi-satellite merged rainfall products, which are then downscaled to higher resolutions for innovative hydrological applications.

Weaknesses
No weaknesses were identified.

Value of data record with the additional 3-6 years of data, and overall data continuity
Like its predecessor TRMM, GPM-CO provides unique precipitation data products that are highly valued by both the scientific community and operational users. Compared to TRMM, GPM products have better resolution, latency, accuracy, and spatial coverage. The recent reprocessing of TRMM, GPM-CO, and partner satellite data have provided a 20-year global precipitation data record. This remarkable data record will continue in an extended mission, providing accurate precipitation measurements at high spatial and temporal resolution. Also during the extended mission, further algorithm work will improve estimates of light precipitation and estimates in variable surface conditions, which will lead to Version 07 GPM products. Additional work will be to explore possible Level 4 model-assimilated precipitation products. Overall, these products are expected to have a significant impact on a wide range of scientific studies.

Standard mission data product quality: Excellent

The GPM-CO instruments are highly stable and performing exceptionally well. There is no degradation noted; therefore, the core data products are expected to continue for many more years. GPM-CO's instruments are advanced versions of TRMM's instruments that lasted for the full 17-year TRMM lifetime. The DPR operates at Ku- and Ka-bands, providing high resolution 3-dimensional precipitation measurements with improved sensitivity to light rain compared to the TRMM PR. The DPR is the only precipitation radar in space. Compared to the TRMM TMI, the GMI has better spatial and spectral resolution, as well as added high-frequency channels. Both DPR and GMI are stable and accurately calibrated; GMI has been credited as being the best-calibrated microwave radiometer in space and is thus used as a reference standard for partner satellite radiometers. These instruments and collaboration with partner missions provide a unique and large dataset that requires substantial science support to maintain the quality of GPM's data products. The NASA effort for processing GPM-CO data is done at GSFC in Greenbelt, MD, in

the Precipitation Processing System (PPS). The hardware at PPS has either exceeded or is nearing the end of its operational life. During the extended mission, an augmented budget would fund the replacement of the PPS hardware and ensure the continued processing and distribution of GPM's widely used, high-quality products.

The GPM data products reached maturity and Level 1 Science Requirements for accuracy and latency during its prime mission period (2014-2017). The data products are grouped into 3 levels:

Level 1: Calibrated DPR powers and GMI brightness temperatures;
Level 2: Precipitation retrievals from DPR, GMI, DPR+GMI combined, and merged GPM-CO + partner radiometers;
Level 3: Gridded, monthly or 30-minute precipitation retrievals from DPR, GMI, DPR+GMI combined, and merged GPM-CO + partner radiometers;

GPM products are currently on Version 05 (passive microwave products) released May 2017 and Version 06 (all other products) released 2018-2019. These current versions have improved precipitation retrievals, particularly in mid-latitude regions outside of TRMM coverage. These releases also included a reprocessing of TRMM (and constellation member) observations back to the year 2000, providing a 20-year global precipitation data record. A joint Version 07 release of all products is planned during the extended period (mid-to-late FY2021). V07 will include changes to address the recently implemented scanning change of the Ka band on DPR to a wide swath scanning mode for added value to the data products. V07 (and other future versions) will include improvements to known algorithm issues, such as (1) detection and estimates of falling snow and light rain, (2) retrievals in variable surface conditions (land vs. ocean; cold/ice/snow cover), (3) range clutter in retrievals near the surface, (4) outdated infrared-based precipitation retrievals, (5) microphysical retrieval biases, and (5) orographic precipitation biases. Additional work will explore possible Level 4 model-assimilated precipitation products, implementation of future Smallsat technologies into the GPM constellation, and further back-processing (to 1987) using partner satellite radiometer measurements.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

GPM directly contributes to NASA's Strategic Objective for Earth Science to "Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet" with a focus on NASA's overarching question of "How and why are Earth's climate and environment changing?" GPM addresses NASA's Strategic Goal to "Advance our understanding of Earth and develop technologies to improve the quality of life on our home planet" through the sophisticated technologies on the GPM-CO and global measurements of precipitation for science and societal benefit. GPM contributes to the Decadal Survey priorities by providing observations related to the designated observable of Clouds, Convection, and Precipitation (CCP). GPM represents a major component of the Program of Record (PoR) for CCP. Additionally, GPM addresses 10 Decadal Survey Science and Application Questions, spanning geological, weather, and hydrological topics.

GPM is directly relevant to the cross-cutting priorities of the NASA 2020 Science Plan. For the Exploration and Scientific Discovery priority, GPM is part of a balanced Earth System Science program addressing water & energy cycles, improving weather forecasts, and reducing uncertainty

in climate models (Strategy 1.1). Also, GPM provides much needed data to a wide variety of applications that help to protect and improve life on Earth (Strategy 1.4). For the Interconnectivity and Partnerships priority, GPM, like TRMM, is partnered with JAXA. In addition, the CNES-ISRO Megha-Tropiques mission is part of the GPM constellation, and GPM has ~30 no-cost international partners from around the world (Strategy 3.2). GPM also actively works with NOAA and other federal agencies (e.g., USDA, DOD), as well as universities through ROSES funding (Strategy 3.3 and 3.4). For the Inspiration priority, the GPM Communications team creates outreach materials that include visualizations and stories about GPM science discoveries and applications, online "Webquests," using GPM data, hands-on activities, STEM career-focused videos and content and other resources (anime book, LEGO model instructions, 3-D printer activities, and visualizations (Strategy 4.2).

Weaknesses
No weaknesses were identified.

Technical and Cost

The technical sub-panel rated the GPM mission as Medium Risk and the Cost sub-panel gave a Medium-Low Risk rating. We concur with the technical and cost sub-panels' findings. The GPM-CO instruments and most of the GPM bus subsystems have performed very well and are expected to continue to operate well through the proposed mission extension. However, two issues arose during the review and are reflected in the sub-panel ratings. First, the Precipitation Processing System (PPS), a critical ground component of GPM, has either exceeded or is nearing the end of its operational life, and there are insufficient resources to fund the urgently needed maintenance and upgrades to the PPS hardware. Thus, the baseline budget was adjusted to the augmented budget in order to make these critical hardware updates in the extended mission timeframe. Second, the GPM-CO spacecraft has experienced reaction wheel issues over the past year. But GPM-CO, like other spacecraft, is overly-outfitted with reaction wheels, and thus continues to have nominal operations. The GPM team believes that the reaction wheel recently experiencing malfunctions will return to normal health soon.

National Interests

The National Interests sub-panel rated the GPM mission as High Utility; we concur with the sub-panel's findings.

Detailed Science Reviews

A4.9 Mission: LIS on ISS

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline with the proposed over-guide budget which sustains operations	Continuation with augmentations to the current baseline with the proposed over-guide budget which sustains operations

Overview

The Lightning Imaging Sensor (LIS) is a total (i.e., intracloud and cloud-to-ground) lightning detection instrument that monitors, during both day and night, high temporal (2 ms) changes of background scenes at a charge-coupled-device (CCD) focal plane with a 1.0 nm narrow band interference filter centered at 777.4 nm (near-infrared spectrum), the highest lightning optical emission band. It was launched to the International Space Station (ISS) on 19 February 2017 and has collected 3+ years of lightning data.

LIS is the identical spare instrument that was built as backup for Tropical Rainfall Measuring Mission (TRMM) satellite (1997-2014). LIS heritage comes from the Optical Transient Detector (OTD), aboard the MicroLab-1 satellite (1995-2000), the prototype design for the LIS concept. All three missions together, OTD, TRMM LIS and LIS on ISS, provide global-scale lightning detection for over 24 years now. **These missions comprise of a very unique dataset because it is the only long-term and global-scale total lightning data with steady and verified detection efficiency**, as opposed to ground-based networks that detect globally only cloud-to-ground lightning with extremely variable detection efficiency (because of instrument technology improvements and increasing number of sensors deployed along the years).

