2023 NASA Earth Science Senior Review

Submitted to:

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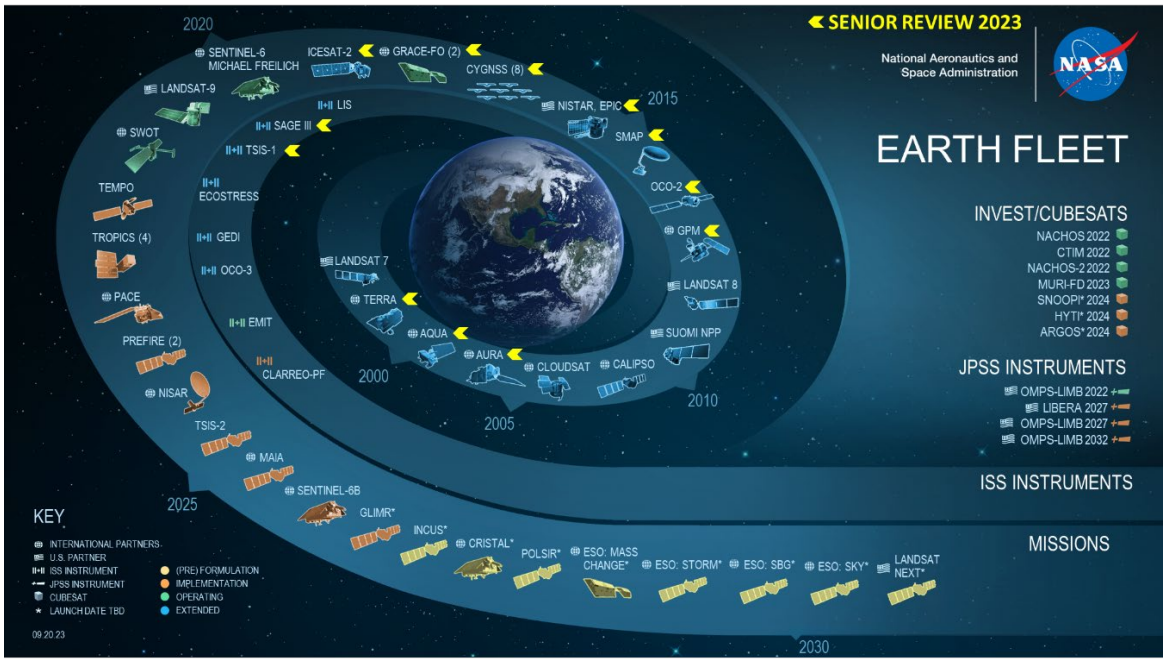

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1. INTRODUCTION

The 2023 Senior Review evaluated 12 NASA Earth Science missions in extended operations: Aqua, Aura, CYGNSS, DSCOVR, GRACE Follow-On, GPM, ICESat-2, OCO-2, SAGE III, SMAP, Terra, and TSIS-1. The review was based on proposals from each of the mission teams, followed by an in-person session where mission representatives presented answers to questions from the Senior Review Panel. Sub-panels reviewed the national interests and cost of the missions, and representatives of those panels met with the Senior Review Panel and their reports are included as Appendices. The following criteria were the basis of review: scientific merit (including uniqueness and new science); relevance to NASA Earth Science Division (ESD) Science Plan; value of standard data products; technical performance; cost; and national interests. The missions were reviewed independently from each other. The portfolio of 12 missions for the 2023 Senior Review includes multiple kinds of missions: ambitious multi-instrument pioneer missions that have been operating for decades (Aura, Aqua, and Terra); missions on the International Space Station (SAGE III, TSIS-1); missions focused on specific components of the earth system (ICESat-2, GRACE-FO, OCO-2, SMAP, GPM); the DSCOVR mission, a joint venture with NOAA and the United States Forest Service (USFS) at the Sun-Earth Lagrange point; and a Venture Class Mission, CYGNSS. The 2023 Senior Review finds that overall, the missions have very high scientific merit and meet the requirements for very high relevance to ESD priorities for extension.

2. REVIEW PROCESS

The 2023 Senior Review process began on February 3, 2023, when ESD issued a Call for Proposals letter inviting 12 NASA missions in extended operations to submit proposals for continuation, due April 14, 2023. The Senior Review Science Panel first convened for a virtual Kickoff Meeting on April 13 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 virtual meetings were held to review progress, discuss process and expectations, and address any issues. In parallel with this process, the National Interests and Cost Sub-panels were convened and met to review the proposals in these areas. The first Science Panel Plenary virtual meeting was held in May with meetings taking place over two days, May 30-31. During this meeting, the Lead Reviewers briefly presented a summary of each mission proposal, and all Reviewers reported their evaluations and preliminary science ratings for their assigned missions.

Each mission review team identified a set of follow-up Questions to Mission Team (QMT) to the respective mission team 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 June 2 with replies due on June 16. The second and final Science Panel Plenary virtual meeting took place on June 20-23. During this meeting 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-minute overview and synthesis discussion

among science panel members in closed sessions 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 and Cost Sub-panels presented detailed briefings during both Science Panel Plenaries. Final reports from each can be found in Appendix 1 and 2, respectively. The Science Panel met on the last day of the second Plenary (June 23) to work collaboratively on the summary of the detailed findings for each mission (Appendix 3). A briefing of the results was presented to Earth Science Division (ESD) management on June 27 by the Science Panel Chair. The workflow chart for the ESD 2023 Senior Review is provided in Figure 1 for reference.

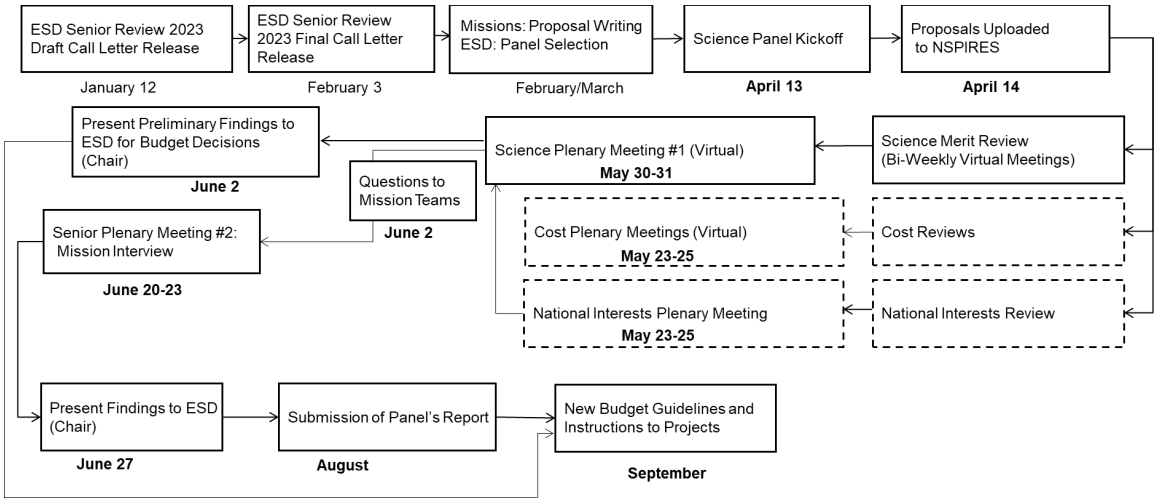


Figure 1 - 2023 Senior Review workflow chart and schedule.

3. GENERAL FINDINGS

Table 1 shows the overall science rating for each of the missions: 9 missions were rated as Excellent (scores of 5), two were rated as Excellent/Very Good (scores of 4.5), and one as Good (score of 3). These scores indicate the overall recognition by the panel of the continued excellence of NASA's Earth Science missions and their associated data products. This group of missions have been extremely successful, some for a remarkably long time (over 20 years). The data products from these missions have been transformative for studying the earth system and have led to innumerable findings and discoveries. The use of these data products continues to increase for science as well as for applications and operational use. The lowest score (Good) was for CYGNSS, a venture-class mission that is a pathfinder for a new kind of observations. The Panel acknowledges the value of the new observations and suggests ways to improve their science utility.

Table 1 - NASA 2023 Earth Science Senior Review Panel Summary

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

Mission	Science Merit		Relevance		Standard Data Products		Overall Score		Overall Science Findings
	Mean	*Median*	*Mean*	*Median*	*Mean*	*Median*	*Mean*	*Median*	
Aqua	4.8	5.0	4.9	5.0	4.8	5.0	4.8	5	Excellent
Aura	4.9	5.0	5.0	5.0	4.9	5.0	4.9	5	Excellent
CYGNSS	2.8	3.0	3.8	4.0	2.1	2.0	2.9	2.75	Good
DSCOVR	4.6	4.8	4.5	4.8	4.2	4.3	4.4	4.5	Excellent/ Very Good
GPM	4.9	5.0	4.9	5.0	4.7	5.0	4.8	5	Excellent
GRACE-FO	5.0	5.0	5.0	5.0	4.8	5.0	4.9	5	Excellent
ICESat-2	4.9	5.0	4.9	5.0	4.8	5.0	4.9	5	Excellent
OCO2	4.7	5.0	4.9	5.0	4.5	4.5	4.7	5	Excellent
SAGE-III	4.4	4.5	4.5	4.5	4.4	4.5	4.4	4.5	Excellent/ Very Good
SMAP	4.8	5.0	4.9	5.0	4.7	4.8	4.8	5	Excellent
Terra	4.9	5.0	5.0	5.0	4.8	5.0	4.9	5	Excellent
TSIS-1	4.8	5.0	4.9	5.0	4.9	5.0	4.8	5	Excellent

Table 2 - NASA 2023 Earth Science Senior Review Extension Findings Summary

Mission	National Interests	Technical Performance	Cost Risk	Science Overall Findings	Mission Extensions	
					FY24-26	FY27-29
Aqua	Very High	Excellent	Medium	Excellent	Continue	Continue
Aura	High	Excellent	Medium	Excellent	Continue	Continue
CYGNSS	High	Excellent/ Very Good	Low	Good	Reduce	Reduce
DSCOVR	Some	Excellent/ Very Good	Low	Excellent/ Very Good	Augment	Augment
GPM	High	Excellent/ Very Good	Med Low	Excellent	Augment	Augment
GRACE-FO	High	Excellent/ Very Good	Medium	Excellent	Continue	Continue
ICESat-2	Very High	Excellent	Low	Excellent	Augment	Augment
OCO-2	High	Excellent/ Very Good	Med Low	Excellent	Augment	Continue
SAGE-III	Some	Excellent	Med Low	Excellent/ Very Good	Continue	Continue
SMAP	Very High	Excellent/ Very Good	Med Low	Excellent	Augment	Augment
Terra	Very High	Excellent	Medium	Excellent	Continue	Continue
TSIS-1	Some	Excellent/ Very Good	Low	Excellent	Augment	Continue

The Technical Performance was found to be Excellent or Excellent/Very Good for all missions. The Cost Risk ranged from Low for CYGNSS, DSCOVR, ICESat-2, and TSIS-1, Medium Low for GPM, OCO-2, SAGE-III, and SMAP, and Medium for Aqua, Aura, GRACE-FO, and Terra. The National Interests Panel found all missions to have at least "some utility", while Aura, CYGNSS, GPM, GRACE-FO, and OCO-2 were found to have "high utility" and Aqua, ICESat-2, SMAP and Terra were found to have "very high utility." The Panel found the high rate of adoption of many of the science data products from these missions for applications and operational usage by a wide variety of agencies and partners to be a strong and impressive endorsement of the quality and relevance of the data products from these missions.

The guidance regarding mission extensions includes cost considerations relative to the currently planned (or in-guide) budgets for the missions. All missions were found to merit extensions for the next 3 years, and consideration was given as to whether extensions should be anticipated beyond that time. It is acknowledged that extensions beyond the next three years would be dependent on the outcome of the 2026 Senior Review. The Panel supports extension at the in-guide levels for 5 missions (Aqua, Aura, GRACE-FO, SAGE-III, and Terra), augmentations above the in-guide budget for 6 missions (DSCOVR, GPM, ICESat-2, OCO-2, SMAP and TSIS-1), and a reduction for 1 mission (CYGNSS). Recognizing the budget pressure within ESD, all of the suggested augmentations are small in magnitude and associated with very specific tasks (often to support an unfunded mandate like Assessment and Authorization [A&A]).

General Comments

Everything about the review process points to the unprecedented success of ESD missions and their data products. The data products have allowed discoveries and engendered understanding of earth system processes in myriad ways by the scientific community, both within the USA and internationally. The focus on validation of science products and making them freely available has been transformational for the science community. Many NASA data products are considered "the gold standard" around the world and used accordingly. Ironically, the fact that it is difficult with ESD to find sufficient funding to continue to support existing missions and their data products beyond their design lives as well as support the new missions identified in the Decadal Survey is entirely the product of the success of ESD.

2023 Senior Review Specific Comments

The Senior Review Panel is very appreciative of the help and support provided by NASA and Cornell Technical Services (CTS) throughout the entire process. Similarly, the information from the sub-panels was provided clearly and contributed significantly to the proceedings.

The Panel made one "spur of the moment" request that was addressed during the time of

the in-person meeting, which was for NASA to provide information regarding the costs of the missions over longer time periods. In particular, it was hard to get an appreciation of the magnitude of the recommended (in-guide) budgets for the missions as it related to the life-cycle costs for the missions. The reason the Panel found this information important and relevant is that many of the missions have now collected data products over previously unprecedented periods of time. As such, these long data records are beginning to support the ability to identify and attribute climate trends and to understand interannual variability. These capabilities greatly exceed the original missions for the sensors, in essence an unanticipated bonus as a result of the remarkable longevity of these missions. The Panel feels that extending these data records for even a few years is extremely valuable. As such, the Panel felt that understanding life cycle costs would provide context for evaluating the expense of continuing the missions relative to the benefits of extending the data records. Cost information provided at the request of the Panel showed that for some of the extremely successful long running missions, the cost associated with extending their data records was often less than a percent of the initial development cost. It was the general feeling of the Panel that extending key data products would greatly increase their value for understanding trends in the earth system and provide a greater ability to evaluate interannual variability. In this regard, it is probable that more will be continued to be learned from these datasets in the future in a highly cost-effective manner.

Several missions, including the flagship multi-sensor missions Terra, Aqua and Aura, are rapidly approaching passivation which poses some important challenges. The most obvious challenge is to continue to provide continuity for many extremely valuable and highly used data products. The Panel recognizes the effort that has gone into supporting continuity of products, particularly the success of many new missions. However, there are two issues in this context that the Panel would like to highlight going forward. The first issue concerns support for the incredible technical expertise of the workers supporting the missions that are nearing passivation. The scientists and engineers that have been managing these missions and their data products are an extremely valuable resource and should be managed as such. Several mission scientists rightly raised the concern that they may lose many of their most valuable people as they look for new opportunities. The effect of these departures could undermine the success of the data products through their final years. The panel encourages NASA to consider creative solutions that will support both the need for orderly ends to the current set of missions, while at the same time allow the highly experienced personnel to find new positions that will continue past the end of the missions they currently support.

A second issue concerns the transitioning of users of data products to the versions that will be supported going forward. From the results of the National Interests Sub-Panel and the experience of the members of the Science Review Panel, it is apparent that even in the cases where new sensors have been brought online in operational situations, the vast majority of users still rely on products from the original missions (many of which are ending soon). The most obvious example is the continued use of products associated with the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on Terra and Aqua rather than transitioning to those from the Visible Infrared Imaging Radiometer

Suite (VIIRS). There are understandable reasons for resistance from the user community to make these kinds of transitions. For example, these products are often used in operational settings, and the coding changes required to transition to a new product are often complicated, lengthy, and expensive. Also, it is clear there is a sense of comfort and trust for the legacy products given their long periods of development, evaluation, and usage. This trust and dedication to existing products is a clear sign of success for the Earth Science Division. While this situation is clearly not NASA's fault and the Panel recognizes there have been significant efforts in this domain, it would behoove the Earth Science Division to find ways to promote and facilitate the transitions to the data products from newer sensors that will continue farther into the future.

4. MISSION SPECIFIC FINDINGS SUMMARY

Aqua

Since its launch in May 2002, Aqua has provided high-quality data from its suite of remote sensing instrumentation. Three of its original six instruments, the Atmospheric Infrared Sounder (AIRS), Clouds and the Earth's Radiant Energy System (CERES), and MODIS continue to perform excellently, while a fourth, Advanced Microwave Sounding Unit (AMSU), is still operating but with only 9 of its original 15 channels producing good data. It is planned for Aqua to operate until July 2026 when data collection will cease in anticipation of "passivation" in September 2026 and eventual de-orbiting. Over the next three years the equator crossing time will slowly drift from 1:30pm to 3:30pm, resulting in challenges to ensure time series are consistent, but also great opportunities to explore the diurnal cycles and Earth system physical processes.

Aqua continues to provide a wealth of high-quality data products (87 in total) covering all aspects of Earth science from all six of the NASA Earth Science focus areas and provides unique time series stretching back 21 years. Its strength is in the high quality of the data collected; the high quality of derived geophysical parameters based on two decades of improvements and experiences; and the 21-year time series of dozens of key datasets. Combined with the potential for innovative new science during the period of drifting equator crossing times, there is a very strong case for continuing the 21-year Aqua data record for three more years.

Aura

Though launched in 2004, the Aura satellite continues to perform well. The two remaining instruments on Aura, the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI) are in excellent health providing high-quality observations, continuing a long-term data record, and new science. There have been no significant changes since the last Senior Review. Aura's orbital drift is expected to be minor and handled by retrieval algorithms.

With Tropospheric Emissions: Monitoring of Pollution (TEMPO) launched in 2023 and

TROPOspheric Monitoring Instrument (TropOMI) in 2017, it is important to continue the OMI observation record to provide continuity with the data sets from the newer instruments. This overlap will be especially important for studies investigating climate impacts on air quality and human health and global events similar to the coronavirus disease (COVID) pandemic. Keeping Aura operational will also minimize the gap between the current satellite record and upcoming missions such as Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere (ALTIUS), Plankton, Aerosol, Cloud, ocean Ecosystem (PACE), and Total and Spectral Solar Irradiance Sensor-2 (TSIS-2). MLS provides many high-quality data products that are unique in the Program of Record such as vertical profiles of O_3, H_2O, ClO, HCl, N_2O, HNO_3, and SO_2, some not observable by the current suite of satellites. MLS is the only instrument to make daily profiles of stratospheric water vapor and O_3 with near global coverage These data are still providing insights into stratospheric composition and dynamics.

Additionally, data from Aura are used operationally by the National Oceanic and Atmospheric Administration (NOAA) Washington Volcanic Ash Advisory Center (OMI SO_2 and Aerosol Index [AI]), National Centers for Environmental Prediction (NCEP) global weather forecasting (OMI O_3), and MLS products are used for assimilation and validation by the European Centre for Medium Range Weather Forecasts (ECMWF) Copernicus Atmosphere Monitoring Service (CAMS).

It's important to note that OMI data are being increasingly used in epidemiologic analysis of human health. Satellite observations provide spatial coverage lacking in surface measurements of air pollution. Investigating a possible relationship between climate/air pollution/human health requires a long-term data record. While some of the satellite observations of surface O_3 precursors (e.g., tropospheric column NO_2) will be continued by newer satellites, it is vital to understand any differences in the data records as the health community moves forward with these types of studies. As stated in the 2017 Decadal Survey "*Satellite data for atmospheric composition from instruments on Terra, Aqua, and Aura, in combination with advanced atmospheric models, have provided the basis for quantifying the global burden of disease from air pollution*".

The panel strongly endorses the continuation of the mission at the in-guide level for both the 2024-2026 and 2027-2029 time periods.

Cyclone Global Navigation Satellite System (CYGNSS)

CYGNSS is a low-cost Earth Venture mission launched in December 2016. The mission was originally designed with the goal of providing critical wind measurements in the core of Tropical Cyclones (TCs) in rainy environments, with a frequent revisit time for monitoring rapid intensification phases. The mission core objective was to provide valuable observations for hurricane research and forecasting, by filling the observational gap in the inner-core of TCs where most of the available satellite sensors at the time of CYGNSS launch did not provide sufficiently accurate winds due to intense rain. Since launch, the mission objective has expanded to include new applications over land (i.e., soil moisture, surface inundation, wetlands, vegetation) and additional ocean products

such as surface heat fluxes. The original mission lifetime of two years was first extended by 18-months (out-of-cycle), and then by an additional 3-years following the guidance of the Senior Review panel in 2020 (SR2020).

To achieve the original mission core objective, the CYGNSS mission was designed as a constellation of eight small satellites (receivers) on an inclined orbit (35 degrees inclination) to measure ocean surface winds over the tropics using the existing network of the Global Navigation Satellite System (GNSS) as transmitters. The principle of operation is a bi-static L-band radar: the Global Positioning System (GPS) reflected signals respond to ocean surface roughness, from which wind speed is retrieved. Over land, the reflected signal is sensitive to soil moisture content and water bodies. The L-band frequency is mostly insensitive to rain, therefore allowing observations even in the inner-core of TCs.

The CYGNSS receivers enable the first bi-static GNSS-Reflectometry (GNSS-R) radar system in space, and as such, there is great value in supporting an extended operation. The mission has the potential to be a significant resource for refining new remote-sensing methodologies and new data products from small, low-cost satellites.

Most of the past data products and proposed works, and accomplishments are only of research-grade quality. Some of this is understandable given that CYGNSS produces new types of retrievals. Nevertheless, the team activities in the past three years seem to have focused primarily on building new versions of research-grade datasets, rather than on careful validation and on bringing the products to a level of accuracy required for robust science investigations and (potential) use in operational settings. It is important to note that, being a low-cost mission, CYGNSS was not originally designed to provide data with short latency (Near Real Time) as required for operational forecasting or storm monitoring. The value of long-latency data products currently lies in post-storm analyses and the impact of CYGNSS data assimilation for historical events.

Since the prime mission, the core objectives seem to have shifted to a lower priority, with significant resources currently being focused on the new land products and applications, rather than the TCs. This conclusion had already been identified as a potential weakness in the SR2020 and has not been sufficiently addressed by the project team since then.

Nonetheless, the mission team has been very active and must be commended for its efforts. The new inundation product is unique and has important potential applications; the soil moisture estimates in the tropical/subtropical regions can fill the gap if other more dedicated missions (i.e., SMAP) fail or their data quality degrades. Furthermore, high revisit inundation measurements under vegetation are unique and highly relevant for a range of science questions in hydrology and carbon cycle studies. These new land-oriented capabilities and the potentially important applications in data assimilation provide confidence that the team can focus on validated products that the scientific community can use with confidence and address the weaknesses in the next funding cycle.

We suggest that the mission be extended with a reduced in-guide budget. The value to NASA and the scientific/operational community for the core mission objective still has

potential, but the data quality is less than optimal, despite the mission being at a mature stage. During the second extended mission, the panel advises the project team to prioritize activities that lead to validated final data products and their science applications, rather than devote significant resources to new products/activities, such as a blended soil moisture product or river width and slope. Suggested high priority activities are to: finalize low level (L1, L2) data products and heat flux products, assess the ability of the storm-centric data product to monitor storm intensification, continue studies of assimilation of low-level data products, finalize and validate one inundation product, finalize and (only if budget allows) validate one soil moisture product.

The panel noted that the varied nature of the data products (land versus ocean, low level versus high level) results in a varied value to different science communities. As a consequence, CYGNSS had a wider spread in the panel scores for scientific merit compared to other missions.

Finally, although the raw intermediate frequency (IF) data proposed in over guide (option 2) could provide potentially interesting measurements of river width and slope, the panel was concerned that this would only serve to further distract the mission team from generating high-quality data. Furthermore, there was no clear validation plan for these data.