The perfect health of LIS instrument and its demonstrated steady detection efficiency are of extreme value to the long-term record of this climate variable, as well as operational monitoring of thunderstorms globally, especially over remote areas such as the oceans. **This assured quality of the data makes LIS on ISS the reference instrument for validation and cross-calibration of the new geostationary lightning detector instruments**, especially GOES-16 and 17 Geostationary Lightning Mapper (GLM). It was using LIS on ISS data that a substantial depletion of lightning flash detection efficiency was detected over a broad northwestern region of the continental US within GOES-16 GLM field-of-view.

With an extended mission, in combination with OTD and TRMM, LIS on ISS will approach the 30-year mark for data record suitable for climate change studies, and will continue with its outstanding contribution with the Cal/Val activities of GOES-R series satellites. It will also continue to contribute with international partners, such as the extensive use of LIS on ISS data to create useful proxy data to optimize the design and development of the European Meteosat Third Generation (MTG) Lightning Imager (LI).

In conclusion, this Science Panel encourages the continuation of this mission with augmentations to the current baseline, as proposed.

Scientific merits: Excellent

Strengths
Research during the past 3 years of LIS on ISS, combined with over two decades of TRMM LIS and OTD, has revealed critical merit of these data for scientific discoveries and applications. LIS on ISS covers higher latitudes and has continuous observations, establishing the dataset with most uniform technology, longest time record and widest area coverage, which are essential to extend the observational record of the foundational space-based component of the global lightning Essential Climate Variable (ECV). It also shows advances in understanding the underlying and interrelated processes of lightning development in thunderstorms (i.e., precipitation and storm processes, release and transport of latent heat, atmospheric chemistry, global electric circuit, ionospheric and magnetospheric physics, and lightning physics).

Another unique capability of the LIS on ISS mission is the simultaneous and complementary lightning observations with other instruments. This allows cross-sensor validation with other space-based, airborne instruments (e.g., the Geostationary Lightning Mapper (GLM) aboard GOES-16/17 satellites, and the European Meteosat Third Generation (MTG) Lightning Imager (LI)) or ground-based measurement systems. Hence, LIS on ISS continues to provide important *apple-to-apple* comparisons with GLM data, confirming that GLM indeed has a significant depletion in flash detection efficiency (DE) in the NW CONUS region, which is observable due to the LIS on ISS high latitude coverage ($\pm 55^{o}$)

One outstanding difference in LIS on ISS, compared to its heritage sensors, is that it provides near-real time (NRT) lightning data: within minutes via the ISS Low Rate Telemetry (LRT) communications channel, as opposed to a latency of hours that were common on the TRMM platform. This is particularly important to operational partners (such as the National Weather Service (NWS), the Aviation Weather Center (AWC), the National Hurricane Center (NHC), the Ocean Prediction Center (OPC), the World Weather Research Program (WWRP), and other government, business and military organizations) for forecast and warning applications in data sparse regions such as the oceans. LIS on ISS data stream has been stable and nearly continuous.

All the panel members concur that LIS science merit is excellent and acknowledges its important science objectives and accomplishments in the past three years. The panel members also acknowledge the value of this lightning data record with the additional 3-6 years of data, and overall data continuity.

Weakness
None were identified.

Value of data record with the additional 3-6 years of data, and overall data continuity
As mentioned before, all three missions together, OTD (1995-2000), TRMM LIS (1997-2015) and LIS on ISS (2017-present), provide a unique global-scale lightning dataset since 1995. This uniqueness is based on being the only lightning dataset on record with near global coverage for

almost 25 years (OTD, TRMM LIS and LIS on ISS), and near global coverage with *same detection efficiency* for 22+ years (TRMM LIS and LIS on ISS). Additional 3-6 years of data guarantee the continuity of the longest and largest area coverage lightning dataset on record, and will set the mark of being the first and only total lightning dataset with 30+ years of observations, an essential attribute for climate variability studies. In these lines, the LIS on ISS mission team submitted these three datasets to the Global Climate Observing System (GCOS) to extend the foundational space-based component of the global lightning ECV.

The known and demonstrated LIS great detection efficiency and location accuracy has made this instrument the "gold standard" for spaceborne lightning cross calibration and validation, as well as proxy data, for the new generations of geostationary satellites with lightning sensors aboard: GLM GOES-R/T series, MTG LI, and FengYun-4a Lightning Mapper Imager (LMI) (as well as the fact that these are *apples-to-apples* comparisons).

The continuity of LIS will also complement GLM data. LIS has approximately twice the spatial resolution of GLM and can detect weaker lightning events that GLM cannot. This is important scientifically and operationally, and, once combined, LIS and GLM provide a more complete view of thunderstorm activity, as also expressed in the letters of support provided.

Standard mission data product quality: Excellent

Strengths

All panel members concur that LIS data product quality is of excellence, presenting outstanding data accuracy, with uncertainties in the data and its products being addressed and updated constantly. As mentioned earlier, LIS dataset is the "gold standard" for cross calibration and validation and for climate studies, because of its steady and high detection efficiency and location accuracy, and no other long-term dataset with comparable quality from a consistent well-characterized sensor is available anywhere else.

All LIS on ISS Level-1 data science requirements were successfully achieved with diligent trouble-shooting the initial issues with geolocation and timing. This effort resulted in better temporal (≤1 ms) and spatial (2 to 2.5 km) accuracies than all heritage instruments. Data loss (from radiation upsets and obscuration from ISS solar panels) was also reduced to only 5% and they are accounted for with viewing time corrections, not impacting the instrument detection efficiency. This dataset is available at the Global Hydrology Resource Center (GHRC), and has been validated against reference datasets. Initially, only Level-1 Non-Quality Control (NQC) in near-real time (NRT) lightning data was provided. This panel questioned why there was not a QC data, and LIS on ISS Science Team promptly bypassed a technical issue that was preventing its delivery and reprioritized delivering a V1 (as well as V2) QC dataset on an accelerated time frame, expected to be completed by third quarter of FY21.

In terms of data usage, LIS on ISS engaged a diverse user community (e.g., Weather and Atmospheric dynamics, Atmospheric Composition Water & Energy Cycle), with 6109 data users. The LIS on ISS data are being used by several research and operational institutions to improve decision making and to benefit humankind.

The Science team has invested in research to assure the synergies between ISS-LIS and the currently operating satellite sensors (e.g., precipitation microwave radiometers) and also ground-radar networks. This synergy will enable a TRMM-era like products for research (e.g., Precipitation Features), which were the basis for the innumerous concurrent precipitation and lightning studies during TRMM. They have a collaboration with Texas A&M University-Corpus Christi and delivered the first version of this product to the scientific community. The team is now going further, and will combine ground-based radar data and derived products, such as updrafts and hydrometeor retrievals, also providing open source algorithms to do the same with radar networks globally. The panel finds this action outstanding and the derived products essential for science advancement. Therefore, the panel encourages LIS on ISS Science Team to take the lead on this task and on the production of these combined products.

LIS on ISS is also important for defense and military activities as it can also provide data information on false alerts for nuclear detonations.

Weaknesses
None were identified.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths
The science core objectives of LIS on ISS are clearly aligned with NASA science goals to understand extreme weather events. It also contributes to the Program of Record for measurements of deep convection and trace gases (e.g., nitrogen oxides, ozone).
On the 2017 Decadal Survey (DS), lightning is specifically discussed and, as in the Program of Record, it is a geophysical variable for all deep convection related topics, as well as the nitrogen oxide related topic, as well as being a Aerosols and Cloud-Convection Precipitation (ACCP) mission Designated Observable. More specifically, lightning measured by LIS on ISS is relevant to the following topics of the DS: W-7a, H-1b, H-4a, H-4b, W-1a, W-2a, W-4a, W-5a, W-6a, W-7a, W-9a, E-5c, C-5a, C-5c.

In the recent SMD Science Plan, LIS on ISS mission spans within several of its priorities. Regarding Priority 1 (Exploration and Scientific Discovery), LIS on ISS is used in the investigation of upper atmospheric electrical phenomena (e.g., sprites, Terrestrial Gamma Flashes), which are of interest to Earth Science, Heliophysics, and Astrophysics (*Strategy 1.3*). ISS LIS data also supports operational decision-making in NOAA and DoD (*Strategy 1.4*). For Priority 2 (Innovation), LIS is a collaboration with the ISS program, including JSC/STP & MSFC/POIC (*Strategy 2.2*). For Priority 3 (Interconnectivity and Partnerships), MSFC is lead NASA center for lightning measurements (*Strategy 3.1*), ISS LIS mission extension will further international collaborations (e.g., ASIM, TARANIS) that are expected to result in new partnerships (e.g., validation of MTG-LI – ESA/EUMETSAT) (*Strategy 3.2*). ISS LIS mission extension will facilitate more widespread applied use by NOAA and DoD (*Strategy 3.3*), and it strongly relies upon the research community to conduct its mission (*Strategy 3.4*).

The majority of the panel members concur that the LIS science program is of excellent relevance to the ESD research objectives and focus areas, and that it is clearly allied with the SMD Science

Plan, to the Program of Record and to the Decadal Survey priorities for observables. The non-consensus may reflect the disciplinary biases within the panel members, as well as the fact that lightning is a relatively new geophysical observable and, compared to the other peers in this evaluation, LIS on ISS is a small size mission, which limits its engagement with the scientific community.

Weaknesses
None were identified.

Technical and Cost

We concur with the sub-panel technical and costs evaluations. It is valuable to add that the total mission costs are very small and the outcomes have been outstanding in both science and operational aspects.

National Interests

We concur with the sub-panel evaluation. It is valuable to add that lightning is a new recognized Essential Climate Variable (ECV), as well as its related applied science. The extension of this mission will guarantee the means to continuously demonstrate its value to the National Interests.

Other Comments

None.

Detailed Science Reviews
A4.10 Mission: OCO-2

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline in accordance with the optimal proposal	Continuation as currently baselined;

Overview

OCO-2 uses a moderate-resolution spectrometer to measure the spectra of scattered solar radiation in three bands in the near infrared and infrared. Absorption by molecular oxygen at 0.765 μm and CO_2 in weak and strong absorption bands at 1.61 μm and 2.06 μm enable the detection of the CO_2 column abundance (XCO_2). Measurements are made along a ~10km wide track in 8 contiguous footprints that have areas of < 3 km^2, with 2 soundings per second. Solar induced chlorophyll fluorescence (SIF) is quantified in the O_2 A-band channel. XCO_2 and SIF are the main products. Measurements are made in a 1:30 pm sun-synchronous orbit in a 16-day repeat cycle.

The OCO-2 mission is continuing to provide the highest precision and highest accuracy atmospheric CO2 mole fraction observations of any space-based mission currently in orbit. Updates to the retrieval algorithm are continuing to improve the quality of available data. The scientific impact of the available observations is continuing to increase as the data maturity and the period of record increase. The instrument continues to function effectively and is likely to do so for the next several years. The augmented budget for the FY2021-2023 period, which is approximately 10% above the baseline budget, will allow for a further refinement of the data products through an update of the instrument calibration, the gas absorption coefficients, and the retrieval algorithm, thereby further increasing the scientific utility of the data. Only a baseline budget was requested for the FY2024-2026 period.

The spacecraft and instrument performance are nominal, and all systems are healthy and stable. The V10 reprocessing campaign of the full 5.75 year OCO-2 data record is almost complete. The instrument has the expected slowly degrading optics for which corrections are possible. The inertial measurement system no longer works but star-tracking compensates for this loss. There have been other anomalies that have been worked around.

Scientific merits: Excellent

OCO-2 has been operational for six years. The data record to date has already served to inform key questions about natural and anthropogenic carbon cycling, especially in regions that are poorly constrained by the in situ network. The value of the data record provided by OCO-2 increases dramatically as the length of the record continues to increase, much as has been the case with the longest-running elements of the in situ network.

Strengths

- The OCO-2 mission continues to provide XCO2 and SIF estimates with better precision and accuracy than any other operating space-based mission.
- Each successive generation of the retrieval algorithm has led to quantifiable improvements in the ability of observations to inform underlying carbon fluxes and in reproducing available observations at validation sites.
- While much of the early literature based on OCO-2 observations focused on the development of the data products and their consistency with what is known from ground-based measurements, the use of OCO-2 observations for deriving new understanding of the global carbon cycle has accelerated over the past three years.
- The main scientific accomplishments over the past three years based on XCO2 and SIF data from OCO-2 include:
    - Characterizing the ongoing impact of El Nino on carbon sinks in the tropics (and elsewhere),
    - Completing an intercomparison of flux estimates based on OCO-2 data,
    - Demonstrating the improved constraints on biospheric carbon estimates provided by four successive generations of the retrieval algorithm,
    - Characterizing linkages between water and carbon cycles, such as the impact of flooding on the seasonality of carbon uptake,
    - Quantifying CO2 emissions in urban areas,
    - Quantifying CO2 fluxes from individual power plants,
    - Contributing to a COVID-19 dashboard that explores impacts on carbon emissions.

Weaknesses

- OCO-2's largest incremental value is in regions that are poorly constrained by the in situ monitoring network. Unfortunately, these are also the regions where the validation network is sparse. The OCO-2 project team is exploring novel strategies for validating the OCO-2 data products in these regions, such that this aspect should be much stronger in the coming years.
- The instrument precision of ~0.5 ppmv makes it challenging to characterize small or diffuse emissions of CO2, as well as in regions with frequent cloud cover.
- Measurements require cloud-free scenes, and persistent clouds limit observations in some tropical regions and the high latitudes. However, the small footprint of OCO-2 observations makes it more effective under such difficult conditions relative to other existing space-borne missions (e.g., GOSAT).
- While the pace of the science is accelerating, the number of fundamental insights about the global carbon cycle gleaned from OCO-2 measurements is still relatively limited. However, it is important to recognize that this is in large part because OCO-2 is the first mission of its sort, and as a result developing, testing, and refining the data reduction algorithms takes substantial time. The impact of OCO-2 observations will therefore continue to grow over time.
- Inversion-derived CO2 flux estimates that leverage OCO-2 data still vary widely in some regions, although recent and ongoing improvements to the retrieval algorithm are helping to provide a stronger constraint over time.

Value of data record with the additional 3-6 years of data, and overall data continuity

Many aspects of the variability in the global carbon cycle operate on temporal scales of multiple years, such as, for example, the response of the terrestrial and oceanic carbon sinks to the El Nino Southern Oscillation. An additional three- to six-year extended mission would allow for an expansion of the range of carbon cycle topics examined and provide opportunities to observe new targets, would provide opportunities for informing more recent and upcoming missions (e.g., OCO-3), and make it possible to track long-term responses to climate anomalies (e.g., droughts, El Nino).

Specific activities planned for the next three years include:

- Combining OCO-2 and OCO-3 observations to support more comprehensive investigations of emissions from local sources, such as large urban areas
- Exploiting the substantially reduced bias over ocean to facilitate expanded efforts to study the ocean carbon cycle
- Using expanding validation capabilities to better assess the product quality in the tropics and boreal regions
- Further exploiting partnerships with GOSAT/GOSAT-2, OCO-3, and TROPOMI to improve calibration, algorithms, validation, and joint data products
- Supporting the development of global atmospheric CO2 inventories that account for both anthropogenic emissions and emissions/uptake by the natural carbon cycle

Standard mission data product quality: Very Good

The OCO-2 data product accuracy has been assessed over a widely distributed set of conditions, locations and time periods via several ground-truth and validation efforts. Uncertainties in the products have been evaluated and documented. The quality of mission data is very good and improving. Data of comparable quality are not available anywhere else.

The OCO-2 team has continued to improve the calibration, retrieval, and validation methods for the primary XCO2 and SIF data products. Published studies have demonstrated that these improvements have increased the ability to constrain fluxes using OCO-2 data, and that the OCO-2 data are increasingly consistent with independent observations, such as those from the TCCON network. The XCO2 and SIF data products are not available from any other NASA missions.

The augmented budget requested for FY2021-2023 would enable a further refinement of the data products (including improved instrument calibration, updated gas absorption cross-sections, and L2 algorithm improvements), likely leading to an "excellent" rating for data quality by the next review cycle.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

The OCO-2 mission provides an excellent fit to NASA Science Goals and the 2017 Decadal Survey.