Deep Space Climate Observatory (DSCOVR)

The DSCOVR was launched on February 11, 2015, to the first Sun-Earth Lagrange (L1) point, 1.5 million kilometers from Earth. From here it provides continuous solar wind measurements for accurate space weather forecasting, and observations of the full, sunlit disk of Earth from a new and unique vantage point. The DSCOVR mission is a joint venture between NOAA, NASA, and the U.S. Air Force (USAF). NOAA operates the spacecraft and performs operational space weather forecasting using DSCOVR's solar wind and magnetic field measurements while the Air Force provided the Space Exploration Technologies Corporation (SpaceX) Falcon 9 launch vehicle. NASA built the spacecraft, performed on-orbit checkout, and operates and calibrates the two Earth science instruments, the Earth Polychromatic Imaging Camera (EPIC) and the NIST Advanced Radiometer (NISTAR). DSCOVR operated until June 27, 2019, when the degradation of the Miniature Inertial Measurement Unit (MIMU) gyro caused an eight-month hiatus until March 2, 2020. Since then, DSCOVR returned to full and continuous operation. The spacecraft is in good health ready for years of more operation.

- DSCOVR continues to provide a new and unique vantage point for observing the full, sunlit disk of Earth multiple times a day.
- EPIC measures back-scattered radiation at 10 wavelengths from ultraviolet (UV) to near infrared (NIR) enabling the retrieval of ozone, 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 spectrum), 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 that is provided primarily from satellites in low Earth orbit (LEO). These data provide a comprehensive global view of quantities such as atmospheric ozone and leaf area index, and also can be utilized in a gap-filler role to cover the loss of other space-based observations.

The Panel unanimously supports the continuation of DSCOVR for the 2024-2026 time period with a modest augmentation relative to the in-guide budget. The in-guide budget is modest and barely able to support continuation of Level 1 products. The augmentation is meant to ensure a reliable supply of Level 1 products.

Global Precipitation Mission (GPM)

The GPM satellite has been providing valuable observations of storms and their impacts from the tropics into the midlatitudes (65°S-65°N) and at varying times of day since its launch in 2014. The two instruments on the GPM satellite are the Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI); together, they form the GPM-Core Observatory (GPM-CO). The DPR is the only weather radar in space, providing unique 3D measurements of storm structure and intensity. The exceedingly well-calibrated GMI employs a wide range of channels, allowing it to act as a calibration standard for a large suite of polar-orbiting passive microwave sensors. The production of the last planned algorithm version (V8) will happen during the extended mission timeframe and will incorporate final improvements to rain and snow retrievals. The GPM-CO also extends the long record of the Tropical Rainfall Measuring Mission (TRMM), which was in space from 1997-2015, into the present, making their combined datasets useful for climate and trend studies. The GPM-CO will remain the main Program of Record for precipitation and convection variables prioritized by the Decadal Survey until the launch of NASA's Atmosphere Observing System (AOS) at the end of the decade. In addition, the virtual GPM constellation of passive microwave sensors on partner satellites (both national and international) allows for the production of the near-real time (NRT), high temporal (30 min) and spatial (0.1°) resolution Integrated Multi-satellitE Retrievals for GPM (IMERG) precipitation product, which is heavily used in operations and societal applications around the globe. The final (non-NRT) IMERG product is also a valuable tool for long-term precipitation variability studies. The DPR and GMI are in good health and should continue operating well through the end of fuel availability, which at this time is expected sometime in 2027 for station-keeping altitude but would be extended to 2030 if the GPM-CO is boosted to 435 kilometers (km) from its current 407 km height.

The Senior Review Panel finds in support of the GPM extension for Fiscal Year (FY) 2024-2026 and FY 2027-2029 with the over-guide budget. The suggested augmented budget will fund the accelerated development of the 2-wheel science mode for the unlikely scenario of operations with only two reaction wheels (one of the spacecraft's five reactions wheels has failed and three are currently necessary for operations) and the continuation of the NRT processing system, which is essential for many of GPM's operational applications.

GRACE Follow-On (GRACE-FO)

The GRACE-FO mission, launched in May 2018 as a joint endeavor between NASA and the German Research Centre for Geosciences, has been tracking the global redistribution of water (including liquid water and ice) mass due to changing climate, growing urbanization, industry, agriculture, and tectonics. With more than 5600 (5 publications per week) peer-reviewed publications, the contribution of the mission to improved understanding of ice mass, land water storage, earthquake processes, sea level rise, and ocean mass variability is clearly documented.

GRACE-FO, as the name suggests was always designed as a mission to continue the mass change time series started by GRACE and perhaps to take monthly mass changes until the NASA Mass Change (MC) mission is launched (2028 nominally). A 20 plus year record of ice mass changes and water storage changes allow us to separate natural variability of ice and water storage from climate warming and more acute anthropogenic changes on the Earth system, distinctions important for predicting the future of and managing fresh water sources. Extending the data record will offer opportunities for new scientific discovery. A consistent reprocessing of the existing data set will improve the precision of observations and improve scientific conclusions.

The case for extension is also pretty clear with extension enabling the link to the MC mission so as to create a long record for increased science value.

Ice, Cloud, and land Elevation Satellite-2 (ICESat-2)

ICESat-2 employs the Advanced Topographic Laser Altimeter System (ATLAS), a photon-counting lidar system, to monitor ice sheet mass loss and sea-ice changes in the polar regions. At lower latitudes, ICESat-2 measures canopy height to estimate large-scale biomass. Launched in October 2018, ICESat-2 has met all prime mission requirements by December 2021 and, since then, has continued to operate nominally.

The extended ICESat-2 mission will generate a decadal-scale record of key essential climate variables with high spatiotemporal resolution and accuracy. ICESat-2 observations have already provided significant new insights into the seasonal and interannual variations of the cryosphere. However, a long-term record is needed to identify climate system trends, assess the mechanisms driving cryospheric changes, and improve predictive ice sheet models. ICESat-2 will also provide observations for numerous other scientific inquiries and applications, such as estimating snow depth, shallow bathymetry, ocean surface elevation, and wave features.

The ICESat-2 mission produces a wide range of data products distributed through the National Snow and Ice Data Center (NSIDC). Additionally, various open-source software packages, cloud-based tools, and custom data products are developed to ensure the broad use of ICESat-2 data. The ICESat-2 mission resulted in 315 peer-reviewed papers and has 6,200 data users (as of April 2023).

The ICESat-2 spacecraft is in excellent condition and operating on primary components across all subsystems. The operating laser shows only slow degradation, suggesting that a single laser may operate for 18-24 years. With a spare laser on board, ICESat-2 can operate nominally until the mission's End of Lifetime (EOL), which is currently estimated in January 2036.

There was strong agreement in the panel about the excellent performance of the mission and the benefits of its continuation. The panel suggests a modest augmentation of the in-guide budget to support the continuing development of the ICESat-2 atmospheric products that could bridge the gap between the cloud-optimized lidar observations after the decommissioning of Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

Orbiting Carbon Observatory-2 (OCO-2)

OCO-2 was launched in July 2014 into a sun-synchronous orbit and has provided nearly continuous measurements of the dry-air, column averaged value of CO_2 (X_{CO2}) since September 2014. The measurements of X_{CO2} are obtained with a measurement precision that exceeds the original baseline mission science precision requirement of 0.3% or 1.2 ppm on regional spatial scales. These measurements of X_{CO2} are obtained in three observing modes: nadir (mainly over land), sun-glint (mainly over the Atlantic and Pacific oceans), and target (mainly over validation sites). In addition, a solar-induced chlorophyll fluorescence (SIF) product has been provided for the terrestrial biosphere. The OCO-2 observations of X_{CO2} and SIF have provided valuable new insights into seasonal and geographic variations in the exchange of carbon between the atmosphere, the world's oceans, and terrestrial biosphere. The first major El Niño – Southern Oscillation (ENSO) event since the launch of OCO-2 occurred in 2015-2016; data from OCO-2 guided the community's understanding of unexpected responses of the global carbon cycle throughout this event. Recently, the OCO-2 team has provided a policy relevant estimate of National Net Emissions and Terrestrial Carbon Stock Changes (with uncertainties) for the world's countries, over the time-period 2015-2020: this product is termed global stocktakes (GST).

Extension of the OCO-2 mission would provide an opportunity for the response of the global carbon cycle to the second major ENSO event since the launch of OCO-2 to be quantified and would allow for a start at using OCO-2 data to assess trends in the oceanic and terrestrial carbon sinks. Currently, the magnitude of interannual variations in the strengths of these two sinks exceeds the size of any possible trend. A six-year extension would allow the GST product to be provided for 2021 to 2026. Finally, OCO-2 is the flagship mission for space-borne measurements of column CO_2: the data are of exceptionally high quality, the science team has executed a very rigorous calibration and validation effort, and the ground footprint (3 km^2 at nadir) is smaller than any other current or known future, space-borne column CO_2 observational effort.

The instrument is in excellent condition. There is enough propellant to allow for operations until 2040. The detectors are exhibiting slow degradation that is well monitored, understood, and quantitatively accounted for in production of the data

products. The Attitude Control System had to be adjusted in June 2019 to work in "gyroless-mode", due to indications that the Honeywell MIMU was reaching end of life unexpectedly early. The loss of the MIMU does not impact the ability of the ACS to meet all performance requirements. As a result, new requirements on observation scheduling were established to ensure that the star tracker assembly (STA) is never occulted by the Earth or Sun.

Stratospheric Aerosol and Gas Experiment III (SAGE III)

The SAGE III instrument on the International Space Station (ISS) uses a solar (and lunar) occultation technique to measure vertical profiles of ozone, aerosol, water vapor, and other trace gases (e.g., nitrogen dioxide) from cloud top to ~70 km. The solar occultation technique has several advantages. It can retrieve trace gases and aerosol extinctions with high vertical resolution (~0.7 to 1.0 km). Because of the strong signal from the Sun (higher signal-to-noise ratio) and self-calibrating feature of the occultation technique, SAGE III can provide measurements with high accuracy and long-term stability compared to other satellites using nadir viewing, limb scattering, or emission techniques. Data from SAGE III are suitable for monitoring long-term trends in stratospheric composition.

Another advantage of SAGE III is that it implicitly measures aerosol extinction coefficients at multiple wavelengths while other satellite instruments with limited wavelengths need to make assumptions of the aerosol properties (e.g., particle size distribution) in order to convert their native measurement to an extinction product. The extension of the SAGE III/ISS mission will enable the continuation of the climate data record for ozone, aerosols as well as water vapor. It will also help to improve retrievals from other instruments and bridge future missions. The overall scientific merit of the mission is excellent/very good. It is highly relevant to NASA Science Goals and the 2017 Decadal Survey. The Panel strongly supports the extension of SAGE-III for 2024-2026 with the in-guide budget. The project should succeed even though the budget is somewhat tight.

Soil Moisture Active/Passive (SMAP)

The SMAP soil moisture data are unique in terms of both accuracy and coverage and have had significant impacts in the areas of hydrology, ecosystems and carbon cycling, weather and climate, and hazard predictions. With the exception of the synthetic aperture radar (which failed shortly after launch) and some minor concerns about non-volatile memory, the instruments are mostly in good health. The low errors of the data products are consistent across the mission record. Thus, mission extension should lead to continued scientific utility. The ability to sample a greater range of climate variability and extremes during a longer mission should help to further increase the utility of SMAP for science applications, particularly given the utility of SMAP data for several different hazards that are the result of extreme conditions (floods, droughts, wildfire, food security). Furthermore, if successful, the proposed effort to enable soil moisture retrieval under forests would significantly enhance the dataset utility. In addition, a SMAP mission

extension will extend the L-band record to the NISAR and once successfully launched European Space Agency (ESA) Conical Imaging Microwave Radiometer (CIMR) satellites, potentially enabling a multi-decadal record that would have significant utility for trend analysis and study of extremes. The panel supports continuation of the mission – with an augmented budget only to support A&A activities and continuation of the near-real-time products.

Terra

Terra was launched in December of 1999 and includes five instruments: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), CERES, Multi-angle Imaging Spectroradiometer (MISR), MODIS, and Measurement Of Pollution In The Troposphere (MOPITT). With the exception of the shortwave infrared (SWIR) bands on ASTER, instrument health is excellent, and all five instruments continue to provide high quality data with substantial value to the science, applications, and operational user communities. Data usage and scientific impacts are both extremely high and continue to grow, which demonstrates the value of Terra.

There are five key benefits to continuing the Terra mission:

1. Extension of the multi-decadal data record from all five instruments is vitally important to both the science and national interests community. Each of the instruments on-board Terra provide critical and unique time series related to ongoing changes in the Earth system.
2. The morning overpass time is an important and unique aspect of Terra. Data from Terra complements data from other missions and provides information related to the diurnal cycle, especially for land and atmospheric process studies.
3. The ongoing mean local time (MLT) drift of Terra provides exciting opportunities for new science and algorithm refinements focused on diurnal variation and that leverage large solar zenith angles for parameter retrievals (e.g., aerosols).
4. From a national interests perspective, data from Terra are exploited by a very large community of end-users and agencies for a suite of important applications including weather forecasting, air quality monitoring, and fire monitoring (among others), all of which have substantial societal value.
5. MISR, ASTER, and MOPITT all provide unique measurements that are not available from other missions.

Overall, given the age of the mission, the health of the spacecraft and instruments is excellent and the Terra team provided a compelling case that high quality data will be collected up to passivation. The Panel unanimously supports the extension of Terra for the 2024-2026 period at the in-guide budget.

Total and Spectral Solar Irradiance Sensor -1 (TSIS-1)

The TSIS-1 mission has two instruments onboard the ISS: total irradiance measurement (TIM) and spectral irradiance measurement (SIM). TIM provides the total solar irradiance (TSI) at all wavelengths as 6-hour averages, while SIM provides the spectral solar irradiance (SSI) in 200 – 2400 nm every 12 hours. During its primary mission from March 2018 to March 2023, TSIS-1 achieved all of its primary mission objectives, including the delivery of the level-3 data products of TSI at the absolute accuracy of 0.01% and SSI at the absolute accuracy of 0.02%. These data products have been used for a wide range of scientific research and applications, by providing reference datasets for (a) calibration or inter-calibration of other satellite measurements of moonlight and reflected sunlight, and (b) climate research and prediction that require accurate time series of TSI and SSI data to understand climate variability (such as temperature) and atmospheric composition (such as ozone). The TSIS-1 mission fulfills the critical need of long-term continuity of the Program of Record for TSI and SSI, as recommended by the 2017 Decadal Survey. TIM and SIM are both healthy, and their continuation in 2024-2029 will lead to the extension of the 44-year TSI and 20-year SSI data sets, ensure a successful overlap between TSIS-1 and TSIS-2 (slated for launch in February 2025), and observe a full range of solar variabilities during Solar Cycle (SC)-24 and SC-25. Its extension plan also asks for an augment to extend the spectral coverage of SSI measurements from 2400 nm to 2800 nm. The extension will continue its delivery of level 3 data products, outstanding contribution to the Climate Data Record of TSI and SSI that are of interest to many agencies (such as NOAA and ESA) as well as NASA's research programs and missions such as AErosol RObotic NETwork (AERONET), TEMPO, CERES, Climate Absolute Radiance and Refractivity Observatory (CLARREO)-Pathfinder, etc. and the climate research community. The panel suggests that the mission should be continued with the proposed modest augmentations to the current in-guide baseline for the FY 2024-26 period and be further continued as currently baselined for FY 2027-29 period.

APPENDIX 1

Report of the 2023 National Interests Sub-panel of the NASA Senior Review

Chair: John Haynes
NASA Applied Sciences Program

Introduction
The 2023 National Interests Panel assessed the contributions of the core data products of the 12 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); US Agency for International Development (USAID); and Microsoft.

The panel met in-person on May 23-25, 2023, in Arlington, VA.

Pre-panel Activities
Each organization represented on the panel pre-assessed three primary factors and one overall rating for each mission. 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 the May meeting, 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 June 2023.

Panel Activities

Following the pre-assessments, the organization representatives met in a formal panel session over three days in May 2023. During this panel, 45 minutes of discussion time were allocated for each mission; however, 75 minutes were allocated for the flagship missions of Terra, Aqua, and Aura.

At the start of each discussion, an assigned Primary Reviewer introduced the mission and their 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 mission value and impact. Each representative was asked to assign 12 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 2023 Earth Science Senior Review *National Interests Panel*		
Rating	**Definition**	**Missions**
Very High Utility	These missions have one or more very relevant and highly valued data products which are routinely used by one or more of the participating organizations for important activities. Loss of the data product(s) would have a significant negative impact on national agencies and organizations.	***Aqua, ICESat-2, SMAP, 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, CYGNSS, GPM, GRACE-FO, OCO-2***
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.	***DSCOVR, SAGE III, TSIS-1***
Not Applicable (aka, Minor / Negilible)	These missions had no identified or significant applied or operational utility to the participating organzations. Loss of the data product(s) would have no or neglible negative impact on national agencies and organizations.	***None***

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

Mission	Civil Agencies									Military / Intelligence Community		NGO		Overall Score
	A	B	C	D	E	F	G	H	I	J	K	L	M	
	NOAA NWS	NOAA NOS	FAA	USDA	USAID	USGS	CDC	EPA	NPS	USACE	NGA	Microsoft	IGES	
DSCOVR ES Instruments	4	1	2	3	1	2	3	2	4	2	1	1	2	28
SAGE III	3	3	1	1	2	1	2	4	1	6	3	2	3	32
TSIS-1	2	2	5	2	3	9	1	1	2	1	2	3	1	34
CYGNSS	6	5	7	4	4	3	6	3	9	5	6	6	4	68
OCO-2	1	4	4	7	5	5	4	8	5	4	5	7	10	69
GRACE-FO	5	11	3	6	8	8	5	7	6	3	11	4	6	83
Aura	10	7	9	5	6	6	10	10	3	10	4	5	9	94
GPM	9	8	12	8	10	7	7	5	7	8	7	9	5	102
SMAP	8	6	8	10	9	4	9	6	11	9	8	10	8	106
ICESat-2	7	12	6	9	11	10	8	9	8	7	12	8	7	114
Aqua	12	9	11	11	7	11	11	11	10	11	9	11	11	135
Terra	11	10	10	12	12	12	12	12	12	12	10	12	12	149

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	USAID	USGS	CDC	EPA	NPS	USACE	NGA	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	Very High Utility	High Utility	Very High Utility
AIRS	High Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	High Utility	High Utility	Very High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable
CERES	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	Some Utility	Very High Utility	Some Utility	Not Applicable	High Utility	Not Applicable	High 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	Very High Utility	Very High Utility	Very High Utility
Aura	High Utility	Very High Utility	Not Applicable	High Utility	Not Applicable	High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable
MLS	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Some Utility	Some Utility	Some Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable
OMI	High Utility	Very High Utility	Not Applicable	High Utility	Not Applicable	High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable
CYGNSS	High Utility	Not Applicable	High Utility	Some Utility	Not Applicable	Very High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	High Utility	Some Utility	Not Applicable
DSCOVR	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable
EPIC	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable
NISTAR	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable
GRACE-FO	High Utility	Not Applicable	Very High Utility	Not Applicable	Not Applicable	High Utility	High Utility	Not Applicable	High Utility	Some Utility	Not Applicable	Very High Utility	Not Applicable	High Utility
GPM	High Utility	High Utility	Not Applicable	Very High Utility	Not Applicable	Very High Utility	High Utility	Some Utility	Not Applicable	Some Utility	Very High Utility	High Utility	High Utility	High Utility
ICE Sat-2	Very High Utility	Some Utility	Very High Utility	Not Applicable	High Utility	Very High Utility	Very High Utility	Not Applicable	High Utility	High Utility	Some Utility	Very High Utility	Some Utility	Not Applicable
OCO-2	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	High Utility	High Utility	Not Applicable	High Utility	Some Utility	Not Applicable	High Utility	Some Utility	High Utility
SAGE III	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable
SMAP	Very High Utility	High Utility	Not Applicable	Some Utility	Very High Utility	Very High Utility	High Utility	Some Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	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	Very High Utility	Very High Utility	Very High Utility
ASTER	High Utility	Not Applicable	Not Applicable	High Utility	High Utility	High Utility	Very High Utility	Some Utility	Not Applicable	Some Utility	Not Applicable	High Utility	Some Utility	Some Utility
CERES	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	Some Utility	Very High Utility	Some Utility	Not Applicable	High Utility	Not Applicable	Not Applicable
MISR	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Some Utility	High Utility	Very High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable
MODIS	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility
MOPITT	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Some Utility	Some Utility	Very High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Some Utility
TSIS-1	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable

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 MODIS for a wide range of applications. The value of other sensors (particularly ASTER, CERES, and MISR) added to utility rating. The panel was unanimous that the loss of Terra data would cause critical impacts. Uses included:

1. FAA noted the unique ability of ASTER to detect venting SO2 from volcanoes. The USGS noted ASTER as a central dataset of the Global Land Ice Measuring from Space effort. NGA uses ASTER data for gap filling elevation products in the polar regions.
2. CDC noted that 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. 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. The EPA states MODIS thermal anomalies products are used operationally to generate fire emissions (wildfire, agricultural, prescribed) for the National Emissions Inventory. NOAA/NWS states that atmospheric motion vectors from MODIS are assimilated into the NWS global weather prediction models. The USDA uses MODIS for mapping and monitoring crop condition and yields. NGA uses MODIS as source of snow cover present around International GNSS Service

(IGS) monitoring stations. These observations impact the long-term times series used to maintain the International Terrestrial Reference Frame.

5. CDC uses MOPITT for CO profiles in S. California and long-term CO trends in megacities. USAID reports that MOPITT data has likely been assimilated in many AQ monitoring tools and datasets.

USDA noted that VIIRS products from the Suomi-NPP and JPSS-1/2 satellites cannot seamlessly replace MODIS-Terra/Aqua products due to coarser spatial resolution for most bands and the lack of an AM orbit for correcting Landsat surface reflectance imagery. Many other agencies concurred with these concerns on transition to VIIRS products.

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 critical impacts on all organizations in the panel. Widespread use of MODIS alone ensured the highest rating. Uses included:

6. The importance and utility of AIRS was widely noted. Profiles are assimilated in NOAA/NWS NWP and considered to be a critical NASA data set. USGS noted that AIRS data are used for volcanic dispersion modeling and forecasting.

7. MODIS supports diverse atmospheric, oceanic, and terrestrial applications. USACE notes use to monitor changes in surface area extents of lakes and reservoirs worldwide. USGS uses MODIS in numerous efforts, including Landsat data product refinement, scientific study, and monitoring areas of vegetation, fire, drought, coastal, volcanoes, and cryosphere. NPS uses MODIS for inventory and monitoring networks in the parks, especially in Alaska and the desert Southwest. USAID stated that ocean chlorophyll products from MODIS were used to inform response, such as during the algal bloom immediately following the 2022 Tonga eruption. Microsoft uses MODIS for annual understanding of crop production and vegetation change.

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

ICESat-2 (Very High Utility)

ICESat-2 is a space based lidar instrument in a near-polar orbit with a primary mission of studying the cryosphere. However, applications of ICESat-2 data have extended far past the polar regions. The panel noted a very high reliance on ICESat-2 for accurate elevation data used in many types of Earth models and derived data products. Six organizations said loss of data would critically impact operations.

9. NOAA National Geodetic Survey (NGS) uses ICESat-2 to measure ice surface elevation changes to augment GRACE and GRACE-FO models of gravity change in Alaska.

10. USDA reported that data support expansion of a Forest Service Model and help bridge the current pause in GEDI data collection.

11. NGA said it was a "workhorse" for the agency. Uses level 2 and level 3 data to validate digital elevation models used for geoid production. These products have been used to inspect whether vegetation has been properly removed from these models, as well as assess the overall accuracy of these models.

12. EPA uses to compare recent and new elevation data near the Waters of the United States (WOTUS) to data from 2018-2020, with the goal of determining unpermitted construction affection WOTUS, in violation of the Clean Water Act.

13. USGS and USDA noted the international SilvaCarbon forest biomass characterization project uses ICESat-2 data to measure above ground carbon stocks.

SMAP (Very High Utility)

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. Nine organizations said loss of SMAP data would critically impact operations. Uses included:

14. NOAA/NWS National Water Center (NWC) uses derived products from SMAP to understand snowpack conditions, particularly in the Red River Basin of North Dakota and Minnesota, which is a data sparse area. The NOAA Climate Prediction Center (CPC) serves the National Drought Mitigation Center (NDMC), which uses SMAP data operationally to determine where drought areas exist, and where drought conditions are improving or getting worse.