Strengths

The 2017 Decadal Survey emphasizes the value of continued support for NASA's program of record:

- OCO-2 is directly relevant to a large number of elements of the NASA SMD Science Plan for 2020-2024.
- OCO-2 is a primary instrument that makes it possible to meet several of the objectives listed in the ESAS 2018 Climate Variability and Change: Seasonal to Centennial Panel, including:
    - C-3a "Quantify CO2 fluxes at spatial scales of 100-500 km and monthly resolution…" (listed as "Very important"),
    - C-3b "Reliably detect and quantify emissions from large sources of CO2 and CH4…" (listed as "Important"),
    - C-3c "Provide early warning of carbon loss from large and vulnerable reservoirs…" (listed as "Important"),
    - C-3d "Provide regional-scale process attribution for carbon uptake by ocean…" (listed as "Important),
    - C-4a "Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture) and other gases (e.g., CO2 and CH4)…" (listed as "Very important"), and
    - C-4d "Evaluate the effect of surface CO2 gas exchange, oceanic storage, and impact on ecosystems…" (listed as "Important")
- OCO-2 data is also key to meeting objectives listed in the ESAS Marine and Terrestrial Ecosystems and Natural Resources Panel, including:
    - E-1c "Primary production. Quantify the physiological dynamics of terrestrial and aquatic primary producers" (listed as "Most important), and
    - E-2a "Fluxes of CO2 and CH4. Quantify the fluxes of CO2 and CH4 globally at spatial scales of 100 to 500 km and monthly temporal resolution…" (listed as "Most important")

Weaknesses

The maturity of the scientific applications based on OCO-2 data is not yet sufficient to meet some of the objectives outlined above, e.g., to "quantify CO2 fluxes at spatial scales of 100-500km" (objectives C-3a and E-2a) on a global scale.

Technical and Cost

The technical panel rated the Technical Risk for OCO-2 as "Low."

The cost panel rated the Cost Risk for OCO-2 as "Medium-Low," primarily noting the lack of detail about the way in which the augmented budget request was determined. The mission team provided more detail on this point during the mission interview.

The success of the OCO-2 mission is contingent on the continued robust support of the OCO-2 science team through the ROSES solicitations.

National Interests

The national interests panel provided a National Interest Score of "Some" to OCO-2, given the relatively limited number of agencies currently making active use of OCO-2 data products. Based on information provided during the mission interview, the use of OCO-2 data by government agencies is expected to increase over the upcoming three years.

Other Comments

The proposal was complete and clear. The main gap in the proposal was the lack of a detailed assessment of the best opportunities for leveraging the relative strengths of the OCO-2 CO2 observations within the context of other existing in situ and space-based datasets. This point was discussed in detail during the mission interview.

Overall, OCO-2 continues to provide a critical and unique set of observations for furthering understanding of the interactions between the carbon cycle and climate. As the first mission of its sort, it is also providing valuable lessons about conducting high-precision measurements of greenhouse gases from space for future missions. Its value now and going forward is extremely high.

Detailed Science Reviews
A4.11Mission: SAGE III

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation as currently baselined	Continuation as currently baselined

Overview

The SAGE III/ISS mission is a young program with tremendous potential to contribute to important climate and atmospheric chemistry research over its lifetime. The instrument and retrieval algorithms draw on the several decades-long heritage of previous SAGE (I, II and III/Meteor) solar occultation measurements and, as a result, provide an extension of long-term data records, particularly for stratospheric ozone and aerosol extinction. These products contribute not only to the advancement of knowledge of atmospheric chemistry and dynamics but also to important statutory (Clean Air Act) and scientific (World Meteorological Organization quadrennial ozone assessment) activities that inform domestic and international policy. Future application of SAGE III data includes study of wildfire and volcanic eruption emissions to the upper troposphere and lower stratosphere, where their effects on climate are poorly understood. The SAGE III instrument is healthy and anticipated to continue returning high quality science data from its location on the International Space Station for the next several years. The panel's evaluation is that the mission should be extended as currently baselined (extend/in-guide) for the FY 2021-23 and FY 2024-26 periods.

Scientific merits: Very Good

The Stratospheric Aerosol and Gas Experiment (SAGE) III instrument was deployed to the International Space Station in February 2017 with the goal of observing the vertical distributions of aerosols, ozone, water vapor and other trace gases in Earth's stratosphere and upper troposphere. These observations will contribute to our understanding of the recovery of stratospheric ozone as the abundance of ozone-depleting chlorofluorocarbons in the atmosphere decreases and will provide insights into climate-related changes in the middle atmosphere.

Using the solar (and to a lesser extent, lunar) occultation technique, the SAGE III/ISS mission currently aims to

(1) assess the state of recovery of stratospheric ozone;
(2) extend the SAGE aerosol measurement record; and
(3) gain further insight into key processes contributing to ozone and aerosol variability.

The SAGE III/ISS data record is relatively short, with science data products available from June 2017 onward, and the majority of the mission team's effort since instrument deployment has been devoted to data validation and implementation of algorithms. Accomplishments over the ensuing three years include the release of version 5.1 data products, which re-establish the long-term record of stratospheric ozone and aerosol extinction that was developed with the predecessor SAGE II

and SAGE III/Meteor-3M instruments. Aerosol extinction data from SAGE III/ISS ends a decade-long gap that had been filled by less accurate methods for estimating stratospheric aerosol optical depth (AOD), a quantity important for both atmospheric radiation and chemistry. The new SAGE III dataset has been used to apply correction factors to the gap-filling data (from OSIRIS and CALIOP) to establish a continuous Global Satellite Stratospheric Aerosol Climatology (GloSSAC, v2) stretching back to 1979.

Despite the short data record, the scientific merit of SAGE III/ISS is judged by the panel to be Very Good largely because it extends the long existing record of SAGE data, which has been instrumental in our understanding of stratospheric ozone and stratospheric aerosol distributions.

Strengths:
SAGE III draws on the legacy of an established and mature retrieval from SAGE II. This provides for a more straightforward extension of the existing SAGE data record (SAGE II – 1984-2005; SAGE III/Meteor-3M – 2002-2005) and the assessment of trends in important stratospheric constituents, such as ozone, aerosol extinction, and nitrogen dioxide (NO_2).

The proposal provided several examples of the use of SAGE III data for scientific research, including tracking stratospheric aerosol optical depth following major wildfires and volcanic eruptions, and assessing the interannual variability of lower stratospheric water vapor. These illustrate the potential contributions that might be made in the future with SAGE III data as the SAGE III Science Team is competed via a ROSES solicitation in the next few months.

Weaknesses:
The ISS orbit and SAGE III viewing geometry limit acquisition of data to latitudes below about 50^o, which limits the science applications to some extent.

As an occultation instrument, SAGE III obtains measurements during sunrise and/or sunset events (supplemented by some lunar observations), gathering about 8000 profiles annually. As such, spatial and temporal coverage of the globe is somewhat limited.

Scientific contributions from the SAGE III team are limited to date, because the mission team has been focused on data validation and algorithm development. The mission team expressed that most of the science will be performed by investigators selected through the ROSES SAGE III Science Team solicitation.

Value of data record
The value of the SAGE III/ISS data record over the next three to six years is likely to be very high. The instrument will be one of only a handful of sources for data about the chemical composition of the stratosphere, during an era when stratospheric ozone is expected to recover toward pre-chlorofluorocarbon values. The existence of a deep and unexpected Arctic ozone loss in winter 2020 illustrates the importance of continuing to monitor the stratosphere and to provide data that can address unanswered questions about stratospheric chemical and dynamical processes.

As noted above, the SAGE III data are particularly critical to extending a forty-year record of stratospheric aerosol loading, a parameter that is essential to our understanding of stratospheric

chemistry and radiation balance. Similarly, ozone observations from SAGE III will continue a long record that has been used since the late 1980s to assess the thickness of the stratospheric ozone layer at mid and tropical latitudes, where its depletion increases the risk of ultraviolet light-related damage to human and ecosystem health.

Standard mission data product quality: Very Good

SAGE III data quality was judged by the panel to be Very Good. The current data quality is high and improving. Some validation activities have taken place. For example, the team is actively engaged in improving the algorithms to reduce uncertainties and biases, and the few publications that have appeared to date do illustrate the scientific value of the data. The uniqueness of the SAGE III ozone and aerosol extinction data are described in the scientific merit section above.

The first major validation study of the SAGE III stratospheric ozone products has just been published, showing that ozone data in the lower and middle stratosphere are of reasonable quality for scientific analysis, but data in the upper troposphere/lower stratosphere (UTLS) exhibit significant bias, which the team is addressing. Validation studies of H_2O, NO_2 and aerosol extinction observations, for which the mission team relies on ROSES-funded science team members, are underway but have not yet been published.

The SAGE III mission team has worked diligently to evaluate precision and bias for all data products, resulting in "provisional" status for most (ozone, aerosol extinction and NO_2). In the SAGE III team's parlance, "provisional" means partially validated, with continuing improvements. The team uses conservative language but considers provisional products to be of high enough quality to support scientific analyses. They plan to revisit the coding of algorithms for retrieval of ozone to take advantage of the ability to simultaneously retrieve ozone, aerosol and NO_2 from one set of channels and to implement other approaches that will benefit from the increased spectral resolution of SAGE III relative to its predecessors.

The team plans to continue validation activities using O_3 and H_2O sondes in collaboration with NOAA's Earth System Research Laboratory (ESRL) and New Zealand's National Institute of Water and Atmospheric Research. The SAGE III mission is fostering the development of low-cost, balloon-borne aerosol sondes at NOAA ESRL and obtaining correlative NO_3 observations through collaboration with JPL/Table Mountain Observatory. The team also plans implementation of major improvements to algorithms for most observables between 2021 and 2024.

The SAGE III team has developed strategies for handling the challenges of making observations from the International Space Station, resulting in a greater than 85% ratio of acquired to planned data collections. They carefully track and analyze the root causes for missed events and adapt observing strategies to improve on that ratio, where possible. For example, the recent docking of the Crew Dragon capsule at the ISS altered the attitude of the platform beyond the SAGE III instrument's ability to adjust. The mission team is exploring software options to compensate.

There are potential synergies among various stratospheric aerosol sensors to develop and extend the existing record of stratospheric aerosol loading, which is important for both atmospheric chemistry and climate studies. In addition, combining different types of measurements can provide

valuable cross-checks and lead to a better calculation of aerosol surface area density. The proposal suggests that the limb-scattering observations from SAGE III are helpful for development of retrievals for OMPS-LP and OSIRIS, yet degradation of the ICE PWA board (p. 34 of proposal) seems likely to limit these observations in the mid-term future.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

The panel judged the relevance of SAGE III/ISS to NASA's science goals and the 2017 Decadal Survey to be Excellent. The mission is already part of the Program of Record and contributes to the 2017 Decadal Survey by providing data to address "important" questions in the Climate Variability and Change category. SAGE III's use of solar occultation provides high vertical resolution in the stratosphere, but the technique is of limited utility in the troposphere where obtaining measurements of water vapor and aerosol are critical, which limit its broader applicability.

The SAGE III/ISS mission contributes to all four priority areas of the 2020-2024 NASA Science Mission Directorate Plan. Under Priority 1, Exploration and Scientific Discovery, SAGE III addresses both strategies 1.1 (National Academies' Science Guidance, as noted above) and 1.4 (information for decision makers). Regarding the latter, ozone and aerosol profiles from SAGE III contribute to NASA's statutory obligation under the Clean Air Act to report on the health of the ozone layer. Further, SAGE II and SAGE III/Meteor data have been used in the World Meteorological Organization's quadrennial assessments of stratospheric ozone and the SAGE III team is prepared to deliver an updated ozone data product in time for the 2022 assessment. The SAGE III team's partnership with NOAA/ESRL to develop a low-cost in situ aerosol sonde is an example of its contribution to Innovation. The mission itself is a joint endeavor within NASA between SMD and Human Exploration and Operations Mission Directorate (HEOMD), and between NASA and the European Space Agency, addressing Partnerships. Finally, the SAGE III mission addresses Inspiration by investing strongly in the NASA Internship program, supporting about twenty aspiring scientists and engineers over the past four years.

Technical and Cost

The Technical and Cost panels both rated the SAGE III/ISS mission "low risk". We concur with the sub-panel reviews.

One important note is the reliance of the SAGE III mission on an external, ROSES-funded science team, especially for validation activity. Strong leadership of this science team, members of which will be selected from an upcoming ROSES solicitation, will be essential for furthering the scientific contributions of SAGE III.

National Interests

The National Interests Panel rated the SAGE III/ISS mission "High Utility". There was some discrepancy among the ratings from individual agencies, which ranged from High Utility to Some Utility (with many "not applicable") versus the strong consensus rating. The importance of the

mission to the extension of long data records for aerosol and trace gas measurements in support of climate science objectives led to the "High Utility" rating. The Science Panel concurs with the National Interests Panel's report.

Other Comments

The proposal text was weighted more heavily toward technical details (section 2) and was relatively light on science accomplishments from the prior mission phase. In part this is likely because of the relatively short data record and the heavy reliance on a ROSES-funded science team. This balance made it difficult to evaluate the strength of the science case for mission extension and should be avoided in future Senior Review proposals.

There were several missing references from the science section and nearly all of the references for the science accomplishments specific to SAGE III were to unpublished manuscripts or conference presentations. This also made evaluation of the mission challenging, especially in terms of scientific merit.

Detailed Science Reviews

A4.12 Mission: Soil Moisture Active Passive (SMAP)

Mission Extension Conclusion:

FY2021-2023	FY2024-2026
Continuation with augmentations to the current baseline which are requested in the over-guide budget, namely to update the SDS, and to incorporate a near-real-time soil moisture product into NASA LANCE	Continuation with augmentations to the current baseline which are requested in the over-guide budget, namely to update the SDS, and to incorporate a near-real-time soil moisture product into NASA LANCE

Overview

Continuing the SMAP mission and its associated soil moisture, vegetation optical depth, freeze-thaw, and potentially sea surface salinity observations at L-band (all unique to the Program of Record) for another three-to-six years will very likely result in the following positive outcomes: a continued stream of new science at the intersection of the water, energy, and carbon cycles; new soil moisture products with enhanced spatial resolution through a partnership with the planned NISAR mission; and the possibility of continuous L-band radiometric observations of the Earth's land surface for more than 20 years, taking into account previous observations made by the European Space Agency's Soil Moisture Ocean Salinity (SMOS) mission since 2010 and potentially observations by ESA's Conical Imaging Microwave Radiometer (CIMR) high-priority candidate mission. In addition, continued funding will allow the SMAP mission to build upon efforts already initiated with the US Air Force Weather Agency to integrate soil moisture information into their operational weather forecasts, an incredibly important step given that: soil moisture is known to influence land surface water, energy, and carbon flux and thus the current state of the atmosphere; and institutions responsible for such forecasts are extremely conservative in incorporating new observations. Since the instrument and spacecraft are healthy, providing SMAP with an extension following the optimal budget would allow the mission to update the Science Data System (SDS) to prevent possible data delays, and to incorporate SMAP near-real-time observations into NASA's Land Atmosphere Near real-time Capability for EOS (LANCE) system so they are more readily available to other users.

Scientific merits: Excellent

The overall science merit score was 5.0 (mean) and 5 (median).

Strengths

SMAP provides unique measurements that link the water, energy, and carbon cycles. No other mission in the Program of Record observes soil moisture, a Targeted Observable for multiple Decadal Survey Science and Application Objectives, to the quality and extent as the SMAP mission. The mission also makes important contributions to carbon cycle science in northern latitudes. Progress has been made toward each of SMAP's five science goals in the last three years.

When these mission science goals were created, each corresponded to a NASA science goal. In their response to panel questions, the SMAP team clearly explained how their science goals are linked to NASA's 2020-2024 goals. The team highlighted as their most important accomplishment of the last three years to be the mission's ability to reveal the relationship between evapotranspiration and soil moisture using only observations from SMAP and weather stations (https://doi.org/10.1029/2018wr023726). Every weather and climate model must parameterize this relationship in some way due to its fundamental nature, namely the transfer of water between Earth's surface and atmosphere. The relationship SMAP has observed is different than what presently appears in models, and consequently SMAP science now provides a way to correct these relationships and potentially improve weather and climate prediction. The proposal does an excellent job of highlighting other work relevant to NASA and mission science goals. The value of the SMAP's data record has the potential to grow considerably with the additional three-to-six years of data, especially in light of the previous (and still functioning but aging) ESA SMOS mission launched in 2010 and potentially the candidate ESA CIMR mission which could result in over 20 years of L-band radiometric observations of Earth's land surface. However, L-band observations from CIMR are not certain and NASA should carefully consider what actions are needed over the next few years to ensure L-band radiometric observations of Earth's surface continue.