15. IGES notes that industries are applying data both in the formulation of climate risk models as well as producing validation reports on their application. These risk models are used to discern climate risk on a parcel-by-parcel level across the US.

16. USDA noted derived data products are used for cropland soil moisture condition monitoring and assessment. These data products are distributed on the NASS online portal application Crop-CASMA. Additionally, soil moisture model outputs are used at the USDA International Production Assessment Division (IPAD) Foreign Agricultural Service (FAS) to estimate relative crop yields worldwide and to provide crop hazard alerts.

17. USACE stated that information from the SMAP sensor is assimilated into the

Land Information System for assessing and forecasting soil trafficability. This information is displayed in a web application called GeoWATCH on the USACE Model Interface Platform (UMIP).

18. Some panelists cited that SMAP data are assimilated into various information systems, along with data from other satellite missions, but were unable to quantify mission-critical impact associated with data loss, as users are unaware of routine ingestion of SMAP data.

GPM (High Utility)
GPM is the advanced successor to 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. Five organizations noted loss of GPM data would critically impact operations. Uses included:

19. Microsoft uses IMERG to estimate precipitation over the majority of the Earth's surface. These data products are available to its customers via the Microsoft Planetary Computer.

20. NOAA/NWS noted utility in data sparse regions. On the West Coast, where there is less radar coverage, it is helpful to understand marine areas and for situational awareness of "atmospheric rivers." Data are also used to examine the structure of developing tropical cyclones.

21. FAA noted GPM as its most important mission. Data are used to train and validate a machine learning model for the FAA's Offshore Precipitation Capability (OPC). OPC creates mosaics of Vertically-Integrated Liquid, Echo Tops, and Composite Reflectivity for eventual inclusion in the FAA Nextgen Weather Processor operational system.

22. USGS stated that data are important for many agency mission goals, including those involving climate modeling, natural hazards and disasters, ecology, agriculture, land classification, and hydrology.

The panel noted the in-guide budget will require the Precipitation Processing System to shut down the Real Time (RT) system in FY25, which would critically impact operations at multiple organizations.

Aura (High Utility)
Aura data are useful for improving our understanding for how various molecular species contribute to changes in the atmosphere and to atmospheric forcing. In recognition of

this fact, and the widespread operational benefits from the mission, the panel rated the value of this mission as high. OMI observations appeared to be the most utilized. Four organizations noted that the loss of Aura data would critically impact operations. Uses included:

23. NOAA is using OMI in a NRT mode to calculate total column ozone, which is currently assimilated into the NCEP Global Forecast System.

24. USGS Volcano Hazards programs uses OMI NRT data for eruption detection, forecasting, and eruption modeling. MLS data have been explored for use in atmospheric correction algorithms and climate change atmospheric composition investigations.

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

26. OMI NRT SO2 and Aerosol Index (AI) data are integrated into the decision support system at the NOAA/ National Environmental Satellite, Data, and Information Service (NESDIS) Washington Volcanic Ash Advisory Center (VAAC).

27. EPA uses OMI Total column Ozone as a CMAQ input, while also using the OMI/MLS Tropospheric Ozone product in model evaluation.

The panel deemed a non-extension of Aura as a large loss operationally based on the inputs received from the varying user communities. The community should be prepared for transition to similar data streams (e.g., TROPOMI); however, it was noted that this is not a quick process.

GRACE-FO (High Utility)

GRACE-FO is a unique, indispensable Earth observation measurement capability for capturing the Earth's mass changes and, thus, gravity fields and anomalies over time. The mission provides continuity from GRACE (2002-2017). It is of high importance in measuring terrestrial water storage, ice mass, oceans, and solid Earth. Continuity of these observations cannot be stressed enough. Four organizations identified a critical impact from loss of GRACE-FO data. Uses included:

28. NOAA/NOS stressed the need for continuity of this data measurement. Within the agency, the National Geodetic Survey (NGS) uses data from GRACE-FO to support the development of a new geopotential datum that is crucial for marine navigation and coastal zone management. The mission is used to track long-wavelength changes in the geoid on decadal timescales. Data are essential for identifying the cause of regional (mean) sea level rise and subsequent coastal

water level datum change and projecting the future change in the vertical datum represented by (mean) sea level rise.

29. NGA stated data are used as a component in constructing the Earth Gravitational Model. It is also used in the subsurface geology program to track movement of subsurface water.

30. NPS uses data in studies of ice mass and water movement in Alaska. Data support more than just climate studies, but also benefit analysis of wildlife, such as seal habitat and ecosystem health.

OCO-2 (High Utility)
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 value for several organizations, and this mission has the potential to positively impact additional programs in the future. One organization noted a critical impact from the loss of OCO-2 data. Uses included:

31. USGS uses OCO-2 data in their climate change and global carbon cycle programs.

32. IGES reported industry use cases of mapping carbon produced across factories and transportation networks.

33. USAID has leveraged OCO-2 data to support tracking individual countries' greenhouse gas emissions. The SERVIR/USAID program uses OCO-2 data routinely in their Air Quality Monitoring tools.

34. NGA finds OCO-2 data useful for identifying “bad actor” emitters and conducting regional assessments.

There was a noted improvement in OCO-2 mission communication and education (ARSET) since the 2020 Senior Review. Publications and applied research endeavors are increasing steadily over time.

CYGNSS (High Utility)
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 is filling a critical need for observations of ocean surface winds over global tropical oceans with revisit frequency high enough to observe the tropical cyclone rapid intensification process. The panel rated CYGNSS as High utility, primarily based on new applications of the data, including for soil moisture retrievals and ionospheric modeling. No organizations identified CYGNSS data as critical for operations. Uses included:

35. USGS uses data in application areas of precision agriculture, soil moisture and natural hazards. Preliminary studies have been conducted on ionospheric scintillation anomalies detected using GNSS-R Data from CYGNSS as possible earthquake precursors.

36. NGA used the data in maturing ionospheric modeling capabilities for improved Over the Horizon Radar performance as a possible source of geospatial intelligence.

37. IGES noted The Aerospace Corporation is examining use of CYGNSS for operating space-based environmental monitoring (SBEM) needs. This includes assessing if and how CYGNSS observations can augment the accuracy of the Weather System Follow-On Microwave (WFS-M) soil moisture data products, one of the most significant unfulfilled SBEM data product needs.

TSIS-1 (Some Utility)
TSIS-1, operating onboard the ISS, collects Total Solar Irradiance (TSI) and Spectral Solar Irradiance (SSI). There are daily and six-hour TSI products, and daily and twelve-hour SSI products. Only a single agency had a direct known application of the data (USGS); however, USGS noted that TSIS-1 data are critical to their operations. Uses noted within USGS included:

38. TSIS-1 data are used by Sustainable Land Imaging scientists and engineers in planning and discussion of calibration, validation, and usage of upcoming missions. Specific examples include several USGS scientists working on the SBG Calibration and Validation Working Group.

39. Similar imaging spectroscopy applied research efforts have high value for this data, including activities around Landsat Next and SLI Cross-Calibration Radiometer mission planning.

40. The USGS EROS Cal/Val Center of Excellence (ECCOE) uses TSIS-1 data in conjunction with other tools for various Earth observation sensor characterization activities.

SAGE III (Some Utility)
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. Only three organizations noted use of SAGE III data; however, the importance of the data to climate applications and continuity of the data record was recognized. No organizations identified SAGE III data as critical for operations. Uses included:

1. USGS noted utility for volcanic research and monitoring programs.

2. NGA noted value in monitoring of industry at regional scales.

3. USAID noted importance in monitoring stratospheric ozone.

DSCOVR (Some Utility)
DSCOVR provides a unique Earth Observation data set from the L1 vantage point. There are two Earth observation instruments: the EPIC Earth Polychromatic Imaging Camera and the NISTAR NIST Advanced Radiometer. 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. No organizations identified DSCOVR data as critical to operations. Uses included:

1. USGS noted EPIC and NISTAR data as important generally to mission goals including geomagnetism and programmatic activities related to satellite telecommunications and GPS. The data have also been discussed as a potential input to Landsat data products, specifically assisting with atmospheric characterization activities.

2. NGA noted 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.

APPENDIX 2

Report of the 2023 Cost Sub-panel of the NASA Senior Review

Chair: Justin Hornback, NASA Langley Research Center, Earth Center Pathfinder Program Office (ESSP). Justin Hornback was assisted by Mark Jacobs, Cathy Stickland, Takenya Roberts, Grace Hu, and Mike Guan

INTRODUCTION

The senior review cost sub-panel team conducted their analysis from January – June 2023. The cost team briefed sub-panel findings and questions to the full Science Panel in May of 2023 and met again with the full Science Panel in June 2023 to review sub-panel analysis methods, rating criteria, and any clarifications. The final meeting in June 2023 included presentations from each of the mission project teams including responses to the review panel's questions, including those submitted by the senior review cost sub-panel.

The cost analysis process was derived from the approach used to evaluate Announcement of Opportunity (AO) proposals, the 2023 Senior Review cost sub-panel process coupled with necessary adjustments to incorporate the unique aspects of the 2023 Senior Review, including mission project budget target reductions for all mission projects.

Findings from the proposal cost review and inputs from the full review panel were 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. Senior review budget targets (in-guide) for all missions' projects included 24-50% funding reductions. Cost review included examination of mission project actuals in prime and extended operating missions to inform the risk of the project being able to perform the content proposed.

The overall risks, mitigation plans, cost threats, and cost actuals all contribute to the overall mission project cost risk rating. Given categories were used and definitions for each are provided in Figure 2-2. This cost risk rating is based on the proposed costs to meet senior review budget targets as part of the 2023 Senior Review call letter and plans during the period of performance. This risk rating portion of the assessment considered prior years, fiscal year FY18 to FY22 expenditures/costs and compared it to the proposed funding. The risk rating portion also did not provide a rating for the cost proposals that exceeded senior review budget targets (over-guide).

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.

HIGH-LEVEL COMPARISONS

Comparisons of the proposed funding levels for combined Mission Operations (MO) and Data Analysis (DA) (MO & DA), mission operations, and the science team are summarized in Figure 2-3. All projects are below primary mission funding levels. The plot on the right shows the rations of the 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) or may have a larger portion of mission science efforts funded by competed Research Opportunities in Space and Earth Science (ROSES) for basic and applied research.

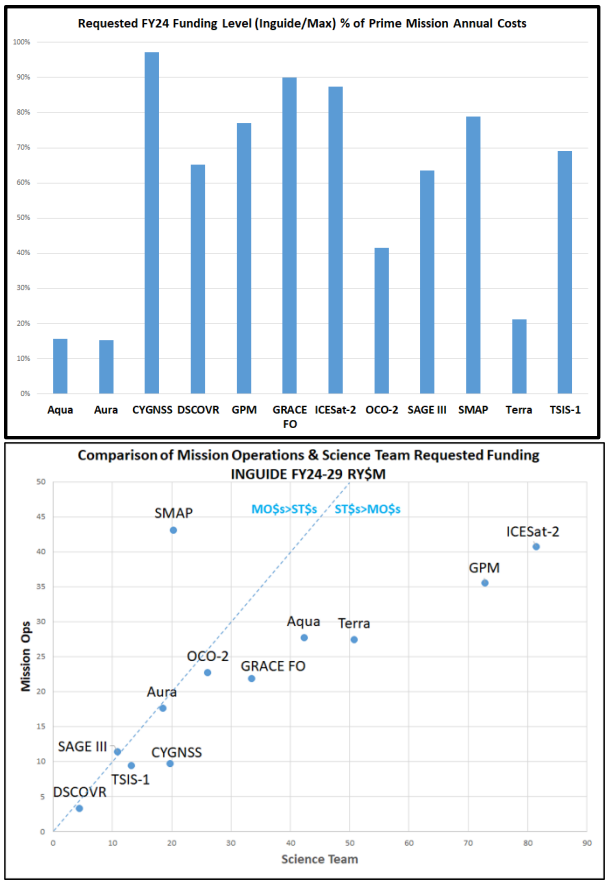


Fig. 2-3 Mission in-guide FY24 costs compared to previous costs (left), and ratio of mission to science funding (right) FY24-29

SUMMARY COST RATINGS

The final cost ratings are shown in Figure 2-4. Details for each project are provided in the next section of this report.

Mission	Cost Risk Rating	Rationale
Aqua	Med Risk	Reasonable request with well supported BoE; Hardware far beyond expected lifetime
Aura	Med Risk	Reasonable request with well supported BoE; Hardware far beyond expected lifetime, expected operation into mid-2026 not supported by Inguide. Will be renegotiated as part of PPBE26.
CYGNSS	Low Risk	Requested funding appears conservative; mention descoping from previous submits but do not specify what that is
DSCOVR	Low Risk	Request appears reasonable
GPM	Med/Low Risk	Request appears reasonable although there is risks associated with ground validation reductions for Inguide and overguide
GRACE FO	Med Risk	Driven by workforce reductions, Hardware performance/lifetime concerns; expiration of MOU with potential cost uppers
ICESat-2	Low Risk	Request appears reasonable
OCO-2	Med/Low Risk	Reductions in IT Security, workforce, hardware replenishment
SAGE III	Med/Low Risk	Request appears reasonable
SMAP	Med/Low Risk	Concerns regarding Inguide reductions and HW degradation
Terra	Med Risk	Reasonable request with well supported BoE; HW far beyond expected lifetime
TSIS-1	Low Risk	Request appears reasonable

Fig. 2-4 Mission extension cost risk assessments for each mission at the budget target (in-guide) as well as the high-level rationale

INDIVIDUAL PROJECT COST ANALYSIS SUMMARIES

Summary details of cost analysis for each project are included in this section, which consists of:

- Project-specific cost assessment summary
- *Findings*: Includes significant items that may affect 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 Senior Call for proposals
- *Project Cost History and Request*: Shows funding and workforce by fiscal year for FY19/FY20 through the proposed operating time. Data includes funding guidelines and uncosted carryover
- *Cost Analysis Comparisons*: This analysis compares costs to the nominal/prime operations level Mission Operation System (MOS)
- *In*-Kind Support/Funding: This area covers all significant contributions toward each project's MO and DA requirements

Additional supporting details covering all cost analysis area were provided to the panel and are covered in a separate presentation ("2023 Senior Review Final Cost Analysis (6-23-2023)").

AQUA

AQUA Summary: Latin for water, Aqua received a Cost Risk Rating of Medium. The project's proposal is in line with the Senior Review cost target reduction (in-guide) of 50%. The 50% reduction in funding reduces the project funding/cost envelope and will require diligent oversight of resources. Aqua no longer performs inclination adjustment maneuvers, and the operations are planned to end in FY26.

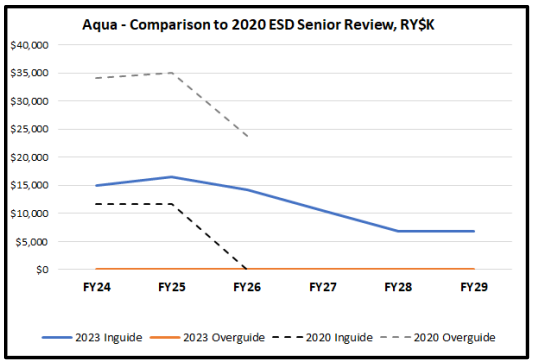
AQUA Findings:

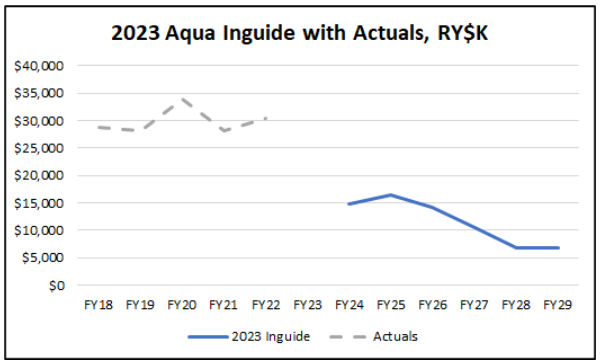
- Some battery degradation but no anomalies since September 2005
- Loss of 23 of 132 solar cell strings
- Lack of inclination maneuvers drove exit of A-Train in January 2022
- Flight Software anomaly associated with an integer overflow is predicted to occur in January 2026, project plans to mitigate in FY2026
- Detailed Basis of Estimate (BoE) of reductions to meet target budget reductions included in the proposal
- In-guide is a 50% reduction to the Aqua PPBE2024 Over-guide, requires Earth Science Mission Operations (ESMO), in coordination with Aura and Terra, to treat Aqua as a Class C mission, increase data response times, reduce algorithm maintenance budgets, and reduce outreach efforts
- No over-guide was proposed

AQUA Evaluation Criteria Assessment:

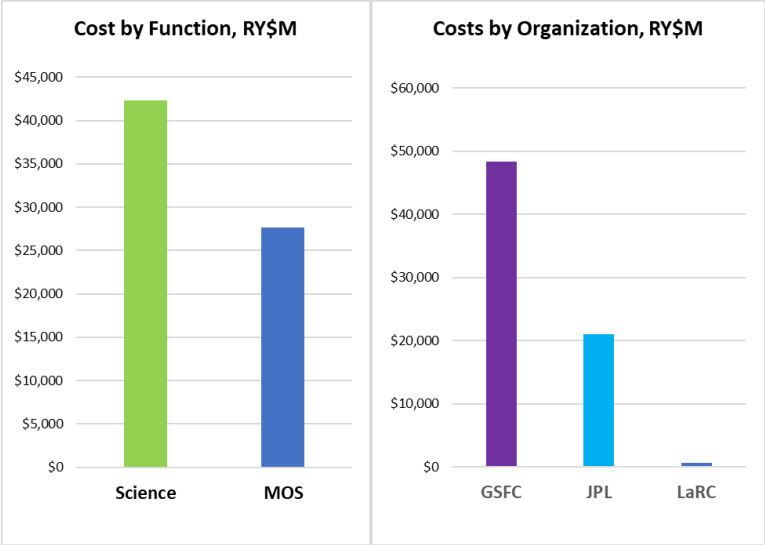
	Rating	Notes
Cost Risk Rating	Med Risk	Reasonable request with well supported BoE; HW far beyond expected lifetime
Technical Risk		
HW Status/Perf/Lifetime	Med Risk	Lifetime limited by fuel levels and EPS performance
Mission Ops Plans	Med Risk	No longer performs Inclination Adj Manuevers (not in tight coordination with A-train satellites); Orbital ops ends in FY26. IT Security Patch reduced cadence, waiver approval in work. Limited reachback.
Cost Performance		
Cost Realism	Excellent	Very good BoE
Potential Cost Risks	Med/Low Risk	Some component degradation & mitigation should be expected. FY23 carryout mitigation. ESMO cost sharing for TAA. Contract changes for inguide.
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	NASA GSFC ESDIS; EOS Project Science Office (Project Scientists & deputies); CERES funded separately (~$3.5M/yr)
Risk from Inguide Reductions	Med Risk	Inguide is ~50% reduction of PPBE2024 Overguide; Requires ESMO to treat Aqua as Class C (vs Class A); DA impacts include longer response times, lower algorithm maintenance budgets, and reduction of Outreach efforts

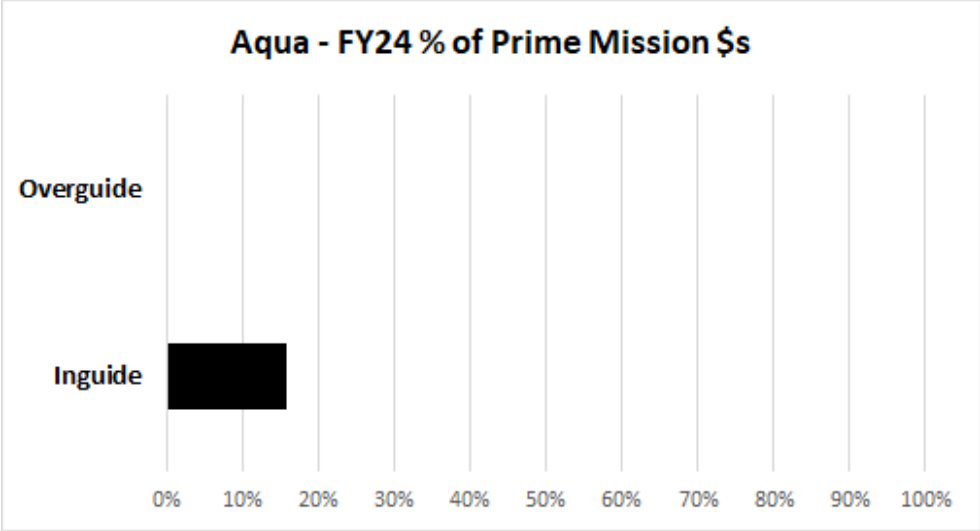
AQUA Cost History and Request:





AQUA Cost Analysis Comparison:





AQUA In-Kind Support (non-ROSES):

- Consolidated CERES budget for instrument calibration and data product generation of $3.5M/yr.
- ESMO resource sharing with Terra, Aqua, Aura (TAA)
- ESDIS Project processing all standard Aqua products
    - GES DISC for AIRS data
    - ASDDC for CERES
    - MODAPS and OBPG for MODIS
- OBPG partially funded by non-ESDIS sources

- EOS Project Science Office provides FTE and procurement funding to mission Project Scientists and their deputies
    - ~358K.yr for labor and procurement needs, in FY2024 and beyond

AURA

AURA Summary: Aura received a Cost Risk Rating of Medium. The project's proposal is in line with the Senior Review cost target reduction (in-guide) of 50%. The 50% reduction in funding reduces the project funding/cost envelope and will require diligent oversight of resources. Aura entered free-drift drag down exit from the A-Train in March 2023. In-guide proposal assumes end of Aura operation in FY2025.