Weaknesses
The panel was not able to identify any weaknesses.

Standard mission data product quality: Very Good

The overall score for science data quality was 4.2 (mean) and 4 (median).

Overall data quality is very good. Products (both soil moisture and freeze-thaw state) exceed science requirements at a global scale due to the mission's extensive efforts at conducting careful validation. Soil moisture retrieval in agricultural regions do not yet meet science requirements. However, the mission team is aware of this issue and will continue to work on this problem. The panel was pleased that the mission will continue to critically evaluate surface temperature ancillary data as well as its role in SMAP retrieval algorithms and impact on products.

Justification of support: The mission plans to evaluate soil moisture retrieval in the presence of larger amounts of vegetation, and thus extend SMAP data validity past the original science requirements, through measurements in two upcoming forest field campaigns. Initial validation of vegetation optical depth (VOD), a measure of vegetation amount that can be retrieved simultaneously with soil moisture using the Modified Dual Channel Algorithm (MDCA), will also be a focus of these field campaigns.

Potential collaborations: The mission plans to partner with upcoming L-band NISAR mission to produce sub-kilometer soil moisture using its original active-passive algorithm that has been tested and improved using the Sentinel-1 C-band radar product. The mission will continue producing both the Sentinel-1 and NISAR soil moisture products for a period of time long enough to understand the strengths and weaknesses of each.

Uniqueness: The European Space Agency's SMOS mission also observes soil moisture globally using L-band radiometry (but with a different technique) and thus has similar sensitivity to the same soil moisture quantity (water in the first 2 to 5 cm of Earth's land surface). SMOS has essentially the same temporal resolution, but its spatial resolution is a little worse and, most importantly, it is much more susceptible to radio frequency interference (anthropogenic noise sources) which prevents the use of SMOS in some regions (parts of Europe, Middle East, Southeast Asia). In addition, SMOS is five years older and at present the only potential future L-band satellite radiometer is not planned to be launched until at least 2025 (ESA's CIMR). Consequently, SMAP plays a key role in the continuity of passive L-band observations. It is important to note that L-band CIMR observations are not certain. NASA should carefully consider options to continue L-band brightness temperature observations into the future.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

The overall score for science relevance was 5.0 (mean) and 5 (median).

Strengths
The proposal highlights links to seven Decadal Survey goals. Soil moisture is a Targeted Observable for nine Decadal Survey Science and Application Objectives, and four of these have Most Important designations. The mission team effectively illustrated how their science goals are consistent with 2020-2024 NASA science goals. The SMAP mission was the first to initiate and Early Adopters program which the National Interests Panel noted has been extremely successful. This program has been replicated by subsequent missions and is now part of the NASA SMD Science Plan (Strategy 1.4: develop a target user-focused approach to applied programs).

Weaknesses
The panel was not able to identify any weaknesses.

Technical and Cost

The panel concurs with and defers to the Technical and Cost Risk panels. The only major technical weakness is the aging SDS and this weakness can be addressed by either replacing appropriate computer hardware or, as proposed by the mission team, by moving the SDS to the cloud.

National Interests

The panel concurs with and defers to the National Interests panel. The SMAP mission is the third-ranked mission overall behind only Terra and Aqua.

Other Comments

The proposal was well written and well organized. The mission team's response to all panel questions was excellent.

All panelists would like to extend the mission through 2026. Furthermore, all panelists suggest a budget that would allow the mission to update its aging SDS. Ten of the thirteen panelists

supported the mission's plan to migrate the SDS to the cloud. Three panelists questioned the use of cloud computing because of cost concerns and asked that NASA critically evaluate the plans for the SDS taking into account the positives and negatives of using the cloud versus simply buying computer hardware.

Given the high scientific merit of passive L-band observations of Earth's surface, the panel encourages NASA to carefully consider how these observations can be continued into the future. The combination of SMOS and SMAP measurements already result in more than a decade of L-band terrestrial brightness temperature observations. The ESA's CIMR mission, a candidate for launch in 2025, may include and L-band radiometer but this is uncertain. If SMAP is able to operate effectively until 2026, and if CIMR includes an L-band radiometer, there will be overlap and potentially a more-than-two-decade record of L-band passive observations. However, if CIMR does not include an L-band radiometer and no other mission is launched, this observation record will end. It is also important to note that potential CIMR observations would not be identical to SMAP observations. CIMR would have a better temporal resolution (sub-daily) and be more sensitive to VOD, but CIMR would have a worse spatial resolution and CIMR soil moisture observations would be degraded more by vegetation.

Detailed Science Reviews
A4.13 Mission: Terra

Mission Extension Conclusion:

FY2021-2023
Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*

FY2024-2026
Continuation with augmentations to the current baseline: *following the proposed optimal/over-guide budget to continue operations beyond the orbit-lower maneuver*

Overview

Terra is the most important Earth Observation mission of the 21st century. Terra has performed for more than 20 years as the flagship of the EOS era with a suite of five complementary sensors that have each generated important and outstanding records of observations and multiple, well-documented data products used widely by the science community worldwide and in diverse applications and operational settings for multiple governmental agencies. Terra is the cornerstone mission of the EOS era. Given (i) the centrality of Terra in general and MODIS products in particular to the Program of Record (POR), (ii) Terra's unique morning descending orbit, and (iii) the good health of the Terra spacecraft and its instruments (with the sole but long-standing exception of ASTER's SWIR bands), the benefits of mission extension are manifold, continuing the observational record for many products, but also generating new science resulting from observations and products at a lower, drifting orbit. Terra's many products have no ready substitute for most of the applied and operational uses on which agencies currently rely. Therefore it is not surprising that the National Interests Panel rated Terra as Very High Utility, both the Technical and Cost Risk Panels rated Terra as low risk, and the Science Review Panel unanimously rated Terra as excellent and unanimously supported extending the Terra mission through FY26 under the proposed over-guide/optimal budget.

Scientific merits: Excellent

Strengths

With more than two decades on orbit, Terra provides the foundation for NASA's Earth Science Mission by providing data and generating high-quality products to address questions about the how and why of changing conditions on Earth.

The five complementary sensors aboard Terra account for 85 different remote sensing products for land, atmosphere, ocean, and cryosphere that are brought together in myriad ways for scientific research in multiple disciplines as well as applied and operational uses for government agencies. ASTER provides moderate/high spatial resolution observations useful for land change monitoring and emergency response to disasters. ASTER has produced a long time series of data about active volcanoes as well as valley glaciers. CERES contributes to understanding the interactivity of clouds-aerosols-radiation on short to long time scales. CERES has contributed to CDRs detecting changes in the Earth's radiation budget. MISR's multi-angular observations inform about aerosols, clouds, and climate interactions at finer spatial resolutions than CERES. MISR also contributes to understanding the vegetated land surface and ice. MOPITT senses tropospheric CO, helping with benchmarking other spaceborne sensors measuring CO and mapping air quality. MODIS' broad spectral range enables its wide range of products to contribute to understanding atmospheric processes, land change, ocean and ice dynamics, and fire in the earth system.

In addition to keeping the mission and sensor product streams running, in the past three years there are notable achievements for each of Terra's sensors:

ASTER: Release of GDEM V3 in 2019 marks "the most complete, consistent high-resolution global topographic data set ever released to the public."

CERES: As the only morning observations of the Earth's Radiation Budget, the CERES on Terra plays a critical role in enabling characterization of diurnal cycles in conjunction with the CERES instruments on other satellites (*viz.*, Aqua, S-NPP, NOAA-20).

MISR: New L2 aerosol product increases spatial resolution from 17.6 km to 4.4 km. New L3 Cloud Top Height-Optical Depth product and expanded the L3 Plume Height Climatology product.

MODIS: Collection 6.1 (re-)processing; improved calibrations to VNIR and TIR bands; three new land products released (i) land surface temperature/emissivity separation; (ii) multi-angle implementation of atmospheric correction (MAIAC), and (iii) surface shortwave radiation and photosynthetically active radiation (PAR).

MOPITT: Processing and delivery of V7 and V8 products, with improved vertical profiles of CO in V8. MOPITT NRT delivery to LANCE.

In addition, as highlighted in the Terra mission's presentation to the review panel, the global COVID-19 pandemic enabled each sensor on Terra to be used to evaluate the near-term biogeophysical consequences of the economic shutdowns aimed at stemming the spread of the novel coronavirus. Key requirements for detecting and quantifying these anomalies were the long records of sensor products against which to compare observations from the first half of 2020.

The Terra team proposes to extend the Terra mission beyond the in-guide budget that aimed at passivation of Terra in 2022. Under the "optimal budget" the team envisions extending operations to 2026 by the removal of Terra from its current orbit and letting the MLT of overpass gradually drift from 1015 to 0900.

MISR and CERES will be impacted by the new orbit and drifting MLT. The Instrument Science Teams have been aware of this possibility and have been preparing to update the algorithms as well as taken advantage of the new science that the new perspective will enable. From other sensors (viz., ASTER, MODIS, and MOPITT), very few products will require substantial algorithmic adjustments, and the majority of the products will remain useful both for basic and applied sciences, for NRT users, and for continuation of CDRs and EDRs.

The Terra mission is also highly responsive to NASA's 2020-2024 Science Plan. First, the Terra mission and its five sensors are very highly responsive to ESAS2017, including 6 of its 'Most Important' priority top-level science goals (H-1, W-2, W-5, C-2, S-1, and S-2), 7 of its 'Very Important' priorities (C-2, C-3, C-4, C-5, C-8, S-1, S-2), and 7 of its 7 'Important' priorities (W-6, W-9, C-2, C-3, C-8, S-4, S-7). (Some top-level goals appear in multiple priorities due to lower-level goals.)

Second, in response to Priority 1, Strategy 1.4 "Develop a target user-focused approach to applied programs", the Terra mission presentation to the review panel listed five activities demonstrating user-focused engagement for applications of MODIS, MISR, and CERES.

Third, in response to Priority 3, the presentation noted that both ASTER and MOPITT are international collaborations with Japan and Canada, respectively, since well before the launch of Terra in 1999. In addition, they highlighted ASTER's engagement with the active volcano monitoring community at both national (USGS Natural Hazards Program and volcano observatories) and international (WOVO: World Organization of Volcano Observatories) levels.

The global scientific impact of Terra is unparalleled. Between 2000 and 2019 Terra's scientific output total nearly 20K peer-reviewed articles by more than 32K unique authors from 8431 unique institutions across 155 countries appeared in 1051 different journals. The average number of citations per article was 25.4 and total number of citations exceeded 500K.

Weaknesses

Given the cap on the POR directed by the last decadal survey, extension of Terra's mission will capture a significant portion of those funds. So, there is a question of opportunity cost if Terra's mission is extended through adoption of the proposed optimal budget. While it is outside the scope of the mission proposal to address this portfolio management question, the question remains about how best to balance continuing a subset of high quality observations and initiation of new but necessarily short-term (3-6 years) observations against the kinds of observations that new missions can bring the POR, especially considering the ESAS2017 emphasized the need for active sensors to advance knowledge about earth system processes. Despite the risk of opportunity costs for extending Terra (and Aqua), the panel was unanimous in its endorsement of mission extension.

Value of data record with the additional 3-6 years of data, and overall data continuity

The proposal provides a cogent analysis of the many impacts of passivation of Terra envisioned by the in-guide budget. Further, it makes an excellent case for gathering additional years of data. First, the climate system is highly variable and changing; thus, extending the record with more high-quality observations helps us to measure, characterize, model, and project the climate system. Second, Terra's well calibrated instruments facilitate in-flight cross-calibration of new sensors. Third, there are no VNIR-TIR satellites in a morning orbit that could stand-in for MODIS and CERES, thus compromising characterization of diurnal processes in the biosphere, atmosphere, hydrosphere, and cryosphere. Fourth, the applied and operational uses of Terra data also do not have a ready substitute. Data continuity is a priority to extend and deepen the POR. The MODIS instrument and product teams have been preparing for the final period of data acquisition when observing conditions will be changing, with data continuity feasible for many products and new science opportunities available, especially for MISR and CERES.

Standard mission data product quality: Excellent

Of the five sensors onboard Terra, just two are replicated elsewhere on orbit—MODIS and CERES—but Terra's morning overpass make these observations unique. Terra data products are many and are of excellent quality: ASTER has 13 products, of which 5 are L3; CERES has 13, of which 9 are L3; MISR has 13 with 6 L3; MOPITT 7 with 3 L3. MODIS has 39 products (3 L1, 7 ATMO, 14 LAND, 2 CRYO, 11 OCEAN, and 2 Other) and 10 of these products are at Validation State 3 while 23 are at Validation Stage 2. Under the proposed "optimal budget" there will need to be some product changes. The Science Review panel asked the Mission Team for a listing of products by sensor that will be impacted by the new observing condition under mission extension,

including those that may require substantial algorithmic changes. The Mission Team provided a comprehensive response that clarified the product vulnerabilities. This response resolved any doubts by the Science Review Team that mission extension is the best course of action. Finally, we note the various systems to support the production and distribution of these products have been performing well amidst continual change in the IT world.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Excellent

Strengths

The Terra mission engages multiple aspects of the SMD Science Plan, including: (1) Climatic Variation and Change [CERES, MODIS, MISR]; (2) Atmospheric Composition [CERES, MOPITT, MODIS, MISR]; (3) Carbon Cycle & Ecosystems [MODIS, MISR, ASTER, MOPITT]; (4) Water & Energy Cycle [CERES, MODIS, MISR, ASTER]; (5) Weather (CERES, MODIS, MISR]; (6) Earth Surface & Interior [MODIS, MISR, ASTER]. All five of Terra's sensors contribute to multiple top-level science goals prioritized in the ESAS2017 report. Of the 15 different ESAS top-level science goals highlighted in proposal and prioritized as most important, very important, or important, MODIS contributes to 13 of them, MISR to 7, ASTER to 4, CERES to 4, and MOPITT to 1. Indeed, it is the view of the panel that loss of Terra's observations in the morning orbit will negatively impact both NASA's contribution to the Decadal Survey and the SMD Science Plan.

Weaknesses

The Science panel did not find any weaknesses.

Technical and Cost

Both the technical and cost risk panels have rated Terra as low risk. The Science review panel concurs with these assessments.

In addition, there will be need for parallel funding sources, such as ROSES, to support mission extension proposals, particularly those that take advantage of the new product versions resulting from the new observing conditions (*e.g.*, MLT drift) resulting from change in orbit altitude and cessation of IAMs.

National Interests

The National Interests Panel rated Terra as Very High Utility. The only other mission with such a designation was Aqua, and these two missions are highly complementary. The Science review panel concurs with this assessment.

Other Comments

The Terra proposal was a monster (273 pp in 52 MB) and complete in most respects. Where the review panel had questions, the Mission Team was able to answer and clarify to the satisfaction of the panel. Indeed, the Terra mission presentation was very interesting, particularly the many ways

that the sensors on Terra have been used to begin to understand the biogeophysical consequences of the COVID-19 pandemic.