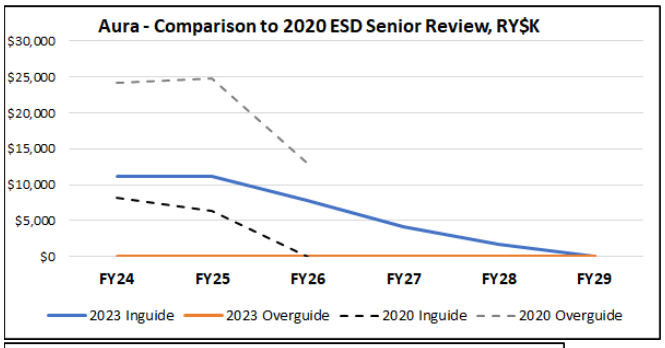
AURA Findings:

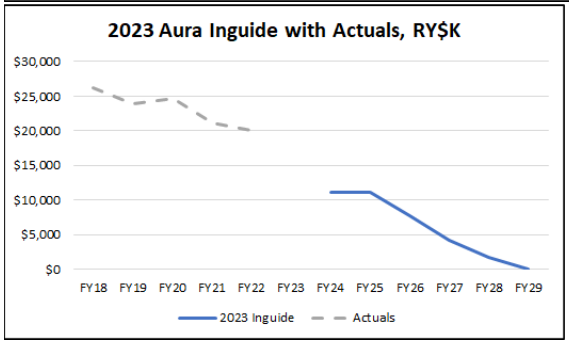
- MLS and OMI are operating well
- TES was decommissioned in January 2018
- HRDLS has not been funded since 2012.
- In-guide is a 50% reduction to the Aura PPBE2024 Over-guide, requires Earth Science Mission Operations (ESMO), in coordination with Aqua and Terra, to treat Aura as a Class C mission, increase data response times, reduce algorithm maintenance budgets, and reduce outreach efforts
- No over-guide was proposed
- Detailed Basis of Estimate (BoE) of reductions to meet target budget reductions included in the proposal
- In-guide proposal less that budget target in FY29 due to project close out activities prior to FY29

AURA Evaluation Criteria Assessment:

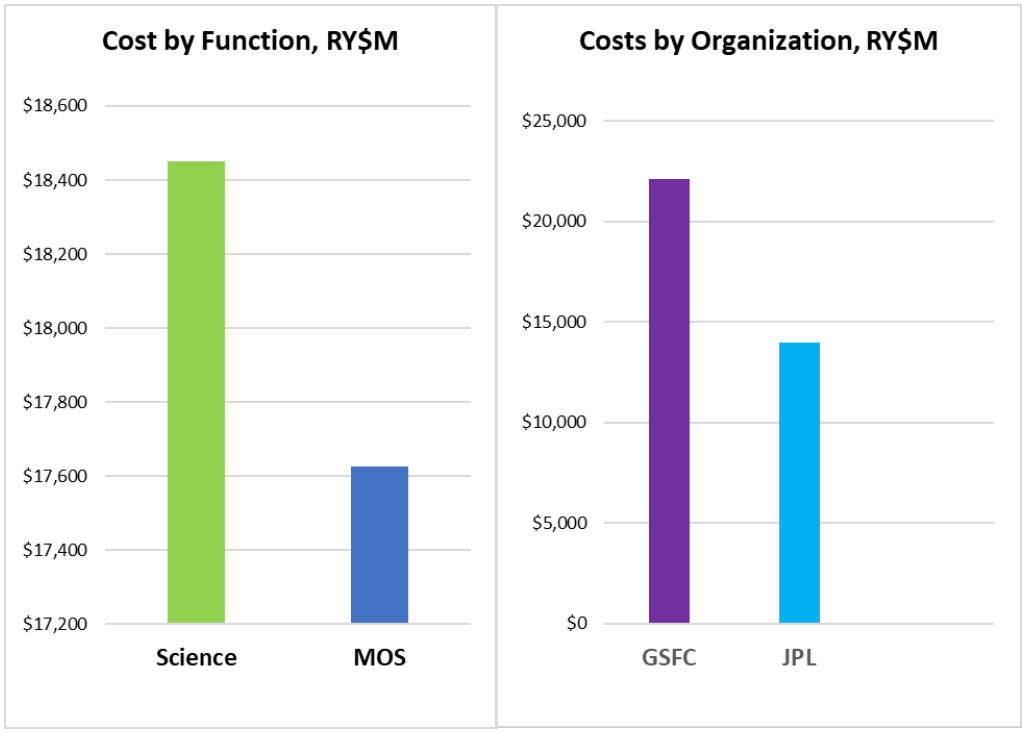
	Rating	Notes
Cost Risk Rating	Med Risk	Reasonable request with well supported BoE; HW far beyond expected lifetime, expected operation into mid-2026 not supported by Inguide. Will be renegotiated as part of PPBE26.
Technical Risk		
HW Status/Perf/Lifetime	Med Risk	S/C, MLS, and OMI appear to be operating well although HW beyond expected lifetime
Mission Ops Plans	Med Risk	50% cost reductions enabled through reduced activities for the MLS & OMI teams and ESMO support
Cost Performance		Inguide request is $1717K under Target costs in FY29. Assumption of all work complete.
Cost Realism	Excellent	Significant cost reductions brought about through sharing among the TAA missions does have a caveat, as sharing links the overall budgets—if one mission ends, ESMO will still require some fraction (estimated at 50%) of the funds previously associated with that mission's operations budget to accomplish its support for the other missions.
Potential Cost Risks	Med/Low Risk	ESMO reductions could affect reliability. FY23 carryout mitigation. Contract changes for inguide. ESMO cost sharing for TAA. Dependency of passivation with Terra.
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	OMI (Netherlands/Finland)
Risk from Inguide Reductions	Med/Hi Risk	Reductions for Inguide (~50%) assume end of Aura science in mid-2025, although actual end may be as late as mid-2026; Reductions also include reduced activities for MLS & OMI teams; Requires ESMO to treat Aura as Class C (vs Class A);

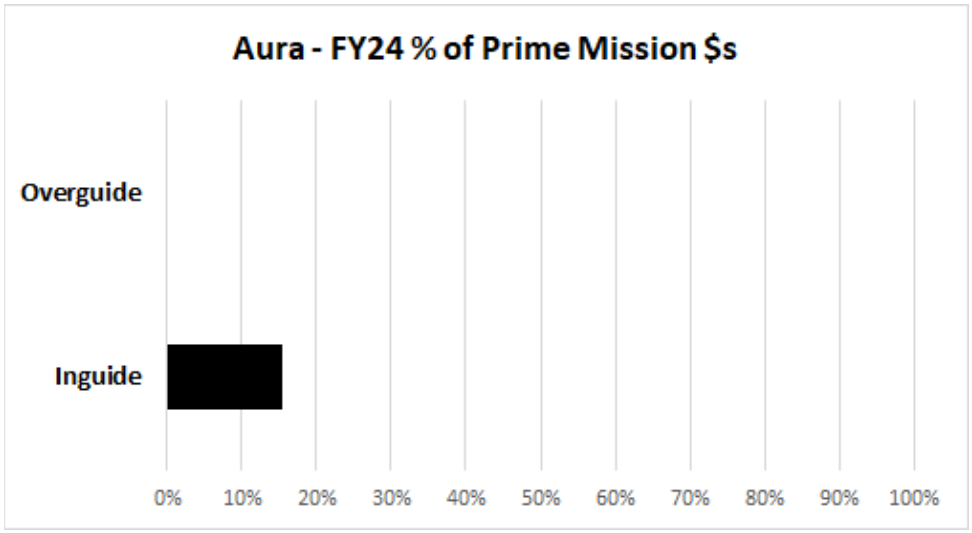
AURA Cost History and Request:





AURA Cost Analysis Comparison:





AURA In-Kind Support (non-ROSES):

- ESMO resource sharing with TAA
- MLS SIPS are responsible for routine processing of MLS data into science product files.
- OMI core team receives support from OMI SIPS for processing all US and some KNMI products

TERRA

TERRA Summary: Terra received a Cost Risk Rating of Medium. The project's proposal is in line with the Senior Review cost target reduction (in-guide) of 50%. The 50% reduction in funding reduces the project funding/cost envelope and will require diligent oversight of resources. In late 2022, Terra equator-crossing reached 10:15 am. The crossing time will continue to move to earlier times, reaching 9:00 am in 2026.

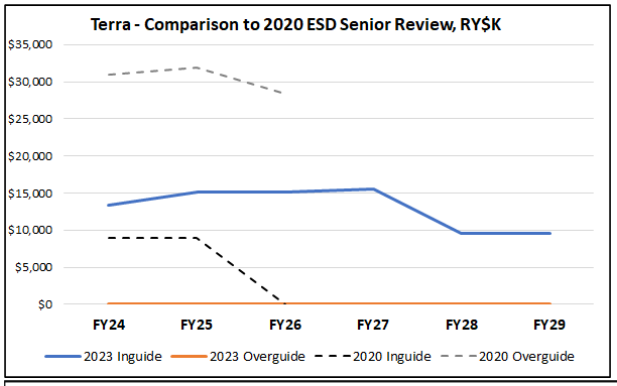
TERRA Findings:

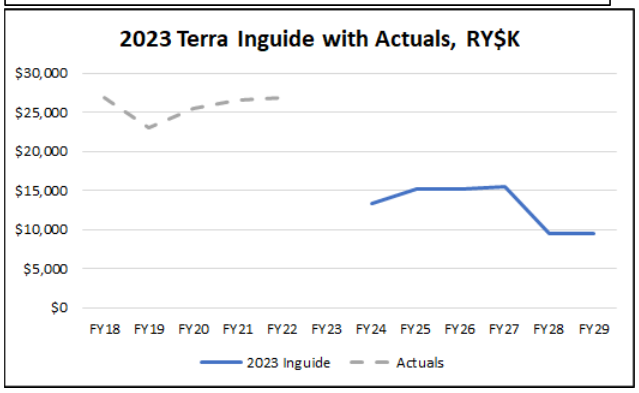
- In-guide is a 50% reduction to the Terra PPBE2024 Over-guide, requires Earth Science Mission Operations (ESMO), in coordination with Aqua and Aura, to treat Terra as a Class C mission, increase data response times, reduce algorithm maintenance budgets, and reduce outreach efforts
- No over-guide was proposed
- Lifetime concerns include battery and available propellant
- End of science operations planned in February 2027
- Detailed Basis of Estimate (BoE) of reductions to meet target budget reductions included in the proposal

TERRA Evaluation Criteria Assessment:

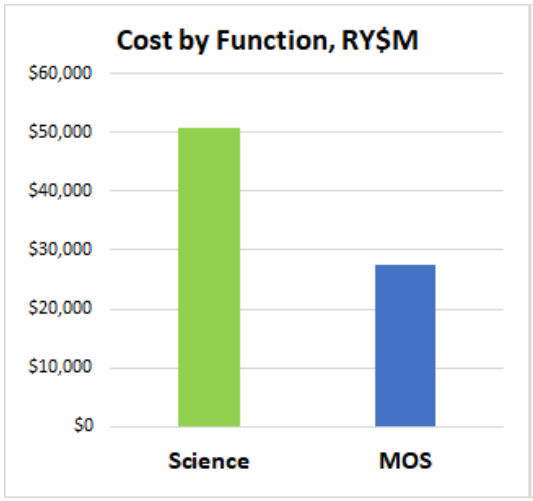
	Rating	Notes
Cost Risk Rating	Med Risk	Reasonable request with well supported BoE; HW far beyond expected lifetime
Technical Risk		
HW Status/Perf/Lifetim	Med Risk	Lifetime concerns include battery and available propellant
Mission Ops Plans	Med Risk	MO thru Feb'27. Move from 24/7 to 12/7 operations. IT Security Patch reduced cadence, waiver approval in work. Limited reachback.
Cost Performance		
Cost Realism	Excellent	Very good BoE
Potential Cost Risks	Med/Low Risk	Some component degradation & mitigation should be expected. FY23 carryout mitigation. Contract changes for inguide. ESMO cost sharing for TAA.
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	CERES funded separately
Risk from Inguide Reductions	Med Risk	50% Inguide reductions include loss of skilled/science personnel limiting the scope of data quality assessments; MO includes more hands-off operation leading to longer delays to respond to instrument and platform anomalies and increased loss of valuable observations. Requires ESMO to treat Terra as Class C (vs Class A).

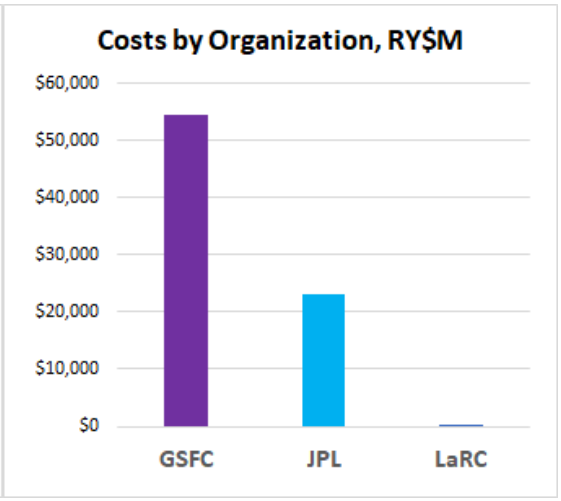
TERRA Cost History and Request:

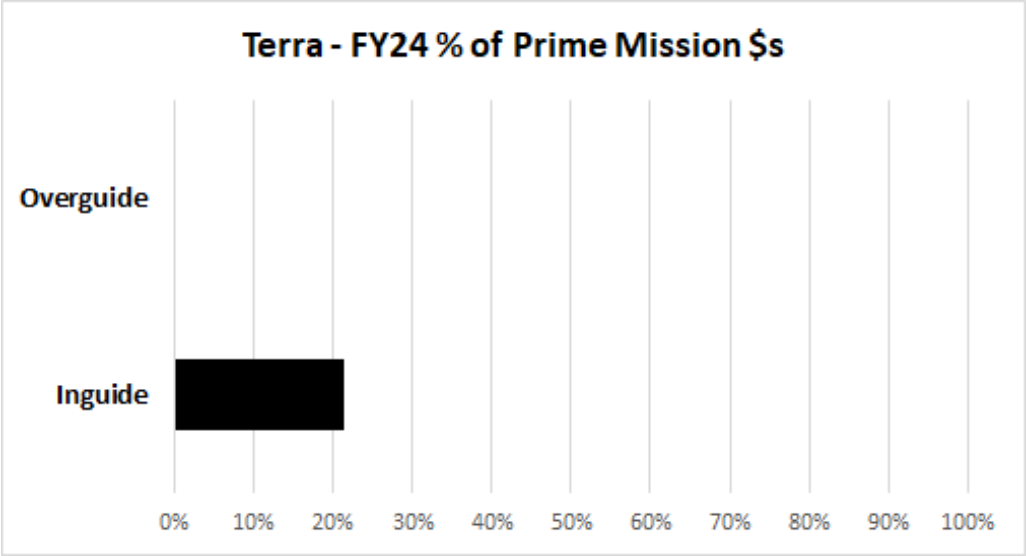




TERRA Cost Analysis Comparison:







TERRA In-Kind Support (non-ROSES):

- ESMO resource sharing of TAA
- Japan ASTER Science Team, Level-1 processing and instrument monitoring and commanding
- CERES DA activities from Radiation Budget Project starting in FY15
- ESDIS Project support of processing at SIPS and DAACs

CYGNSS

CYGNSS Summary: CYGNSS received a cost risk rating of low and proposed an over target baseline (over-guide) to increase science activities through the period of the science review.

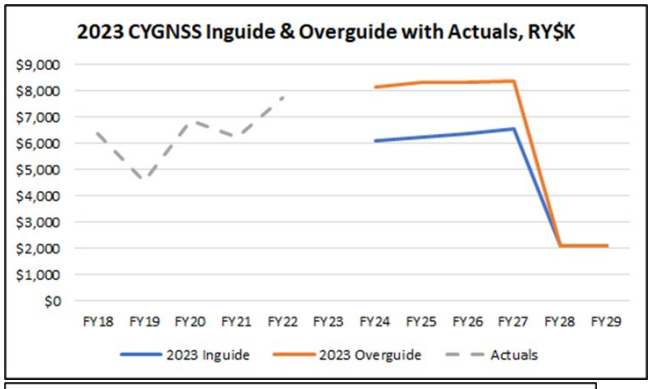
CYGNSS Findings:

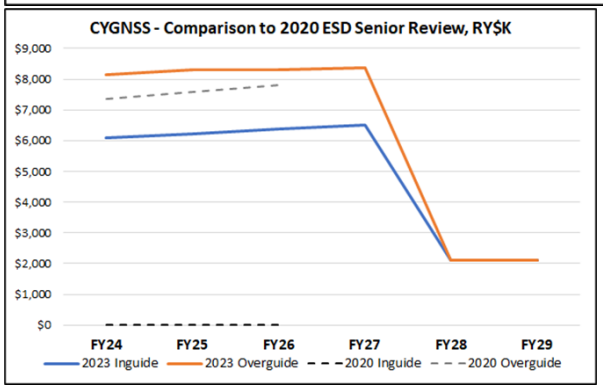
- An over-guide was proposed
    - Adds new science measurements in addition to the primary mission science
- 7of 8 MicroSats operating, and payloads appear to be in reasonable health
- Proposed cost and workforce are well correlated
- Assessment supports both proposed budgets
- In-guide proposal aligned with project costs since FY2018
- Basis of Estimate (BoE) was at a high level
- Assumes operations end after FY2027
- Largest % in-guide total cost compared to prime mission costs of all senior review projects
- Over-guide proposal exceeds prime mission operations cost

CYGNSS Evaluation Criteria Assessment:

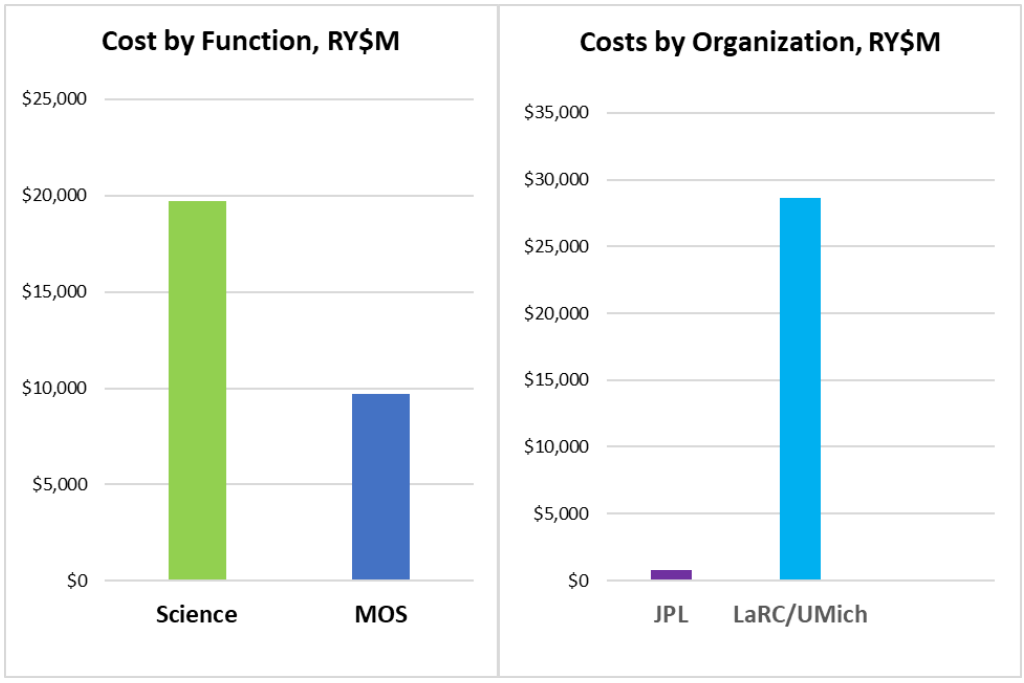
	Rating	Notes
Cost Risk Rating	Low Risk	Requested funding appears conservative; mention descoping from previous submits but do not specify what that is
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	Loss of comm with 1 of 8 s/c (Nov'22); All systems of the 7 S/C are healthy; Expected life is at least 4 add'l years but likely to be at least 6 add'l years with some changes to ConOps
Mission Ops Plans	Low Risk	7 of 8 s/c are operating nominally; FSW enabled significant reduction of safings/yr since 2017
Cost Performance		
Cost Realism	Good	BoE, and definition of Inguide & Overguide scope, is somewhat high-level; Costs somewhat higher than during Prime Mission; Mentions IG supports descoped version of the Phase E activities during the previous extended mission Phase E (FY21-23) but does not clearly mention what that is
Potential Cost Risks	Low $ Impact	Mission can still functon without the OG
Overguide Request?	Yes	Covers expansion of science scope and applications leveraging new measurement technique. Did not breakout OG options cleanly
Contributions? (*beyond ROSES*)	No	
Risk from Inguide Reductions	Med/Low Risk	~24% reduction not clearly described

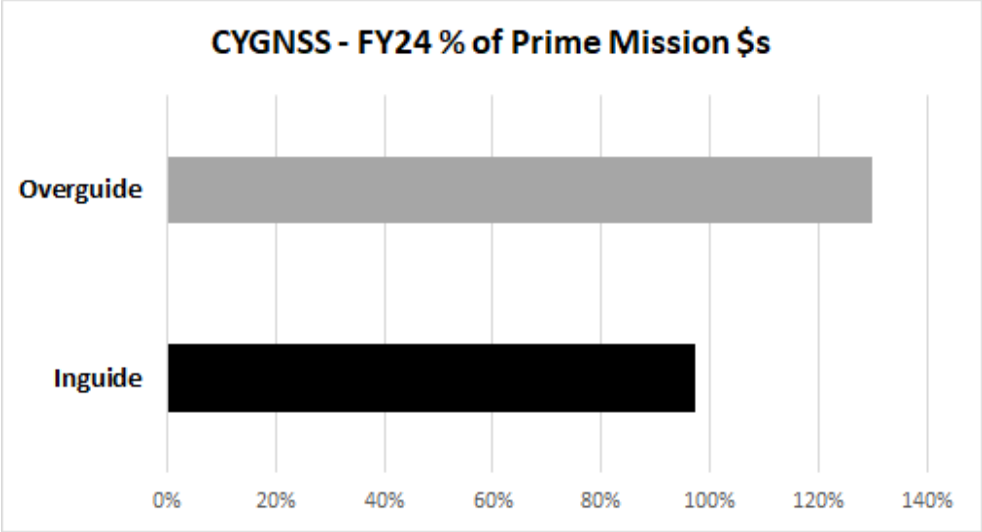
CYGNSS Cost History and Request:





CYGNSS Cost Analysis Comparison:





CYGNSS In-Kind Support (non-ROSES):

- None

DSCOVR

DSCOVR Summary: Deep Space Climate Observatory (DSCOVR) received a Cost Risk Rating of Low and the proposal meets target baseline. The DSCOVR project has been performing well. Risks appear to be within the project's ability to cover within proposed funding.

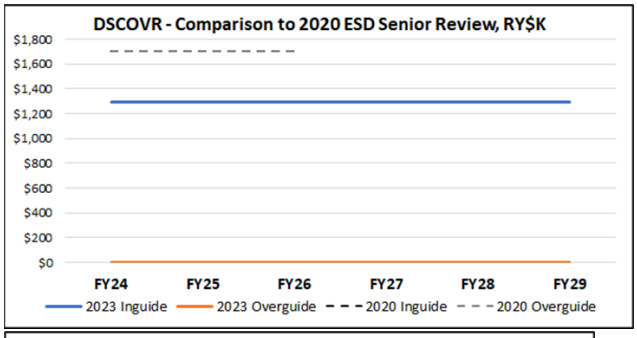
DSCOVR Findings:

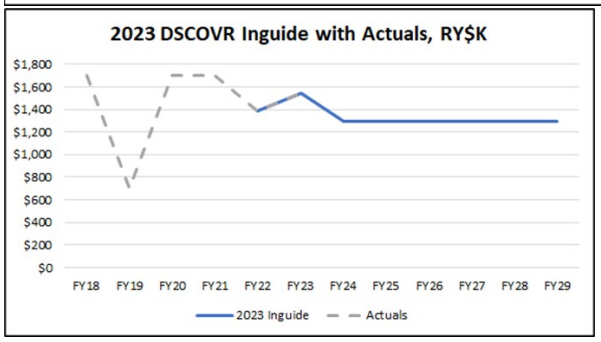
- No over-guide was proposed
- Spacecraft and payload appear to be operating nominally
- Requested funding appears reasonable
- Assessment supports the proposed budget

DSCOVR Evaluation Criteria Assessment:

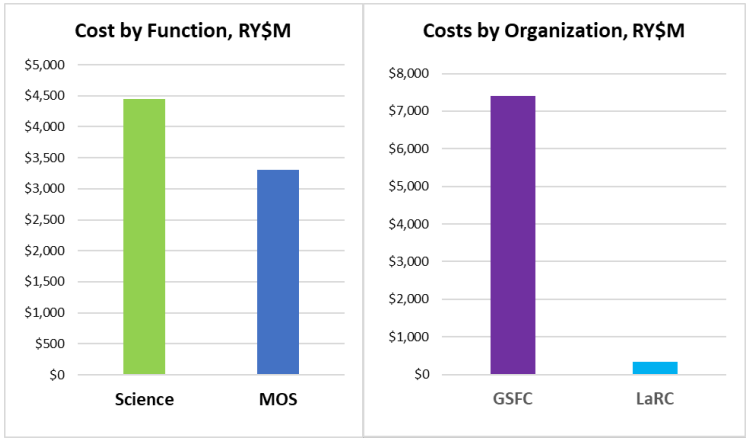
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	S/C & payload operating nominally since 8mo hiatus from MIMU issue
Mission Ops Plans	Low Risk	Impacted by Inguide cost reductions
Cost Performance		
Cost Realism	Good	Reasonable BoE
Potential Cost Risks	Low $ Impact	Inguide cost reductions add risk
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	NOAA (Mission/spacecraft MOC)
Risk from Inguide Reductions	Med/Low Risk	~24% reduction not clearly described;

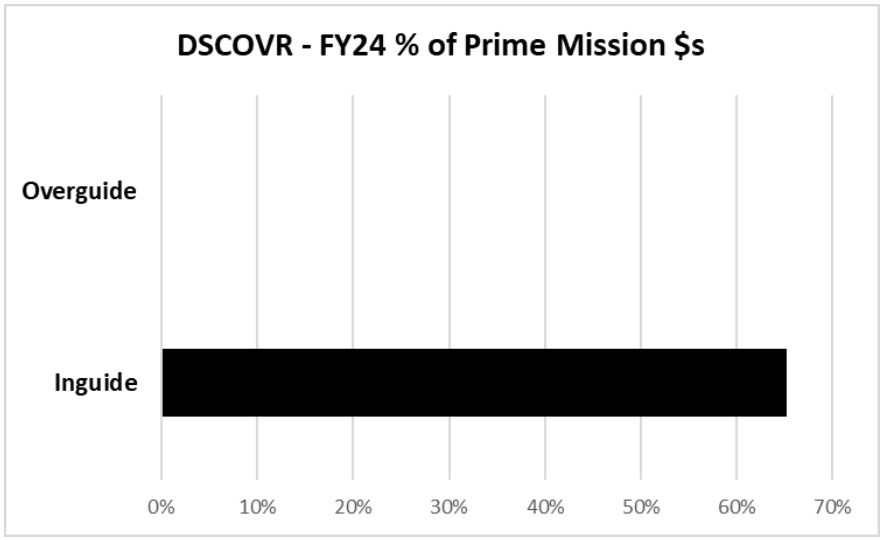
DSCOVR Cost History and Request:





DSCOVR Cost Analysis Comparison:





DSCOVR In-Kind Support (non-ROSES):

- NOAA operates the Mission/Spacecraft MOC

GPM

GPM Summary: Global Precipitation Measurement (GPM) received a Cost Risk Rating of Medium/Low and the proposal includes an over-guide proposal to restore real-time systems after FY24 removed from the in-guide proposal to meet the 24% funding cut to meet target baseline.

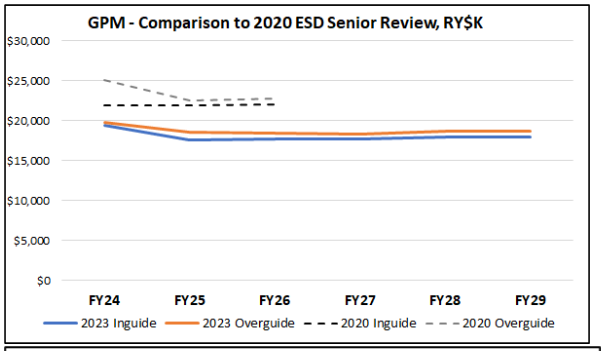
GPM Findings:

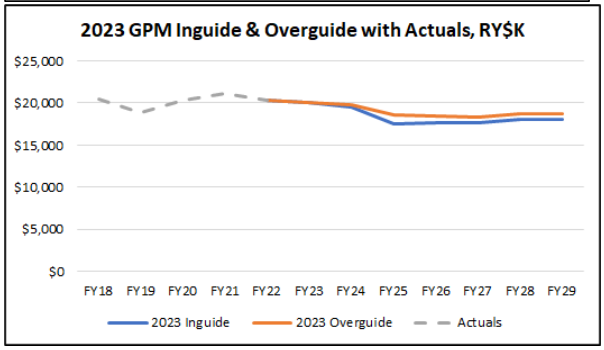
- Propellant for Operations expected through 2031
- Reasonable Basis of Estimate (BoE)
- Reductions for In-guide reduces support for promising retrieval and analysis concepts, creative analysis now support by Ground Validation, loss of experience personnel provides insufficient funds to staff and operate Real Time (RT) beginning in FY2025
- In-guide proposal in family with project cost actuals since FY18 reducing risk of meeting in-guide budget target reductions
- Proposed over-guide will enable 1) continued computation of Near Real Time (NRT) data products, enabling continuing use of GPM data in a range of NRT operations and applications; and 2) timely patching for possible reaction wheel failures, reducing mission risk; both of which are prevented by the in-guide budget

GPM Evaluation Criteria Assessment:

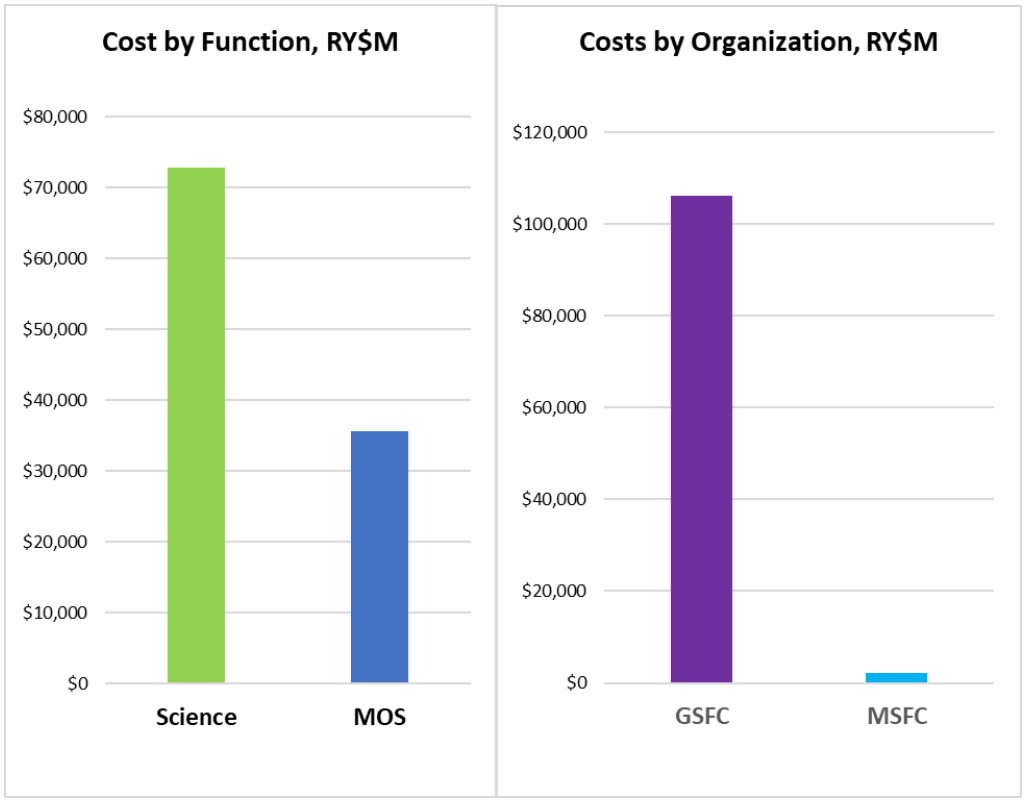
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Request appears reasonable although there is risks associated with ground validation reductions for Inguide and overguide
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	Propellant for science ops into 2031
Mission Ops Plans	Low Risk	MOC refresh in 2020; DA reductions for Inguide add risk
Cost Performance		
Cost Realism	Good	Reasonable BoE
Potential Cost Risks	Med/Low Risk	Inguide and overguide reductions add cost risk
Overguide Request?	Yes	Adds the IG-descoped real-time (RT) system after FY24 and a critical patch. Does not add back Ground Validation.
Contributions? (*beyond ROSES*)	Yes	DPR (JAXA)
Risk from Inguide Reductions	Med Risk	~22% reductions for Inguide reduces support for promising retrieval and analysis concepts, creative analysis now supported by Ground Validation, loss of experienced personnel; provides insufficient funds to staff and operate the RT beginning with FY25 (severe impacts on the many users)

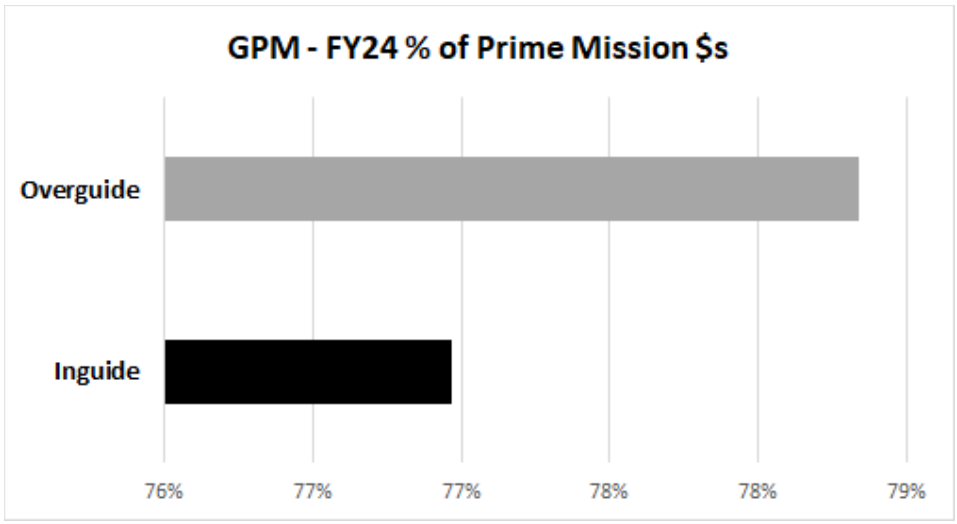
GPM Cost History and Request:





GPM Cost Analysis Comparison:





GPM In-Kind Support (non-ROSES):

- Dual-frequency Precipitation Radar (DPR) provided by Japan Aerospace Exploration Agency (JAXA)

GRACE FO

GRACE FO Summary: The Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) Deep Space Climate Observatory (DSCOVR) received a Cost Risk Rating of Medium to meet the Senior Review target baseline. GRACE-FO risk driven by HW performance/lifetime concerns and MOU in kind risk.

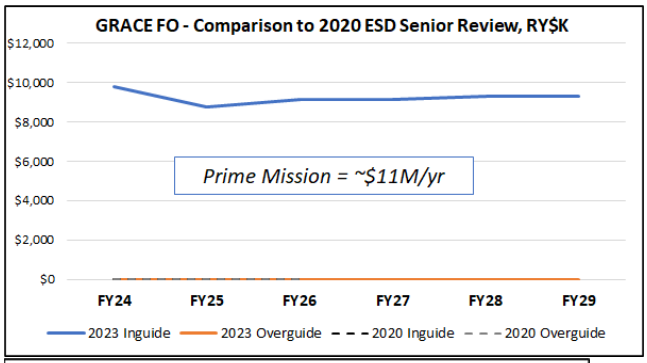
GRACE FO Findings:

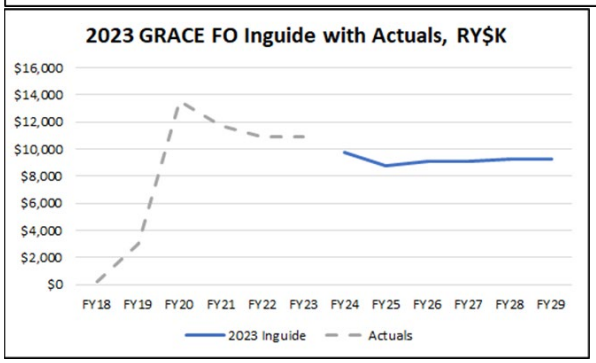
- Reasonable Basis of Estimate (BoE) based on experience with GRACE extended mission and the initial five years GRACE-FO prime mission
- Project is planning to leverage some prime mission operations funding to meet reduced budget targets in extended operations
- CCGPS leakage may be a mission life limiting by 2028
- No over-guide proposed
- Failed primary instrument Processing Unit (IPU) of GRACE-FO 2
- Degraded performance on GRACE-FO 2 since July 2018
- OBC Mil-Bus fault was detected on GRACE-FO 2 that forced autonomous switchover Feb 2019 (FY19)
- In-guide proposal in family with project actual costs since FY18.
- The MOU with GFZ that provides all routine telemetry, tracking, and command capabilities at no cost to NASA has been extended through Dec 2026 (FY27)

GRACE FO Evaluation Criteria Assessment:

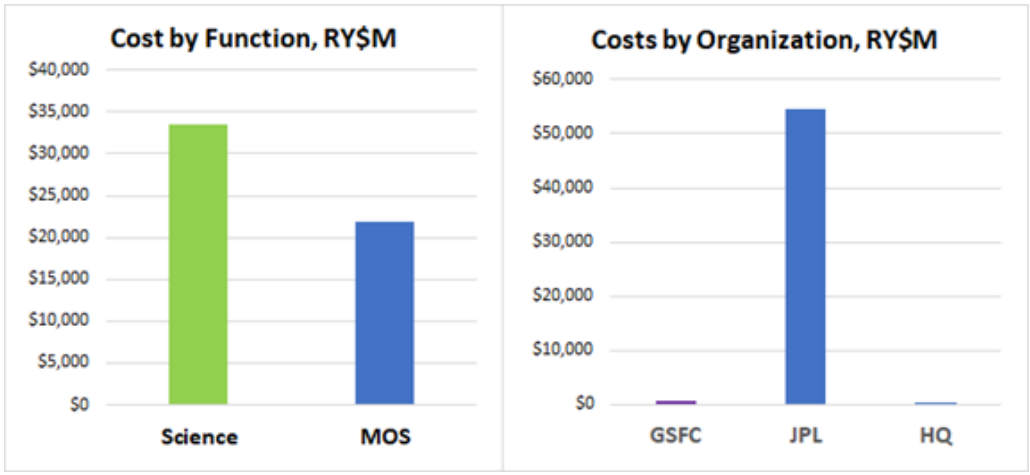
	Rating	Notes
Cost Risk Rating	Med Risk	Driven by workforce reductions, Hardware performance/lifetime concerns; expiration of MOU with potential cost uppers
Technical Risk		
HW Status/Perf/Lifetim	Med Risk	CGPS leakage may be life limiting by 2028; Still maintains ample margins in power and propellant, battery capacity is > 90% of the capacity at launch; does not expect life-limiting items to affect S/C until at least 2028 in the worst case
Mission Ops Plans	Med/Low Risk	Some workforce reductions (adds risk); Recovery operations, especially ones that require new procedures, will likely cause larger science data gaps
Cost Performance		
Cost Realism	Good	Reasonable BoE; based on experience with GRACE extened mission and the initial five years of the GRACE-FO mission; Confusion of the use of Prime Mission obligation authority to offset shortfall in SR guidelines
Potential Cost Risks	Med $ Impact	Workforce reductions and HW performance/lifetime add risk; The MOU with GFZ expires 12/31/26 without mention of follow-on through proposal horizon. Potential cost risk if MOU is not extended
Overguide Request?	No	
Contributions? (*beyond ROSES*)	Yes	DLR (GFZ) operations support and ground stations
Risk from Inguide Reductions	Med Risk	Reductions spread cuts across project management, project system engineering, safety and mission assurance, flight system engineering and mission operations system engineering; Moderate reductions for the project's major subcontracts with Airbus, ONERA and CSR are also necessary

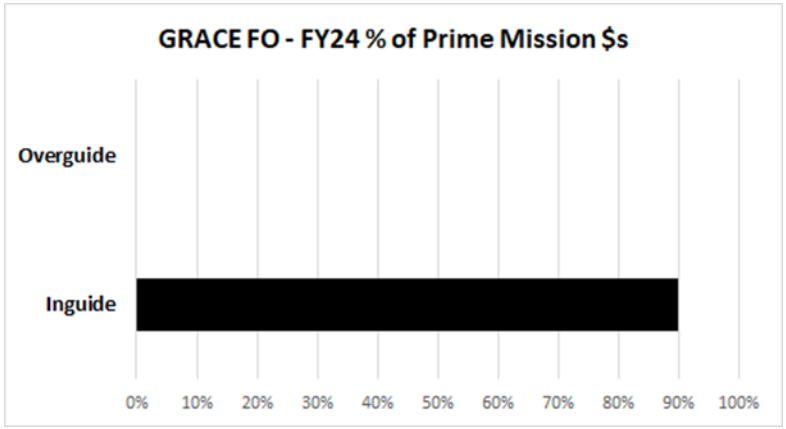
GRACE FO Cost History and Request:





GRACE Cost Analysis Comparison:





GRACE In-Kind Support (non-ROSES):

- DLR (GFZ) operations support and ground stations

ICESat-2

ICESat-2 Summary: Ice, Cloud, and land Elevation Satellite (ICESat-2) received a Cost Risk Rating of Low and the proposal meets target baseline.

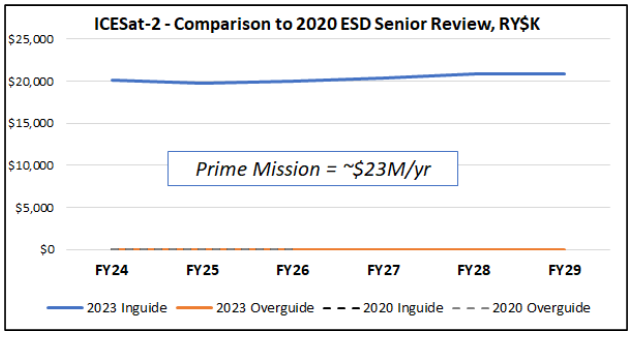
ICESat-2 Findings:

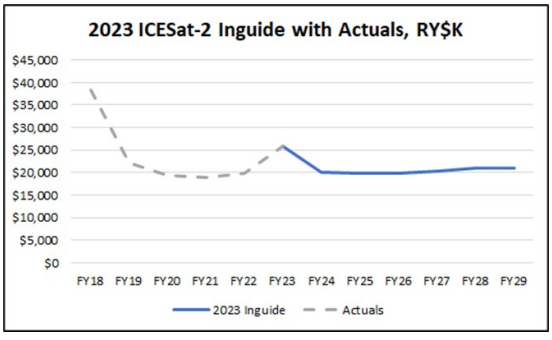
- Mission is operating on primary components across all subsystems
- Estimated operations through June 2037
- No over-guide proposed
- Reasonable Basis of Estimate (BoE)
- In-guide funding reductions in family with project actuals since FY18
- To meet the target baseline represents some risk, but the project proposal asserts ability to maintain science data requirement of 98%
- In-guide reductions of 24% result in a loss of skilled personnel resulting in increased risks to science data capture, ground system availability, and IT security threats
- For data analysis, the reductions decrease field calibration campaigns and result in a focus on the cryosphere and biosphere data products, at the expense of further development of the ocean, atmosphere, and inland water data products
- Small and expected degradation in laser transmit energy and receiver sensitivity reduction over the last three years.

ICESat-2 Evaluation Criteria Assessment:

	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetim	Low Risk	Operating on primary components across all subsystems; Estimated lifetime is Jun'37
Mission Ops Plans	Med/Low Risk	Inguide reductions add risk
Cost Performance		
Cost Realism	Good	Reasonable BoE
Potential Cost Risks	Low $ Impact	Inguide reductions add risk
Overguide Request?	No	
Contributions? (*beyond ROSES*)	No	
Risk from Inguide Reductions	Med/Low Risk	Inguide reductions result in a loss of skilled personnel resulting in increased risks to science data capture, ground system availability, and IT security threats; For data analysis, the reductions decrease field calibration campaigns and result in a focus on the cryosphere and biosphere data products, at the expense of further development of the ocean, atmosphere, and inland water data products

ICESat-2 Cost History and Request:





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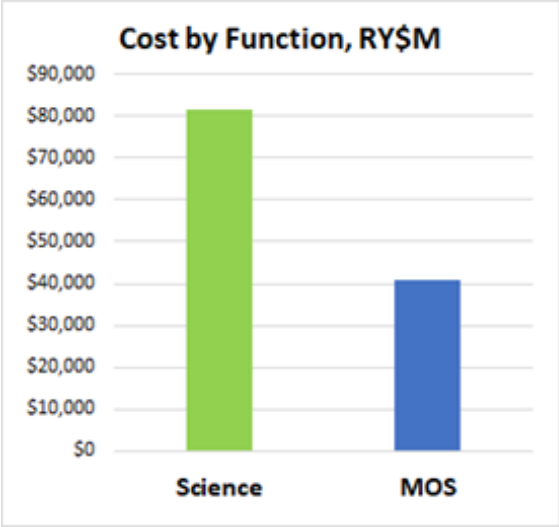
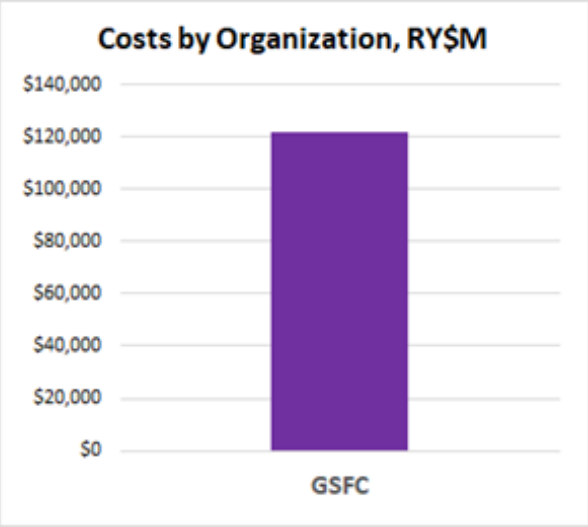
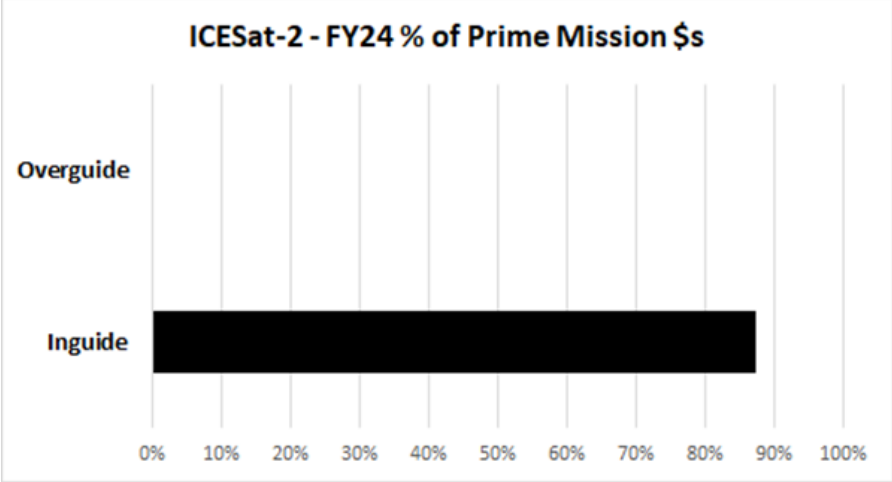






ICESat-2 In-Kind Support (non-ROSES):

- None

OCO-2

OCO-2 Summary: Orbiting Carbon Observatory 2 (OCO-2) received a Cost Risk Rating of Medium/Low and the proposal includes an over-guide proposal to fund NASA Assessment & Authorization (A&A) increased security requirements, among other additions.