APPENDIX 5

Acronyms and Abbreviations

TERM	DEFINITION
ABI	Advanced Baseline Imager
ACCP	Aerosol, Cloud, Convection, and Precipitation
add'l	additional
ADM	angular dependence model
AGU	American Geophysical Union
AI	Aerosol Index
AIRS	Atmospheric Infrared Sounder
aka	also known as
ALTIUS	Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere
AMS	American Meteorolgical Society
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOD	aerosol optical depth
AR	Area of Responsibility
ARM	Atmospheric Radiation Measurement
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWS	Aviation Weather Center
BESS	Breathing Earth System Simulator
BoE	Basis of Estimates
CALIOP	Cloud-Aerosol LIdar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCD	charge coupled device
CCD	charge-coupled-device
CCE	Carbon Cycle & Ecosystems
CCP	Clouds, Convection, and Precipitation
CDC	Centers for Disease Control and Prevention
CDR	climate data record
CENTCOM	Central Command
CERES	Clouds and the Earth s Radiant Energy System
CI	Conservation International
CIMR	Conical Imaging Microwave Radiometer
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CLIMCAPS	Community Long-term Infrared Microwave Coupled Product System
CMAQ	Community Multi-scale Air Quality
CMIP	Coupled Model Intercomparison Project
CNES	Centre national d'études spatiales
CO	carbon monoxide
CO2	carbon dioxide
CONUS	continental United States
COVID-19	coronavirus disease 2019
CPC	Climate Prediction Center
CPF	CLARREO Pathfinder
CPR	Cloud Profiling Radar
CrIS	Cross-track Infrared Sounder
CYGNSS	Cyclone Global Navigation Satellite System
DA	data analysis
DDM	delay Doppler maps
DE	detection efficiency
DOD	Department of Defence
DOE	Department of Energy
DO-Op	Daylight-Only Operations
DPR	Dual-frequency Precipitation Radar
DS	Designated Observables
DSCOVR	Deep Space Climate Observatory
ECMWF	European Centre for Medium Range Weather Forecasts

ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ECV	Essential Climate Variable
EDR	Environmental Data Record
EFU	Exposed Facility Unit
EIK	Extended Interaction Klystron
ELC	EXPRESS Logistics Carrier
ENSO	El Niño – Southern Oscillation
EOL	end of life
EOS	Earth Observing System
EPA	Environmental Protection Agency
EPHTN	Environmental Public Health Tracking Network
EPIC	Earth Polychromatic Imaging Camera
ERB	Earth radiation budget
ERB	Earth Radiation Budget Explorer
ES	Earth science
ESA	European Space Agency
ESAS	Earth Science and Applications from Space
ESD	Earth Science Division
ESDIS	Earth Science Data and Information System
ESDS	Earth Science Data Systems
ESMO	Earth Science Mission Operations
ESR	electrical substitution radiometer
ESRL	Earth System Research Laboratory
ET	evapotranspiration
etc.	et cetera
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EVM	Earth Venture Mission
EVI	Earth Venture Instrument
EXPRESS	EXpedite the PRocessing of Experiments to Space Station
FAA	Federal Aviation Administration
FEWS NET	Famine Early Warning Systems Network
Fig.	figure
FRAM	Flight Releasable Attachment Mechanism
FTE	full-time equivalent
FY	fiscal year
GCOS	Global Climate Observing System
GDEM	Global Digital Elevation Map
GEMS	Geostationary Environment Monitoring Spectrometer
GHCN	Global Historical Climatology Network
GLM	Geostationary Lightning Mapper
GloSSAC	Global Satellite Stratospheric Aerosol Climatology
GMI	GPM Microwave Imager
GNSS	Global Navigation Satellite System
GNSS-R	GNSS-Reflectometry
GOES	Geostationary Operational Environmental Satellite
GOSAT	Greenhouse gases Observing Satellite
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement
GPM-CO	GPM Core Observatory
GPP	gross primary production
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HEOMD	Human Exploration and Operations Mission Directorate
hi	high
HIRS	high resolution infrared radiation sounder
HQ	headquarters

HSB	Humidity Sounder for Brazil
HSRL	High Spectral Resolution Lidar
HW	hardware
HWRF	Hurricane Weather Research and Forecasting
Hz	Hertz
IAM	inclination adjust maneuver
IASI	Infrared Atmospheric Sounding Interferometer
ICE	Instrument Control Electronics
IGES	Institute for Global Environmental Strategies
IIR	Infrared Imaging Radiometer
IMERGE	Integrated Multi-satellitE Retrievals for GPM
IR	infrared
ISRO	Indian Space Research Organisation
ISS	International Space Station
IT	information technology
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
km	kilometer
KMNI	Koninklijk Nederlands Meteorologisch Instituut
L1	Lagrange 1
LANCE	Land, Atmosphere Near real-time Capability for EOS
LaRC	Langley Research Center
LEO	low Earth orbit
LI	Lightning Imager
LIS	Lightning Imaging Sensor
LMI	Lightning Mapper Imager
LP	Limb Profiler
LS	lower stratosphere
LST	land surface temperature
LSTE	land surface temperature and emissivity
M	million
m	meter
M	million
MAIAC	multi-angle implementation of atmospheric correction
max	maximum
MD	Maryland
MDCA	Modified Dual Channel Algorithm
med	medium
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MHS	microwave humidity sounder
MI	most important
MISR	Multi-angle Imaging Spectroradiometer
MJO	Madden-Julian Oscillation
MLS	Microwave Limb Sounder
MLT	mean local time
MO	mission operations
MO&DA	mission operations and data analysis
MOC	mission operations center
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurement Of Pollution In The Troposphere
MOS	mission operations systems
MSFC	Marshall Space Fligiht Center
MTG	Meteosat Third Generation
N/A	not applicable
NAFP	not allowed to flight program

NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
neg.	negative
NESDIS	National Environmental Satellite, Data and Information Service
NGA	National Geospatial-Intelligence Agency
NGO	non-governmental organization
NHC	National Hurricane Center
NIR	Near InfraRed
NISAR	NASA-ISRO Synthetic Aperture Radar
NISN	NASA Integrated Services Network
NIST	National Institute of Standards and Technology
NISTAR	NIST Advanced Radiometer
NIWA	National Institute of Water and Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NPS	National Park Service
NQC	Non-Quality Control
NRT	near real time
NVM	non-volatile memory
NWP	numerical weather prediction
NWS	National Weather Service
OCO-2	Orbiting Carbon Observatory-2
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OPC	Ocean Prediction Center
ops	operations
OSIRIS	Optical Spectrograph and InfraRed Imager System
OTD	Optical Transient Detector
PAR	photosynthetically active radiation
perf	performance
PM	Particulate Matter
POR, PoR	program of record
PPS	Precipitation Processing System
PR	Precipitation Radar
PTO	priority targeted observable
PWA	printed wiring assembly
QC	quality control
QMT	questions to mission team
RAD	RADiometer
ROSES	Research Opportunities in Space and Earth Science
RW	reaction wheel
RWA	reaction wheel assembly
RY	real year
s	second
S/C	spacecraft
SAGE III	Stratospheric Aerosol and Gas Experiment III
SAR	synthetic aperature radar
SBG	Surface Biology and Geology
Sci	science
SDS	Science Data System
SIF	solar induced chlorophyll fluorescence
SIW	Stratospheric Inferred Winds

SMAP	Soil Moisture Active/Passive
SMD	Science Mission Directorate
SMOPS	Soil Moisture Operational Product System
SMOS	Soil Moisture and Ocean Salinity
SMR	Sub-Millimetre Radiometer
SOMA	Science Office for Mission Assessments
SPoRT	Short-term Prediction Research and Transition Center
SR	Senior Review
SSMI	Special Sensor Microwave/Imager
STEM	science, technology, engineering and mathematics
SW	shortwave
SWIR	shortwave infrared
TC	tropical cyclone
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TIR	Thermal Infrared
TMC	Technical, Management, and Cost
TMI	TRMM Microwave Imager
TOMS	Total Ozone Mapping Spectrometer
TRMM	Tropical Rainfall Measuring Mission
TROPOMI	TROPOspheric Monitoring Instrument
UMI	University of Michigan
US	United States
USACE	US Army Corps of Engineers
USDA	US Department of Agriculture
USGS	US Geological Survey
UT	upper troposphere
UTLS	upper troposphere/lower stratosphere
UTS	upper troposphere and stratosphere
UV	ultraviolet
UV-VIS-NIR	ultraviolet-visible-near infrared
VAAC	Volcanic Ash Advisory Center
VI	very important
VIIRS	Visible Infrared Imaging Radiometer Suite
VOD	vegetation optical depth
W	Watt
WFC	Wide Field of View Camera
WOVO	World Organization of Volcano Observatories
WUE	water use efficiency
WWRP	World Weather Research Program
yrs	years