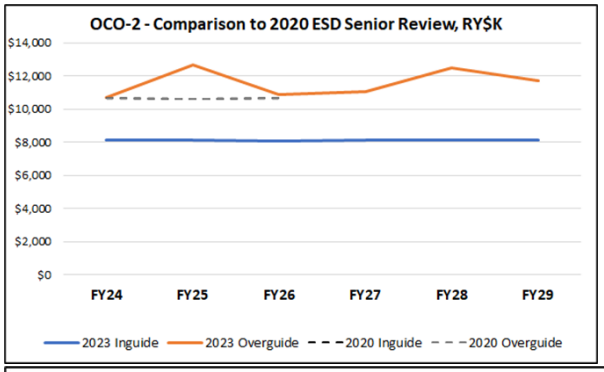
OCO-2 Findings:

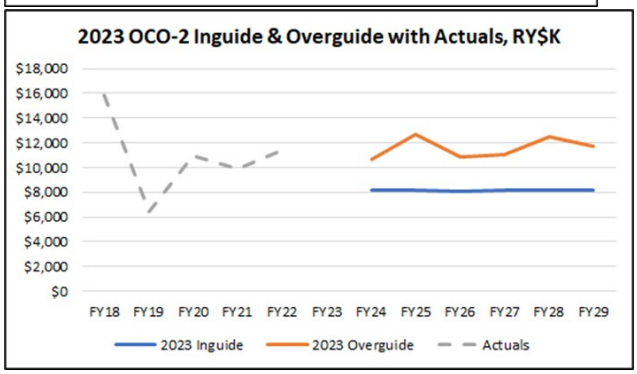
- Proposal included an over-guide proposal
- Reasonable Basis of Estimate (BoE)
- In-guide does add some risk, but in-guide proposal is in family with project cost actuals since FY18
- Expected mission life into FY2040
- In-guide proposal relates risk to meeting ~24% budget reductions in Data Generation and Downlink, Meeting; Product Development, and Decontamination Cycle Cadence; Risk Mitigation and Verification, Algorithm Development and Reprocessing; and other activities
- Instrument experiencing transient degradation in the O2 A-band sensitivity
- Over-guide proposal Funds A&A activities imposed by new NASA cybersecurity requirements, enhancement to the SDOS Compute & Storage Hardware Replenishment, and reinstates several of the key functions and workforce descoped in the In-guide

OCO-2 Evaluation Criteria Assessment:

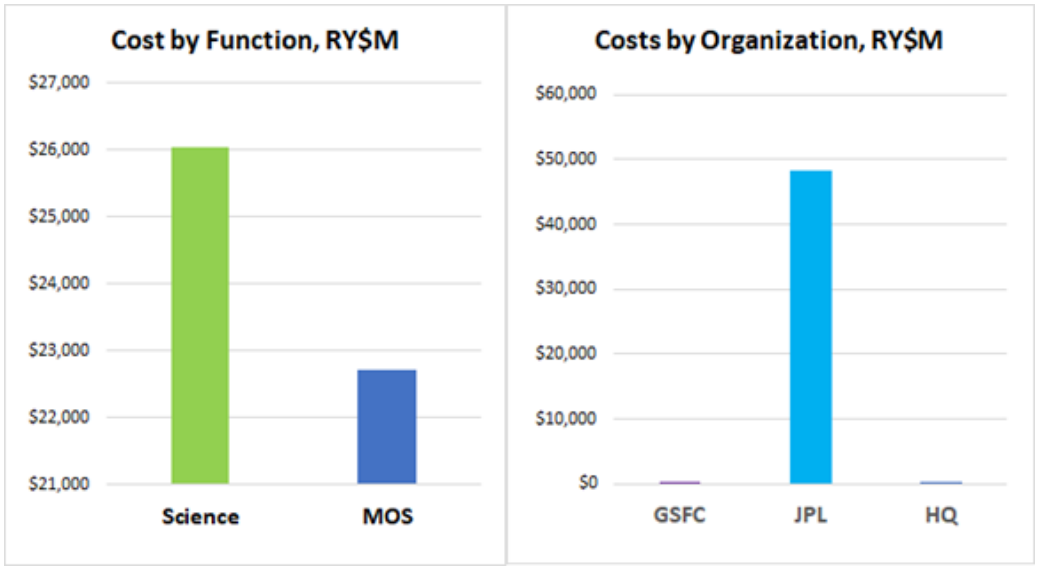
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Reductions in IT Security, workforce, hardware replenishment
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	Expected mission life into 2040
Mission Ops Plans	Med/Low Risk	Inguide costs add risk -IT Security, reductions, etc
Cost Performance		
Cost Realism	Good	Reasonable BoE
Potential Cost Risks	Med $ Impact	Inguide reductions add risk; No inflation
Overguide Request?	Yes	Funds A&A activities imposed by new NASA cybersecurity requirements, enhancement to the SDOS Compute & Storage Hardware Replenishment, and reinstates several of the key functions and workforce descoped in the Inguide
Contributions? (*beyond ROSES*)	Yes	NASA NEN and SN support (outside requested budget); GES DAAC and the CARA Operations Center
Risk from Inguide Reductions	Med/Low Risk	~24% Inguide includes reductions in Data Generation and Downlink, Meeting; Product Development, and Decontamination Cycle Cadence; Risk Mitigation and Verification, Algorithm Development and Reprocessing; and other activities

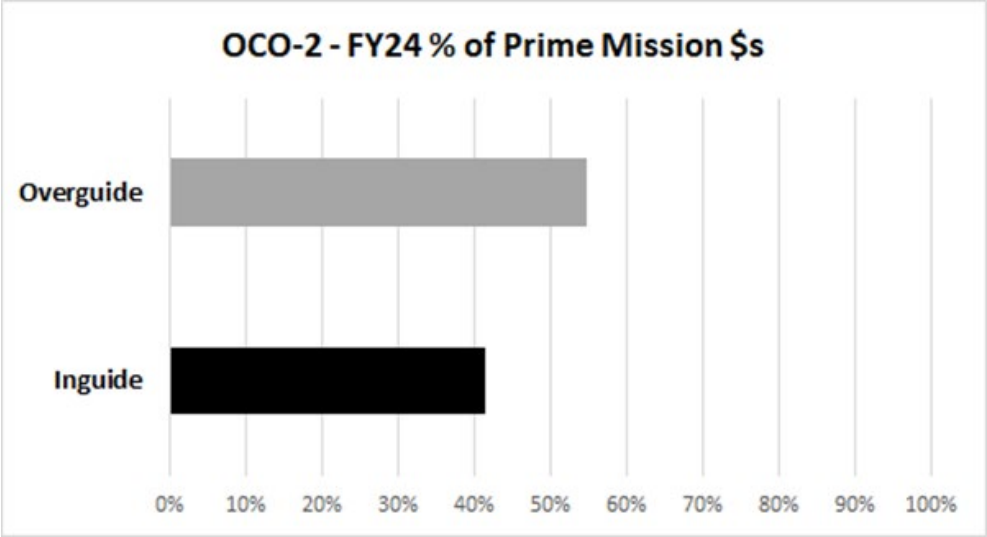
OCO-2 Cost History and Request:





OCO-2 Cost Analysis Comparison:





OCO-2 In-Kind Support (non-ROSES):

- NASA NEN and SN support (outside requested budget); GES DAAC and the CARA Operations Center

SAGE III

SAGE III Summary: Stratospheric Aerosol and Gas Experiment III (SAGE-III) received a Cost Risk Rating of Medium/Low and the proposal includes an over-guide proposal for science advancement and maintains the cadence of data delivery and response to anomalies.

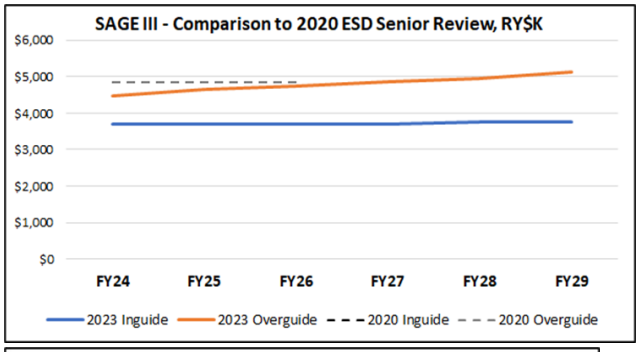
SAGE III Findings:

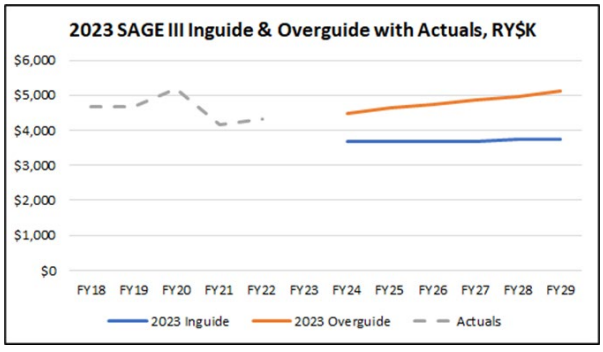
- Reasonable Basis of Estimate (BoE) included in proposal, but at a high level. Detailed Basis of Estimate provided by the project through supplemental project responses to the Senior Review Panel questions
- Hardware (HW) is of reasonable health, six additional years of operating lifetime expected
- Proposal includes an over-guide request
- In-guide severely undercuts advances in science, and the ability to respond to anomalies and delays payload response time for changes to the ISS attitude and visiting vehicle schedule.
- In-guide, with target funding cuts, represents demonstrable funding cuts with cost actuals since FY20.
- Over-guide adjusts operations and ground support to a level of basic sustainability with no or limited redundancy for anomaly resolution and does not restore external validation effort in coordination with NOAA and NZ National Institute of Water and Atmospheric Research (NIWA).

SAGE III Evaluation Criteria Assessment:

	Rating	Notes
Cost Risk Rating	Med/Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	Reasonable health; 6yrs add'l lifetime expected
Mission Ops Plans	Med/Low Risk	Functioning well but Inguide reductions add risk
Cost Performance		
Cost Realism	Fair	BoE discussions somewhat high-level
Potential Cost Risks	Med $ Impact	Inguide reductions add risk
Overguide Request?	Yes	Supports science advancement and maintains the cadence of data delivery and response to anomalies. In line with actuals.
Contributions? (*beyond ROSES*)	Yes	ISS (attached payload); ESA, NIWA (New Zealand)
Risk from Inguide Reductions	Med/Low Risk	~24% Inguide severely undercuts advances in science, and the ability to respond to anomalies. Significant reduction from operating cost actuals.

SAGE III Cost History and Request:





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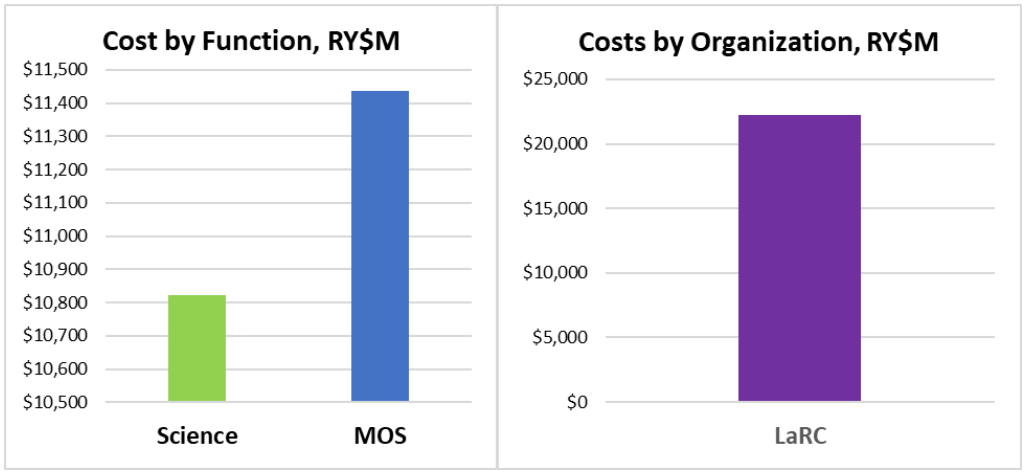
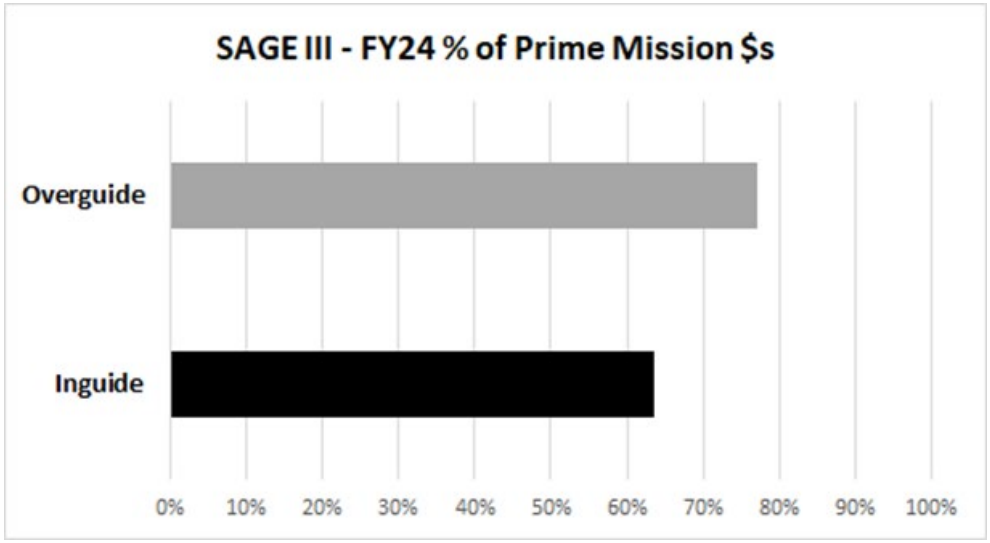




SAGE III In-Kind Support (non-ROSES):

- ISS (attached payload), ESA, NIWA (New Zealand)

SMAP

SMAP Summary: Soil Moisture Active Passive (SMAP) received a Cost Risk Rating of Medium/Low to relate concerns regarding In-guide reductions and HW degradation. The project included an Over-guide proposal to restore in-guide reductions, fund new A&A security requirements, and restore Near Real Time (NRT) functionality.

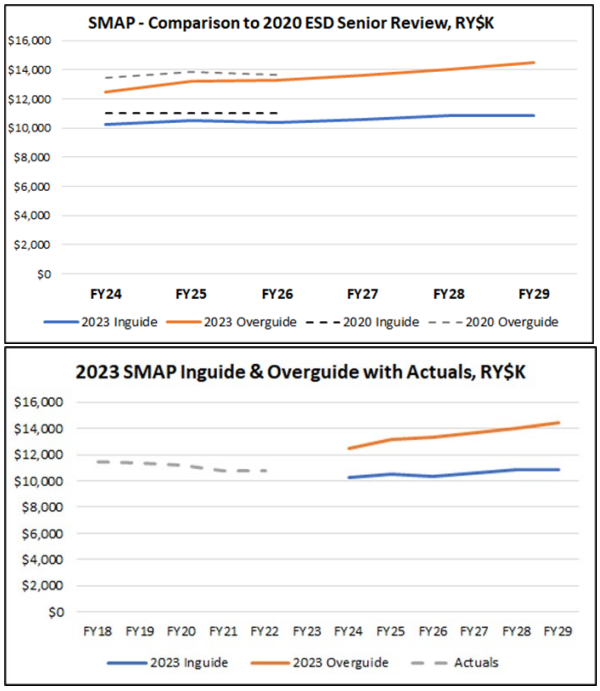
SMAP Findings:

- Proposal Basis of Estimate (BoE) were at a somewhat high level.
- Orbit lifetime expected through FY2029 with some HQ degradation
- In-guide reductions include no funding for hardware maintenance or disk storage growth due to data processing moving to the AWS cloud, no funding for NRT Ops support, no funding for redundant NRT processing in the AWS cloud, reduction in collision avoidance workforce; add risk, reduce response times, decreased redundancy, and a reduction to only a single science product update during the extension. No escalation for FY29

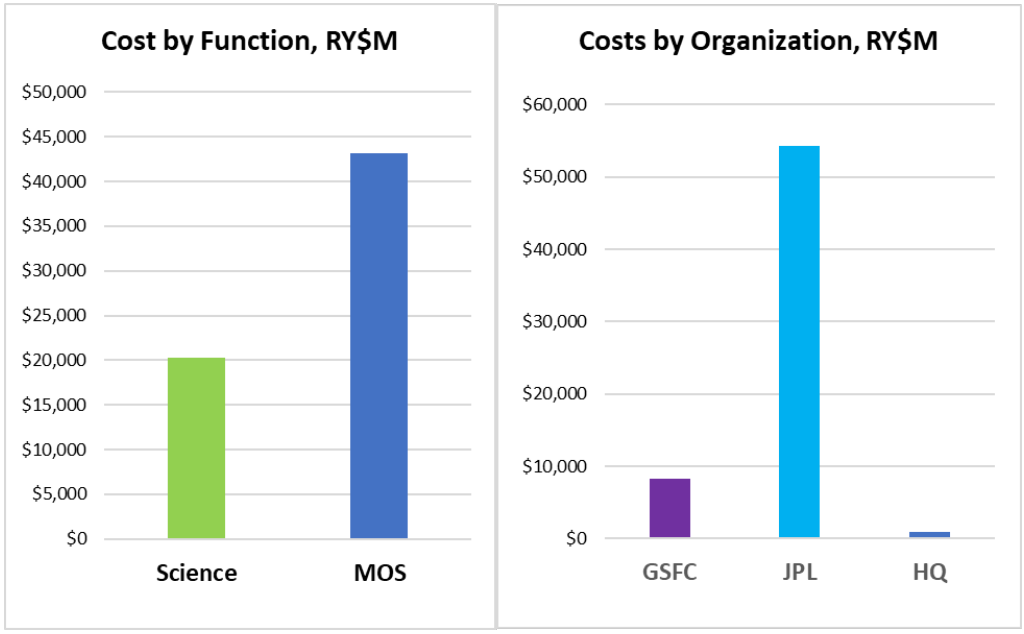
SMAP Evaluation Criteria Assessment:

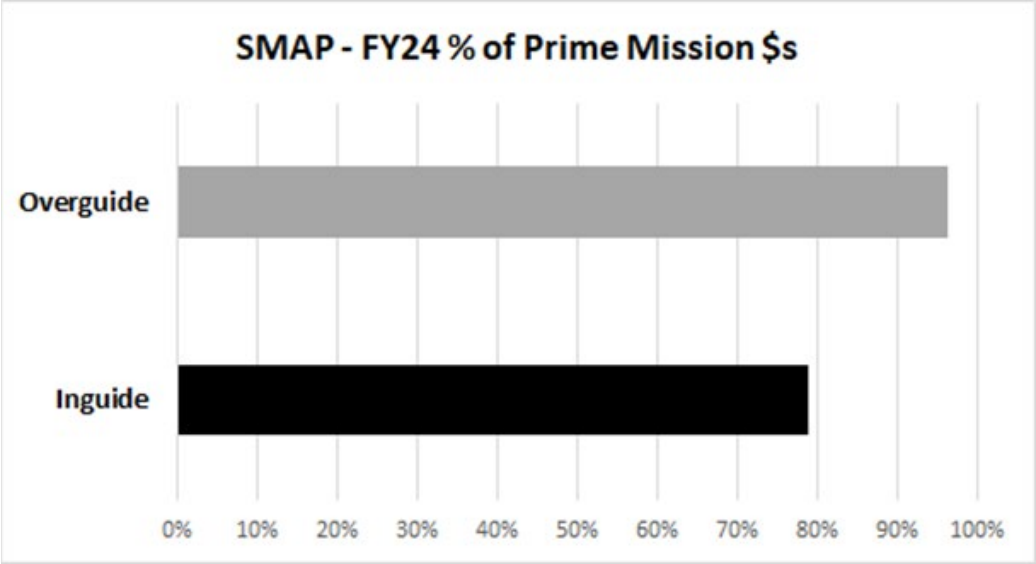
	Rating	Notes
Cost Risk Rating	Med/Low Risk	Concerns regarding Inguide reductions and HW degradation
Technical Risk		
HW Status/Perf/Lifetim	Med/Low Risk	Orbit lifetime to 2029; Some HW degradation
Mission Ops Plans	Med/Low Risk	
Cost Performance		
Cost Realism	Fair	BoE discussions somewhat high-level
Potential Cost Risks	Med $ Impact	Inguide reductions; such as no funding for hardware maintenance or disk storage growth due to data processing mvoing to the AWS cloud, no funding for NRT Ops support, no funding for redundant NRT processing in the AWS cloud, reduction in collision avoidance workforce; add risk, reduce response times, decreased redundancy, and a reduction to only a single science product update during the extension. No escalation for FY29
Overguide Request?	Yes	Restores Inguide reductions and funds A&A activities imposed by new NASA cybersecurity requirements; maintain the FY24 workforce profile through entire mission extension period, reinstate the capability to perform annual algorithm updates and their associated Cal/Val and reprocessing campaigns, reinstate flight ops staffing levels required for conjunction risk mitigation, and restores NRT functionality that is required by the USAF
Contributions? (*beyond ROSES*)	Yes	NASA NEN support (outside requested budget), NSIDC and ASF DAACs, CARA
Risk from Inguide Reductions	Med/Low Risk	~24% Inguide reductions spread evenly across the board to all SMAP elements

SMAP Cost and Request:



SMAP Cost Analysis Comparison:





SMAP In-Kind Support (non-ROSES):

- NASA NEN support (outside requested budget), NSIDC and ASF DAACs, CARA

TSIS-1

TSIS-1 Summary: Total and Spectral Solar Irradiance Sensor (TSIS-1) received a Cost Risk Rating of Low. The project included an Over-guide proposal to enable new Spectral Solar Irradiance (SSI) observations in the 2400-2800 nm range.

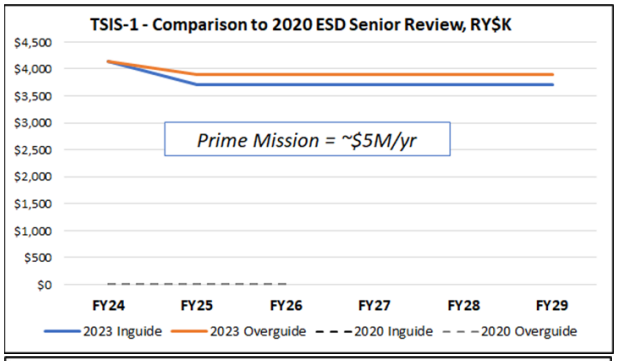
TSIS-1 Findings:

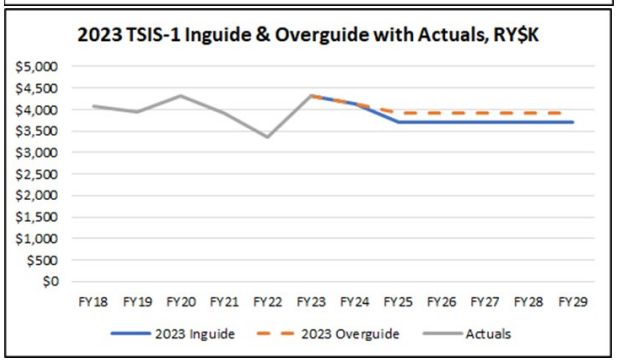
- Proposal included a reasonable Basis of Estimate (BoE)
- Instruments and subsystems are healthy, with an expected operational lifetime beyond 2028
- Currently on ISS ELC-3 location; In-guide reductions add some risk
- Over-guide proposal is relatively small at $200K/year
    - All increases in the science area
- Flat year over year budgets do not mitigate inflation impacts
- In-guide proposal in family with project cost actuals since FY18
- Agreements in place to host the payload on the International Space Station (ISS) throughout the senior review period.

TSIS-1 Evaluation Criteria Assessment:

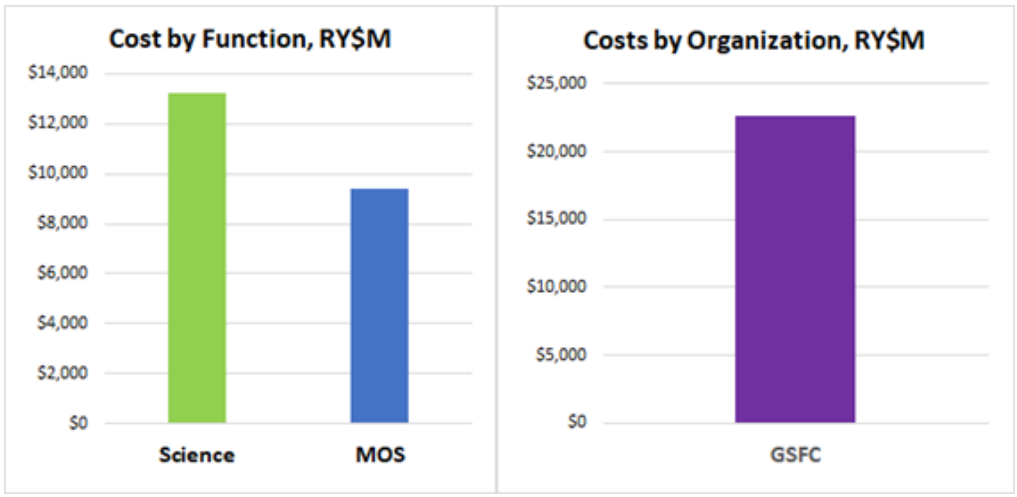
	Rating	Notes
Cost Risk Rating	Low Risk	Request appears reasonable
Technical Risk		
HW Status/Perf/Lifetime	Low Risk	Instruments and subsystems are healthy, with an expected operational lifetime beyond 2028
Mission Ops Plans	Low Risk	Currently on ISS ELC-3 location; Inguide reductions add some risk
Cost Performance		
Cost Realism	Good	Reasonable BoE
Potential Cost Risks	Low $ Impact	Reductions made to Inguide & Overguide requests add risk
Overguide Request?	Yes	Enables new SSI observations in the 2400-2800 nm range. $200K/year.
Contributions? (*beyond ROSES*)	Yes	ISS (attached payload)
Risk from Inguide Reductions	Med/Low Risk	Inguide reductions add potential for longer data gaps, delayed response time to ISS events, and delays in identifying and resolving any new anomalies

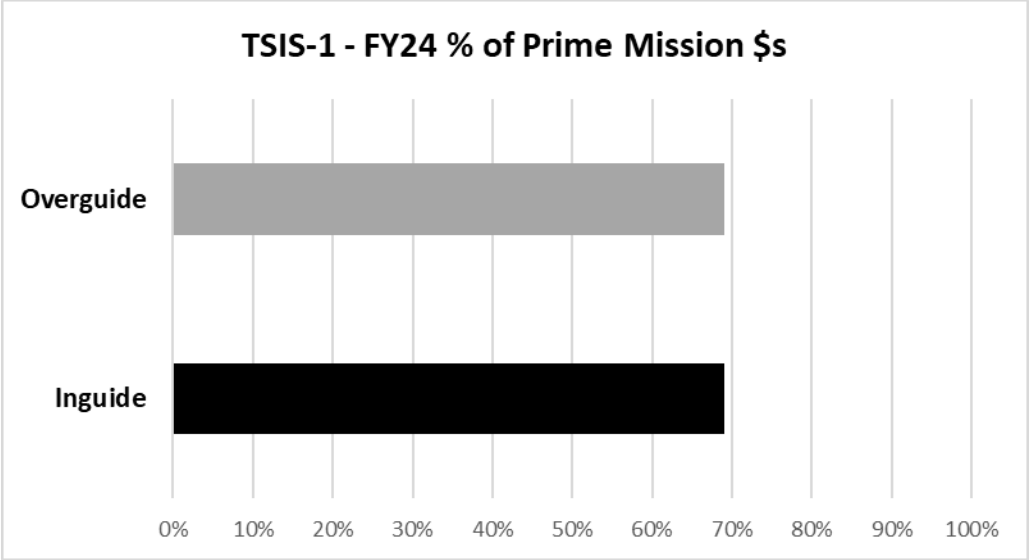
TSIS-1 Cost History and Request:





TSIS-1 Cost Analysis Comparison:





TSIS-1 In-Kind Support (non-ROSES):

- ISS hosted payload

APPENDIX 3

Detailed Science Reviews

A3.1 Aqua

A3.2 Aura

A3.3 CYGNSS

A3.4 DSCOVR

A3.5 GPM

A3.6 GRACE-FO

A3.7 ICESat-2

A3.8 OCO-2

A3.9 SAGE III

A3.10 SMAP

A3.11 Terra

A3.12 TSIS-1

Detailed Science Reviews

A3.1 Mission: Aqua

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation as currently baselined.	Continuation as currently baselined.

Overview

Since its launch in May 2002, Aqua has provided high-quality data from its suite of remote sensing instrumentation. Three of its original six instruments (AIRS, CERES, and MODIS) continue to perform excellently, while a fourth, AMSU, is still operating but with only 9 of its original 15 channels producing good data. It is planned for Aqua to operate until July 2026 when data collection will cease in anticipation of "passivation" in September 2026 and eventual de-orbiting. Over the next three years the equator crossing time will slowly drift from 1:30pm to 3:30pm, resulting in challenges to ensure time series are consistent, but also great opportunities to explore the diurnal cycles and Earth system physical processes.

AQUA continues to provide a wealth of high-quality data products (87 in total) covering all aspects of Earth science from all six of the NASA Earth Science focus areas and provides unique timeseries stretching back 21 years. Its strength is in the high quality of the data collected; the high quality of derived geophysical parameters based on two decades of improvements and experiences; and the 21-year time series of dozens of key datasets. Combined with the potential for innovative new science during the period of drifting equator crossing times, there is a very strong case for continuing the 21-year Aqua data record for three more years.

Scientific merits: Excellent

Strengths

Aqua data are very highly regarded by the scientific community. Over 13,000 Terabytes of Aqua data have been distributed to over 500,000 users in 2022 alone. The vast majority of these data were from the MODIS instrument. In the last three years there have been over 6000 publications produced using Aqua data.

Aqua data is extensively used in NASA's six Earth Science Focus Areas. These include

- Atmospheric composition: AIRS detects CFC-11, O_3, CO, CH_4, N_2O and NH_3 and is crucial in monitoring long term trends of these species. MODIS is a key data source in improving estimates of biomass burning and air quality monitoring.
- Weather and dynamics: AIRS plays a crucial role in gravity wave research including the unique signals observed during the 2022 Tonga eruption. The radiative fluxes observed by CERES helps evaluate differences between NWP

models. Both AIRS and MODIS allow remote sensing of cloud and process-based studies such as convective systems and the core temperature structure of tropical cyclones.

- Climate Variability and Change: AIRS temperature and relative humidity retrievals and CERES fluxes are extensively used in studies of climate processes and trends. Recent studies have also used AIRS radiances directly, comparing with trends in the synthesized radiances from reanalysis systems. Long term trends in CERES fluxes have shown a doubling of the Earth's Energy Imbalance since 2005. MODIS gives invaluable information on the long-term trends of aerosol and land-surface temperature monitoring.

- Water and Energy Cycle: Water cycle studies are informed from water vapor retrievals from AIRS. e.g., HDO/H2O ratios derived from AIRS help inform the Amazon water balance across timescales. MODIS and AIRS provide long-term time series of cloud optical properties.

- Carbon Cycle and Ecosystems: CO_2, CO and CH_4 AIRS retrievals are used in carbon cycle studies. MODIS provides extensive monitoring of vegetation properties for both land and ocean (ocean color products), and marine phytoplankton.

- Earth Surface and Interior: AIRS and MODIS track land, sea, ice and snow temperatures as well as volcanic emissions.

Radiances from AIRS and cloud-tracked winds from MODIS are operationally assimilated at Numerical Weather Prediction centers as well as contributing to re-analysis efforts.

AIRS is a Global Space-based Inter-Calibration System (GSICS) reference sensor used in cross-calibration of other infrared instruments.

Weaknesses

The capability of Aqua instruments are partly replicated on satellites in the JPSS constellation. AIRS is a close analog to the Cross-track Infrared Sounder (CrIS), although there are some minor differences due to CrIS being an interferometer and AIRS being a grating spectrometer; AMSU has flown on multiple NOAA satellites and is now superseded by ATMS on the Joint Polar Satellite System (JPSS) series; VIIRS is the successor to MODIS (although VIIRS is missing some MODIS channels around 0.4 to 1.0 µm, 7µm and 13µm, resulting in some products having lower quality and some unique MODIS products such as natural fluorescence of chlorophyll-a and Photochemical Reflectance Indices not being available); CERES flies on JPSS as well.

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

The benefit to continued operation of the Aqua system in the next three years is twofold:

1) Continued long term monitoring of all aspects of the Earth system with consistent instrumentation and algorithms.
2) As the MLT drifts to later in the day, Aqua observations (through comparison with other satellite products) will provide additional information on the relevant diurnal cycles and processes.

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

Strengths
AIRS, CERES, and MODIS measurements contribute to 10 of the 22 Targeted Observables of the 2017 Decadal Survey through the measurement and long-term monitoring of aerosol and cloud properties; ocean biological studies; polar winds; observations of clouds, humidity and precipitation; greenhouse gas monitoring (CO_2 and CH_4); and trace gas monitoring. Efforts are underway to ensure that time series are continued using successor instruments.

Weaknesses
No major weaknesses.

Standard data product quality: Excellent

Strengths
The status of the Aqua datasets is excellent. As stated above AIRS, MODIS, and CERES between them produce 87 high-quality data products that are routinely used by thousands of researchers worldwide and which have produced over 6000 presentations in the last three years alone. The quality of AIRS measurements is such that it is considered a GSICS reference sensor and is extensively used to ensure consistent calibration between infrared sensors in both geostationary and polar orbits.

Weaknesses
There is some uncertainty regarding the quality of data products as the equator crossing time drifts to later in the afternoon. While the mission team is confident that quality can be maintained, the team will need to closely monitor products to ensure that MLT drift does not introduce systematic biases in the data products.

Technical Performance: Excellent/Very Good

Strengths
The satellite is in good shape to operate until September 2026 when data collection will cease in anticipation of "passivation". AIRS and MODIS continue to work extremely well, as does CERES apart from one of the two shortwave (SW) modules.

Weaknesses
The Humidity Sounder for Brazil (HSB) and Advanced Microwave Scanning Radiometer-EOS (AMSR-E) are no longer functional, the shortwave side of CERES FM-4 is not functional (but FM-3 is still working), and AMSU is missing six channels. There are a small number of technical challenges that are not expected to cause issues: there is a software clock rollover in 2026; the MODIS solar diffuser door has exceeded its lifetime design for number of operations; and small power drops in the Electrical Power Subsystem (EPS). The proposed change from 24/7 to 12/7 operations is expected to result in only a very small loss of data (<1%).

Cost Performance
We concur with the Cost Panel's evaluation.

Operational, Applications, and Non-research Value
The National Interests Panel determined that Aqua was the second most important mission being reviewed. We concur with this assessment of the high operational utilization of this mission.

As noted by the National Interests Panel, Aqua products (mostly MODIS products) are used operationally by most agencies polled. Products that are used operationally include: reflectance and bio-indicators; water color and clarity; land properties; wildfire and flood risk prediction; wildfire detection and emission monitoring; polar winds; snow and ice coverage; sea surface temperature; and direct use of radiances.

As AIRS products will no longer be available after 2026, it is imperative that users transition in a timely manner to similar products from JPSS and other satellites where possible.

Other Comments
The Aqua team submitted a detailed and comprehensive proposal that was more than sufficient for this review.

A3.2 Mission: Aura

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation as currently baselined.	Continuation as currently baselined.

Overview

Though launched in 2004, the Aura satellite continues to perform well. The two remaining instruments on Aura, the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI), are in excellent health providing high-quality observations, continuing a long-term data record, and new science. There have been no significant changes since the last senior review. Aura's orbital drift is expected to be minor and handled by retrieval algorithms.

With TEMPO launched in 2023 and TropOMI in 2017, it is important to continue the OMI observation record to provide continuity with the data sets from the newer instruments. This will be especially important for studies investigating climate impacts on air quality and human health and global events similar to the COVID pandemic. Keeping Aura operational will also minimize the gap between the current satellite record and upcoming missions such as ALTIUS, PACE, and TSIS-2. MLS provides many high-quality data products that are unique in the Program of Record such as vertical profiles of O_3, H_2O, ClO, HCl, N_2O, HNO_3, and SO_2, some not observable by the current suite of satellites. MLS is the only instrument to make daily profiles of stratospheric water vapor and O_3. These data are still providing insights into stratospheric composition and dynamics.

Additionally, data from OMI and MLS are used operationally by the NOAA Washington Volcanic Ash Advisory Center (OMI SO_2 and AI), NCEP global weather forecasting (OMI O_3), and MLS products are used for assimilation and validation by ECMWF's Copernicus Atmosphere Monitoring Service (CAMS).

It's important to note that OMI data are being increasingly used in epidemiologic analysis of human health. Satellite observations provide spatial coverage lacking in surface measurements of air pollution. Investigating a possible relationship between climate/air pollution/human health requires a long-term data record. While some of the satellite observations of surface O_3 precursors (e.g., tropospheric column NO_2) will be continued by newer satellites, it is vital to understand any differences in the data records as the health community moves forward with these types of studies. As stated in the 2017 Decadal Survey "*Satellite data for atmospheric composition from instruments on Terra, Aqua, and Aura, in combination with advanced atmospheric models, have provided the basis for quantifying the global burden of disease from air pollution*".

Scientific merits: Excellent

Strengths

Aura data are highly regarded in the scientific community and have led to ~4150 peer-reviewed journal articles with over 800 papers published within the last three years. Since the last senior review, MLS observations have been central to numerous studies of these events. For example, MLS team members led high-profile papers describing MLS observations of:

- The record injection of highly polluted air into the lower stratosphere by pyro-convection during the catastrophic December 2019/January 2020 "Australian New Year's" (ANY) fires [Schwartz et al., GRL, 2020]
- Prolonged and pervasive perturbations in lower stratospheric chlorine chemistry following the ANY injection [Santee et al., GRL, 2022]
- Direct injection of exceptional amounts of water vapor into the lower stratosphere following the January 2022 Hunga Tonga–Hunga Ha'apai (HT-HH) eruption [Millán et al., GRL, 2022]
- Further prolonged and pervasive perturbations in lower stratospheric chlorine chemistry following the HT-HH water vapor enhancement [Santee et al., JGR-A, submitted]
- The exclusion of the HT-HH plume from the 2022 southern polar vortex, precluding it from impacting the 2022 Antarctic ozone hole [Manney et al., GRL, in revision]

Some highlights from OMI include:

- Continued science- and trend-quality data used for numerous scientific research areas and applications, including impacts of societally-relevant events (e.g., COVID-19 lockdowns; see OMI team's COVID website: https://so2.gsfc.nasa.gov/no2/no2_index.html) on atmospheric composition.
- Transition from KNMI to Goddard Space Flight Center (GSFC) for instrument operations and L1b processing.
- Collection 4 L1B has been delivered. [Improvements for 1) irradiance goniometry correction; 2) radiometric calibration to account for small optical degradation; 3) dead and random telegraph signal (RTS) pixel flagging; and 4) handling of transients.]
- Development of high precision OMI SSI data. Their high spectral resolution makes them important for development of the next-generation solar models and characterization of the unusual solar cycle 25 (expected to peak in 2025).

Looking forward, MLS daily profiles of stratospheric water vapor and O_3 will provide important insight into the impact of the Hunga Tonga-Hunga Ha'apai (HT-HH) eruption on stratospheric ozone. HT-HH is unique in the satellite era; the underwater eruption may lead to an increase in warming due to a ~10% increase in water vapor injected directly into the stratosphere, while having a smaller SO_2 loading than eruptions of comparable magnitude. It is expected that the increased stratospheric humidity will lead to more polar stratospheric clouds (PSCs) and subsequent chlorine activation. Thus, HT-HH could increase wintertime polar ozone loss. Extending the mission will allow MLS to monitor

all aspects of this process; tracking the water vapor plume, and subsequent changes to HCl and ClO, and finally decreased O_3.

Additionally, maintaining the continuity of the MLS O_3 profiles and total column O_3 from the OMI data record is important for monitoring the spatial and temporal evolution of the ozone layer as ozone recovery competes with a changing climate. These data are still of excellent quality.

TEMPO retrieval algorithms have been significantly influenced by OMI and there is some overlap in personnel between the OMI and TEMPO science teams. Extending the Aura mission will allow the OMI team to help with calibration of the TEMPO L1B radiances and validation of TEMPO data products as they become available.

Weaknesses
There are newer satellites (e.g., TropOMI) making similar observations as OMI at roughly the same time of day though with better spatial resolution. The communities that currently rely on OMI data products need to switch to the newer satellite retrievals. The review committee questioned whether there has been enough overlap to understand possible biases in the older and newer satellite records. Continuity of data products was one of the main concerns of the review panel as the community switches from OMI to TropOMI, TEMPO, etc. The mission team stated that while there has been enough overlap in data sets some biases remain that have not been completely understood. TropOMI radiances continue to be affected by spectral aging.

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

Strengths
MLS provides datasets that contribute to the research objective in NASA's Science Plan and observing system priorities highlighted in the 2017 Decadal Survey for Earth Science and Applications from Space. There are no new instruments planned this decade from any US or international space agency with similar capabilities to MLS (ALTIUS will measure O_3 only in solar occultation). Aura's science objectives meet part of the science and applications priorities of the 2017 Decadal Survey for "*Ozone and Trace Gases: Vertical profiles of ozone and trace gases (including water vapor, CO, NO_2, CH_4, and N_2O) globally and with high spatial resolution*". Observations from MLS make vital contributions to understanding the chemical and dynamic processes that affect stratospheric O_3. Second, OMI solar spectral irradiances (SSI) contribute to "climate sensitivity and inter-calibration of in-flight radiometers" for the "*Radiance Intercalibration*" targeted observable.

Weaknesses

No significant weaknesses.

Standard data product quality: Excellent

Strengths
The data products from both MLS and OMI are ranked excellent. There have been no significant changes since the last review and the data are expected to be of high quality for the remainder of the mission. The "OMI row anomaly", first identified in 2007, has been well characterized and the affected data are flagged. The MLS team is working on a version 6 (V6) retrieval algorithm that will address issues with the N_2O observations in the lowermost stratosphere caused by a slow drift in the MLS 190-GHz measurements. A correction in the V5 algorithm reduced this problem in the H_2O retrievals. V6 will focus on a correction to the N_2O profiles. V6 will likely be the final version so the MLS team is revisiting other MLS products to confirm that no substantive final modifications are needed. The current budget provides a timeline for submission of the final, reprocessed data set, approximately 19 months after the project shutdown order is given.

Weaknesses
No significant weaknesses.

Technical Performance: Excellent/Very Good

Strengths
The satellite is expected to operate until mid-2025 when it may no longer have sufficient power generation from the solar array, though it is possible that there will be enough power through mid-2026. These dates will be reevaluated in 2024. Regardless, there is no expected degradation in data quality until then. There is a well-developed plan for passivation of Aura, final reprocessing of the MLS and OMI datasets, and meeting the agency reentry requirement of 25-years. Orbital drift is expected to be minor, ~25 minutes by mid-2025. Aura will meet the agency reentry requirement of 25-years.

Weaknesses
The current budget moves away from 24×7 operations which brings a risk of data loss if a problem occurs overnight. The flight operations team will no longer be able to chase data lost due to communications or ground stationed problems (expected to be ~1% of all data).

Cost Performance

The panel concurs with the sub-panel assessment. During the June review panel, the Aura team noted that the lifetime of the satellite is expected to continue until 2026, a year later than what was planned. The panel did not include this information in this evaluation and expects this request for additional resources to continue the mission past 2025 to be made directly to NASA.

Operational, Applications, and Non-research Value

The review panel concurs with the National Interests sub-panel assessment.

Other Comments

The proposal was comprehensive and clearly detailed the ongoing science activities as the mission winds down.

The review panel noted that many of the newer satellite missions rely on the expertise of the MLS/OMI retrieval algorithms and the expertise of the science teams. It was suggested that NASA find some way to maintain this expertise past the lifetime of the Aura satellite to assist the new and upcoming satellite missions.

A3.3 Mission: CYGNSS

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation with reductions to the current baseline.	Continuation with reductions to the current baseline.

Overview

CYGNSS is a low-cost Earth Venture mission launched in December 2016. The mission was originally designed with the goal of providing critical wind measurements in the core of Tropical Cyclones (TCs) in rainy environments, with a frequent revisit time for monitoring rapid intensification phases. The mission core objective was to provide valuable observations for hurricane research and forecasting, by filling the observational gap in the inner-core of TCs where most of the available satellite sensors at the time of CYGNSS launch did not provide sufficiently accurate winds due to intense rain. Since launch, the mission objective has expanded to include new applications over land (i.e., soil moisture, surface inundation, wetlands, vegetation) and additional ocean products such as surface heat fluxes. The original mission lifetime of two years was first extended by 18-months (out-of-cycle), and then by an additional 3-years following the findings of the Senior Review panel in 2020 (SR2020).

To achieve the original mission core objective, the CYGNSS mission was designed as a constellation of eight small satellites (receivers) on an inclined orbit (35^{o}) to measure ocean surface winds over the tropics using the existing network of the Global Navigation Satellite System (GNSS) as transmitters. The principle of operation is a bi-static L-band radar: the GPS reflected signals respond to ocean surface roughness, from which wind speed is retrieved. Over land, the reflected signal is sensitive to soil moisture content and water bodies. The L-band frequency is mostly insensitive to rain, therefore allowing observations even in the inner-core of TCs.

The CYGNSS receivers enable the first bi-static GNSS-R radar system in space, and as such, there is great value in supporting an extended operation. The mission has the potential to be a significant resource for refining new remote-sensing methodologies and new data products from small, low-cost satellites.

Most of the past data products and proposed works, and accomplishments are only of research-grade quality. Some of this is understandable given that CYGNSS produces new types of retrievals. Nevertheless, the team activities in the past three years seem to have focused primarily on building new versions of research-grade datasets, rather than on careful validation and on bringing the products to a level of accuracy required for robust science investigations and (potential) use in operational settings. It is important to note that, being a low-cost mission, CYGNSS was not originally designed to provide data with short latency (Near Real Time) as required for operational forecasting or storm monitoring. The value of long-latency data products currently lies in post-storm analyses and the impact of CYGNSS data assimilation for historical events.

Since the prime mission, the core objectives seem to have shifted to a lower priority, with significant resources currently being focused on the new land products and applications, rather than the TCs. This conclusion had already been identified as a potential weakness in the SR2020 and has not been sufficiently addressed by the project team since then.

Nonetheless, the mission team has been very active and must be commended for its efforts. The new inundation product is unique and has important potential applications; the soil moisture estimates in the tropical/subtropical regions can fill the gap if other more dedicated missions (i.e., SMAP) fail or their data quality degrades. Furthermore, high revisit inundation measurements under vegetation are unique and highly relevant for a range of science questions in hydrology and carbon cycle studies. These new land-oriented capabilities and the potentially important applications in data assimilation provide confidence that the team can focus on validated products that the scientific community can use with confidence and address the weaknesses in the next funding cycle.

We suggest that the mission be extended with a reduced in-guide budget. The value to NASA and the scientific/operational community for the core mission objective still has potential, but the data quality is less than optimal, despite the mission being at a mature stage. During the second extended mission, the panel advises the project team to prioritize activities that lead to validated final data products and their science applications, rather than devote significant resources to new products/activities, such as a blended soil moisture product or river width and slope. Suggested high priority activities are to: finalize low level (L1, L2) data products and heat flux products, assess the ability of the storm-centric data product to monitor storm intensification, continue studies of assimilation of low-level data products, finalize and validate one inundation product, finalize and (only if budget allows) validate one soil moisture product.

The panel noted that the varied nature of the data products (land versus ocean, low level versus high level) results in a varied value to different science communities. As a consequence, CYGNSS had a wider spread in the panel scores for scientific merit compared to other missions.

Finally, although the raw IF data proposed in over-guide (option 2) could provide potentially interesting measurements of river width and slope, the panel was concerned that this would only serve to further distract the mission team from generating high-quality data. Furthermore, there was no clear validation plan for these data.

Scientific merits: Good

The new type of measurements, and the wide range of applications (surface winds, soil moisture with high revisit time, inundation, and even potentially riverine width at high resolution) they allow, was widely deemed by the panel to have substantial scientific merit. The scientific merit is further enhanced by the commercial interest in GNSS-R receivers and the proposed European HydroGNSS mission, suggesting the eventual possibility (though not certainty) of a long L-band GNSS-R record. The CYGNSS team has done an excellent job identifying new scientific uses of the GNSS-R data. Furthermore, for the tropical cyclone and inundation applications, the datasets are unique in their frequency of coverage. The ability of CYGNSS to derive inundation at high revisit under vegetation, in particular, is not matched by any other instrument. Furthermore, the tropical cyclone and inundation applications are related to weather extremes, and their scientific investigations would thus benefit from the longer record created by an extension.

However, the panel mostly also felt that (as described further below in the data products section), so far, the mission's focus on disperse research-grade efforts (with many versions of each dataset, not all of which are public) has limited the scientific utility of the data. Some delay in operational data production and scientific use was to be expected because the GNSS-R data produced by CYGNSS have relatively little heritage. Nevertheless, the panel felt that the mission's past and proposed activities to support parallel research into multiple data and algorithm versions of each product was also a substantial contributor to the limited utility of the data. As a result, there is a relatively large gulf between the potential scientific merit and the degree to which this has been realized during the previous extension period. This gulf was reflected in a relatively large range of scores by the different panelists.

Since SR2020, there have been several interesting studies by the CYGNSS-competed ROSES science team members: studies of the relationship between surface heat fluxes and convective or extratropical storm systems, investigation of the impact of surface heat fluxes on propagation of the Madden and Julian Oscillation (MJO) across the Maritime continent; assimilation of the L2 wind retrievals into hurricane prediction models; a novel approach of assimilating of the L1 Doppler Delay maps using a physics-based forward model; the assimilation of CYGNSS winds into storm-surge models; the creation of several research-grade soil moisture products; models of GNSS-reflectometry signals for surface topography, including vegetation; and a study demonstrating that improved estimates of water bodies (using CYGNSS estimates) are also important for (water-dependent) land methane emission models. The relevance of the outcomes of these scientific investigations is dependent on the data quality.

An extended mission would ensure that the data products reach a maturity level required for assimilation into numerical prediction models at the global scale and for TC predictions, and that the land products can be used with confidence.

Strengths

The CYGNSS mission is the first-ever GPS reflectivity space-based mission using signals of opportunity and has a pathfinder-role for future missions based on similar methodologies. It is low cost, and relatively low risk, with redundancy provided by multiple copies of the spacecrafts. The rapid-repeat time and sampling focused on the tropics allow frequent views (~hourly, rather than once/twice daily as in polar orbiters) of rapidly evolving systems such as TCs or land inundation during floods. L-band allows observations under rainy conditions, even during heavy precipitation events (tropical storms). This capability is important if NASA expands interest into weather/fast-evolving systems. Interesting new land products include: inundation, wetlands, rivers, and soil moisture. The additional new heat fluxes products allow new studies of air-sea interaction, and intraseasonal/interannual variability (MJO, ENSO). If data maturity is reached, the CYGNSS retrievals create an opportunity for assimilating wind products into a multi-agency new generation of NWP models (i.e., Unified Forecast System [UFS], Hurricane Analysis and Forecast System [HAFS], and Joint Effort for Data assimilation Integration [JEDI]) and, if Near-Real-Time latency is achieved, even into TC forecast models. The storm-centric wind product can be used for post-storm analyses and for the basis of a TC database. The possibility of assimilation of L1 delay Doppler maps (DDMs) is new and interesting, as it would reduce the impact of the assumptions in the retrievals (a priori information). The team also proposes a future synergy with the TROPICS mission, for better understanding of TCs and joint efforts in data assimilation. The future overlap with the planned NISAR mission (which includes an L-band

synthetic aperture radar [SAR]), provides opportunity for cross-calibration. The inundation products are unique and have potentially important applications (i.e., floods, methane), as described below. Finally, the mission team, with members from different disciplines, has been very active, has produced numerous publications, and it is expected to continue this level of productivity during the extended mission.

Weaknesses

The major weakness noted in the SR2023 is that the team seem to have shifted the core mission objective (TC observations) to a lower priority. Most efforts seem spent on building on other products (i.e., land products; heat fluxes) rather than ensuring the high quality of any individual product. This weakness has already been stated in SR2020 and the panel noticed that, since then, it has not been convincingly addressed. Additionally, it was noted that the uniqueness of data in TCs is not as strong as stated: since CYGNSS launch, there have been several high-quality satellite observations in TCs (i.e., SMAP and SAR provide winds in TCs in the range 10-70 m/s, they are unaffected by rain and currently used in operations, by the US Navy and the Joint Typhoon Warning Center; Advanced Scatterometer (ASCAT) and AMSR2 are also available in TCs, just slightly affected by rain). The storm-centric dataset is interesting for post- and potentially NRT-storm analysis, but its quality has not currently been demonstrated sufficiently clearly to allow for such investigations. The data quality of all products (ocean winds, soil moisture, heat fluxes and the new inundation products) has not been sufficiently investigated to allow their potential scientific merit to be realized. The panel was concerned that the proposed activities seemed to exacerbate rather than ameliorate these concerns. There was no clear plan on how to validate the proposed river width/slope products, for example. Furthermore, both the inundation and soil moisture efforts planned to continue to support algorithm development along a large range of parallel lines for each product. The panel was concerned that so many parallel efforts would impede and delay efforts to rigorously demonstrate the quality of any one individual dataset (and if needed, to improve each individual algorithm), to make these different datasets publicly available, and for the scientific community to understand the different datasets well enough to use them. This concern was felt analogously for both the proposed inundation and soil moisture efforts. Furthermore, the proposed soil moisture work aimed to produce a blended product from a range of datasets with different time spans, resolutions, etc. This would mean that any blended product would be too variable in composition (and thus quality/statistics) to be useful, and that the many parallel efforts would limit the budget and time available for careful validation and dissemination of any single product.

Relevance to NASA Science Goals & the 2017 Decadal Survey: Very Good

The past and proposed research applications fit into the NASA SMD categories of "Weather and atmospheric dynamics", and potentially into "Carbon cycle and ecosystems". Future applications also fit into some focus areas of the DS2017: "Climate variability and change", "Global hydrologic cycle and water resources", "Weather and air quality" and "Climate variability and change".

Strengths

The potential ability to observe winds in the inner-core of TCs is very relevant to weather and atmospheric dynamics. Soil moisture products are a relevant added product. Atmospheric winds, ocean surface winds, and soil moisture are all Targeted Observables in the Decadal Survey

Weaknesses
The research applications depend on the data quality, which at this time has not been sufficiently demonstrated.

Standard data product quality: Fair

Due to the innovative nature of the observational methodology, unforeseen calibration issues and a unique sampling geometry, early on the wind retrievals proved to be more challenging than expected. The mission team explored different algorithms for the wind data products. A major accomplishment in the last 3 years, since the SR2020, has been a real-time calibration of the GPS transmitted power, which led to new recalibrated L1 data, and improved L2 wind products. An additional accomplishment has been the creation of a new Storm-Centric Gridded wind data product (SCG), which reorganizes the tracks sampled over a Tropical Cyclone in a time window of +/- 6 hours into storm-centric maps, and a preliminary (not public) version of merged storm (SCG) winds "nested" into a global low-wind product. These are potentially useful for historic storm analysis and data assimilation. Using the CYGNSS ocean surface wind retrievals, the mission team developed a new science-oriented product: the ocean surface latent and sensible heat fluxes. The mission team also moved in a new direction and explored data products derived from the GPS signal reflected over land: soil moisture, wetlands, river, and inundation products.

All the CYGNSS data products are still research-grade or have less than optimal accuracy/precision for robust science investigations. Data are uploaded to the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) with a latency of 1-6 days. This prevents any operational application at this time. The prime limiting factor for NRT data is the downlink segment, which meets the original 6-day requirement. The CYGNSS team is developing a plan to reduce latency and possibly achieve a NRT data distribution to operational agencies.

Large calibration biases were noted in the L2 and L3 products in previous versions (V2.1 and V3.0), requiring track-wise bias corrections (Said et al, 2019, leading to NOAA CYGNSS wind product, and CYGNSS Climate Data Record [CDR]). These were addressed during the first extended period by accurately calibrating the GPS transmitted signals and developing new L1 and L2 V3.1 data. The aggregation of the L2 data into the SCG wind data product also serves as a quality control to remove residual inconsistencies among the observed tracks that fit into the aggregated window. These activities led to recent improvements in these data products.

As mentioned previously, the CYGNSS team has discovered several new applications of the data product since the primary mission. Because they are new applications for a relatively low-heritage data type, it is to be expected that turning these applications into carefully validated and publicly available data products takes some time. Still, in previous work, there has been relatively little focus on rigorous data validation rather than supporting new retrieval versions. The panel is concerned that if efforts continue to be divided across a high number of different algorithms and data versions, they will be of little value for science applications.

In summary, a high priority during the extended mission should be to devote significant efforts into an extensive validation and down-selection of the data products and ensure that the data

accuracy necessary for science and operational use is reached.

Strengths

In the past three years, since SR2020, the team has developed interesting new land products which include: inundation, wetlands, rivers, and soil moisture. An additional new product is provided by ocean surface heat fluxes (note that its quality depends on the quality of the wind products), which can be used for air-sea interaction, and intraseasonal/interannual variability studies. The wind products can be used for data assimilation into global and regional weather prediction models, provided a sufficient data quality is reached. The storm-centric wind product is unique and interesting, but prone to large uncertainties (see weaknesses). The L1 DDM observations also have potential for data assimilation. The inundation product is new and has potentially important societal applications (i.e., flooding) and significant scientific applications in terms of its potential for improved understanding of methane fluxes. While not unique as a retrieved variable (already available from MODIS, VIIRS and Sentinel-1), L-band inundation retrievals have the additional capability to penetrate into vegetation. Furthermore, CYGNSS has a much higher revisit rate than Sentinel-1 (and to a lesser extent, MODIS and VIIRS), which is particularly relevant since inundation dynamics can change rapidly during floods. Although there is not currently an inundation product that is publicly distributed on a DAAC, the application of CYGNSS data to inundation is newer than the soil moisture application, and the panel was optimistic that if (and only if) the team focuses on making a widely disseminated and carefully validated inundation product, this would have significant science and societal utility. The panel was pleased to see this among the mission's proposals for the extension period, and agrees that more than one dataset may be suited to be official (e.g. a fractional and a binary one), but noted that the current approach of having ~8 different products is so large that continuing along such a large number of approaches is likely to prevent sufficient resources and focus to perform validation at a level necessary for scientific use.

Weaknesses

The most important weakness relates to the data quality: the mission is still "relatively" young, but after 6 years of observations the data quality has not yet been sufficiently demonstrated, particularly for winds in TCs, but also regarding soil moisture and the new inundation retrievals. The long data latency (several days) currently prevents any operational applications in TCs, but the team is confident that shorter data latency can be achieved in the future. The storm-centric data is interesting but aggregating fast-moving storm features over several hours distorts the wind field, which can result in unrealistic TC size/shape. Due to the aggregation technique and possible data gaps over the storm's core, the SCG product seems to lead to very large biases in intensity (-20 to -30 m/s) compared to observationally-based International Best Track Archive for Climate Stewardship (IBTrACS) (see example Figures 13 and 14 from Mayers et al., 2023), that could have catastrophic consequences if used in operations. The team addressed this caveat of the SCG product by determining the storm intensity from fitting a wind parametric model to the SCG partial-view of the storm to infer the "actual intensity", with preliminary good results.

The promised ability to detect rapid intensification and accurate storm parameters (intensity/radii) has not been proven. This is a significant weakness as it relates to the core mission objective. The panel noted that an additional, albeit minor, potential weakness is also the approach of having two different wind algorithms (Fire Dynamics Simulator [FDS], young seas

with limited fetch [YSLF]) at different wind regimes: this could result in complications when assimilating CYGNSS L2 data for weather systems transitions from one regime to the other. The team recently created a preliminary merged L3 product for this purpose, which uses the FDS winds and smoothly transitions to the SCG winds in storm regimes. The accuracy of this product will need to be assessed before being distributed to the public and operational centers.

Regarding the land products, the soil moisture datasets have so far seen relatively limited validation beyond research-grade evaluations in sub-parts of peer-reviewed papers. This limits the utility of these products for further scientific research. The proposed work of blending multiple products, with different spatial resolutions and different temporal coverage, is likely to lead to severe swings in data quality between time periods and would likely prevent that data from being usable for further scientific application as well. While the panel thought there was potential value in the CYGNSS data for high temporal revisit soil moisture data, it was unclear to the panel whether the mission is on track to create these soil moisture products at a high enough quality and validation standard to be useful to the community.

Technical Performance: Excellent/Very Good

The system is in excellent health: seven spacecraft are still operating, with one failing in 2022 (lost communication). This configuration still meets the baseline requirements of at least six spacecraft. Normal operation is expected through and beyond 2027. There is no fuel onboard causing the spacecraft to drop by 4-5 km/year. The mission team reported that a 20 km drop in the next 5 years is not expected to affect the quality of science operations.

Strengths
No major concerns.

Weaknesses
No major concerns.

Cost Performance:

The mission extension is relatively low cost, with low risk. Nevertheless, the panel was concerned that the science components of the proposed budget (e.g., those outside mission operations) were not sufficiently focused on establishing carefully validated datasets that would be of most use to the wider community.

Operational, Applications, and Non-research Value:

Some operational applications for TCs or weather forecasts depend on the possibility of providing the ocean data in NRT. If that is not feasible, the science applications of the ocean products will be limited to post-storm historical analyses and research investigations, such as studies of storm formation and evolution, investigations of air-sea interactions, use of heat fluxes in data assimilation experiments, and analyses of intraseasonal and interannual variability of tropical winds and related geophysical variables. The land applications for societal benefit depend on the latency of the data. The benefit to scientific and societal applications also depends on a demonstrated data quality, which is unclear. For societal benefits, the new inundation

products may have important applications, and be of high national interest, if properly validated and provided with sufficiently low latency. As it stands, however, the panel did not feel that the mission's proposed plans during the extension would enable operational, non-science applications of the data.

Other Comments

The panel is concerned that the CYGNSS team is not properly planning/coordinating activities that can result in data quality that meets the standard for robust science applications. Several years after the end of the prime mission, there seems to be no urgency for a quality data product that can be of high interest to the TC forecasting/research community. This lack of data quality, rather than insufficient outreach activities, is possibly the main reason limiting applications. At the same time, the panel recognizes that some delays in dataset maturity are to be expected given the fundamentally new type of GNSS-R measurement from CYGNSS and is strongly supportive of continuing the mission given the key unique ocean winds and inundation applications. The panel was supportive of NASA giving strong direction to the mission to focus more on the key ocean winds and inundation applications and to reduce focus on soil moisture and other applications of more limited uniqueness, and for the mission to receive strong guidance that they need to focus more on improving, disseminating, and validating a small handful of products rather than a large number of parallel efforts.

A3.4 Mission: DSCOVR Earth Science Instruments

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation with augmentations to the current baseline.	Continuation with augmentations to the current baseline.

Overview

The Deep Space Climate Observatory (DSCOVR) was launched on February 11, 2015, to the first Sun-Earth Lagrange (L1) point, 1.5 million kilometers from Earth. From here it provides continuous solar wind measurements for accurate space weather forecasting, and observations of the full, sunlit disk of Earth from a new and unique vantage point. The DSCOVR mission is a joint venture between NOAA, NASA, and the U.S. Air Force. NOAA operates the spacecraft and performs operational space weather forecasting using DSCOVR's solar wind and magnetic field measurements while the Air Force provided the SpaceX Falcon 9 launch vehicle. NASA built the spacecraft, performed on-orbit checkout, and operates and calibrates the two Earth science instruments, the Earth Polychromatic Imaging Camera (EPIC) and the National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR). DSCOVR operated until June 27, 2019, when the degradation of the Miniature Inertial Measurement Unit (gyro) caused an eight-month hiatus until March 2, 2020. Since then, DSCOVR returned to full and continuous operation. The spacecraft is in good health and ready for years of more operation.

- DSCOVR continues to provide a new and unique vantage point for observing the full, sunlit disk of Earth multiple times a day.
- EPIC measures back-scattered radiation at 10 wavelengths (UV to NIR) enabling the retrieval of ozone, 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 spectrum), 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 that is provided primarily from satellites in LEO. These data provide a comprehensive global view of quantities such as atmospheric ozone and leaf area index and can also be utilized in a gap-filler role to cover the loss of other space-based observations.

Scientific merits: Excellent

Strengths

From the position at the L-1 Lagrange point, DSCOVR provides unique synoptic observations of the full sunlit disk of Earth continuously with a 1- to 2-hour cadence not available from any other platform. EPIC data products make it possible to study the diurnal variation of ozone, aerosols, cloud height, cloud reflectivity, the sunlit leaf area index, and fraction of photosynthetically active radiation absorbed by vegetation. In addition, EPIC provides an important dataset for

intercalibration of data to be obtained by TEMPO and two other Geostationary satellites, Geostationary Environment Monitoring Spectrometer (GEMS), and Meteosat. NISTAR observations provide for the first time a measure of the reflected and radiated energy by Earth near the critical backscatter directions. Decade-long measurements are critical for the study of the Earth's energy budget.

Both EPIC & NISTAR have addressed numerous issues raised during the past two Senior Reviews. Recent improvements have produced new Level-2 data products funded through ROSES. Level-2 products have matured significantly during the past two Mission extensions.

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

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 (Minor)
NISTAR retains a significant calibration offset when compared to CERES, although a method of correcting this offset has been determined. Resolution of this discrepancy is an activity that will be pursued during the upcoming Mission extension, so this is a minor weakness.

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

Strengths
The DSCOVR science objectives directly address the following Earth Science questions identified in the 2020-2024 NASA Science Plan and in the 2017 Earth Science Decadal Survey:

Energy Cycle. EPIC and NISTAR have the capability to measure factors affecting the Earth's energy balance by measuring the backscattered radiance and irradiance from the sunlit Earth. The accuracy of this determination is supported by how data from the well calibrated EPIC filter spectrometer agrees with the NISTAR whole Earth reflection of incident solar energy. [2017

Decadal Survey H-2]

Ecosystem Changes. EPIC measures the hourly solar leaf area index as a function of local time. This quantity is a measure of plant bioproductivity as a function of location and time that is unique to EPIC. [2017 Decadal Survey E-1]

Reducing Climate Uncertainty. NISTAR and EPIC provide a missing component of Earth's reflection of solar energy back to space at backscatter angles near 180°. This missing component is not captured by other Earth viewing satellites. [2017 Decadal Survey C-2]

Weaknesses
None.

Standard data product quality: Excellent/Very Good

Strengths
DSCOVR provides Level-1 data products that are calibrated and geolocated. These reflectivity/radiance observations are provided as images in 10 bands by EPIC or radiance time series by NISTAR. Based on comments from previous Senior Review panels, these data sets have shown significant improvement during the most recent extended mission time period.

An important example involves the NISTAR team's response to an offset between their results and those generated by CERES. During the most recent extended mission the NISTAR team has identified a process to correct the background offset in the NISTAR Level-1 calibrated data. This correction will be implemented during the next extended mission.

Level-2 data products are generated as part of the ROSES program. Due to improvements in Level-1 data quality, Level-2 product quality has increased as well. Most notably, Level-2 values of total column ozone, tropospheric column ozone, and UV aerosol index are now available. In addition, new Level-2 products have been released (photosynthetically active radiation [PAR] & Volcanic SO_2). Standard Version-3 EPIC Level 2 cloud products include a cloud mask, cloud effective pressure, cloud effective height, and cloud optical thickness. Leaf area index, normalized difference vegetation index, sunlit leaf area index, fraction of incident photosynthetically active radiation (400-700 nm) absorbed by vegetation, directional area scattering function, Earth reflector type index and canopy scattering coefficient at 443 nm, 551 nm, 680 nm and 779 nm are derived from DSCOVR EPIC L2 bidirectional reflection factor.

The panel noted that DSCOVR data sets could be used in a gap-filler role assuming ROSES based Level-2 products are ongoing or could be expanded.

Weaknesses (Minor)
NISTAR Level-1 calibrated data in 3 broad spectral bands still retains the offset described above but the NISTAR team has identified a solution to address this offset which is scheduled to be implemented during the extended mission.

Technical Performance: Excellent/Very Good

Strengths
The DSCOVR Spacecraft is in good health and has adequate fuel and pointing stability to continue through the next six years for continued operation through the extended mission. The spacecraft was placed in a Safe Hold in mid-2019 due to degradation of one inertial navigation system gyro but regular operations resumed after ~ eight months using new flight software to operate with the star tracker and sun sensor alone. Since that time, operations have shown the spacecraft point stability meets requirements to maintain data quality requirements. No other anomalies were reported.

The two instruments (EPIC & NISTAR) continue to operate nominally and provide continuous observations. Since they are relatively simple with minimal mechanisms, continued nominal performance is anticipated.

Weaknesses (Minor)
Spacecraft – A gyro failed in 2019 so navigation and pointing has relied solely on the star tracker and sun sensor. There have been minimal pointing errors since that time, so this is a minor weakness.

Cost Performance

DSCOVR is an extremely cost-effective mission in terms of Operating Mission Costs given that NOAA pays for spacecraft operating costs. In addition, all Level-2 data product development and processing is done through ROSES.

The panel felt that the DSCOVR (EPIC & NISTAR) budget should be augmented to retain or perhaps even exceed the over-guideline budget to ensure adequate mission management, uninterrupted processing of Level-1 data, and long-term provision of several Level-2 products. Currently, Level-2 data products are processed and provided only through proposals selected under ROSES calls. The DSCOVR mission did not fare well in the National Interests Panel assessment, mainly because many U.S. Federal agencies outside of NASA seem to be unaware of the DSCOVR data products. NASA and DSCOVR would benefit from a person who, under DSCOVR project support, could continue to process and supply, validate, and promote at international scientific meetings such as the American Geophysical Union (AGU) and/or the American Meteorolgical Society (AMS) a Level-2 product provided by DSCOVR, such as either total & tropospheric column ozone & UV aerosols, leaf area index & NDVI, or a radiative flux product. Project provision of a Level-2 product would allow DSCOVR to function in a manner close to that of all of the other missions reviewed by this panel.

Operational, Applications, and Non-research Value

As additional Level-2 data processing is accomplished through ROSES programs, DSCOVR observations may fulfill a gap-filler role in the case of loss of other flight resources.

Images of the Earth-Moon system from L1 have incredibly significant social value that is of

great benefit to NASA.

Other Comments

None.

A3.5 Mission: GPM

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation with augmentations to the current baseline.	Continuation with augmentations to the current baseline.

Overview

The Global Precipitation Mission (GPM) satellite has been providing valuable observations of storms and their impacts from the tropics into the midlatitudes (65°S-65°N) and at varying times of day since its launch in 2014. The two instruments on the GPM satellite are the Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI); together, they form the GPM-Core Observatory (CO). The DPR is the only weather radar in space, providing unique 3D measurements of storm structure and intensity. The exceedingly well-calibrated GMI employs a wide range of channels, allowing it to act as a calibration standard for a large suite of polar-orbiting passive microwave sensors. The production of the last planned algorithm version (V8) will happen during the extended mission timeframe and will incorporate final improvements to rain and snow retrievals. The GPM-CO also extends the long record of the Tropical Rainfall Measuring Mission (TRMM), which was in space from 1997-2015, into the present, making their combined datasets useful for climate and trend studies. The GPM-CO will remain the main Program of Record for precipitation and convection variables prioritized by the Decadal Survey until the launch of NASA's Atmosphere Observing System (AOS) at the end of the decade. In addition, the virtual GPM constellation of passive microwave sensors on partner satellites (both national and international) allows for the production of the near-real time (NRT), high temporal (30 min) and spatial (0.1°) resolution IMERG precipitation product, which is heavily used in operations and societal applications around the globe. The final (non-NRT) IMERG product is also a valuable tool for long-term precipitation variability studies. The DPR and GMI are in good health and should continue operating well through the end of fuel availability, which at this time is expected sometime in 2027 for station-keeping altitude but would be extended to 2030 if the GPM-CO is boosted to about 430 km from its current 407 km height.

The Senior Review Panel finds in support of the GPM extension for FY 2024- 2026 and FY 2027-2029 with the over-guide budget. The augmented budget will fund the accelerated development of the 2-wheel science mode for the unlikely scenario of operations with only two reaction wheels (one of the spacecraft's five reactions wheels has failed and three are currently necessary for operations) and the continuation of the NRT processing system, which is essential for many of GPM's operational applications.

Scientific merits: Excellent

Strengths

GPM is a partnership between NASA and the Japan Aerospace Exploration Agency (JAXA). The GPM mission integrates the GPM-CO, which is comprised of the DPR and GMI, and data from a virtual constellation of about 10 passive microwave sensors on satellites of opportunity

(particularly from NOAA, but also international partners) to: i) advance precipitation observations from space, ii) improve knowledge of precipitation systems, water cycle variability, and freshwater availability, and iii) provide data for improving hydrological, climate, and weather modeling and prediction.

In the past three years, the GPM project transitioned its data products to V7, which entailed many algorithmic improvements and full dataset reprocessing. The algorithm changes included updated DPR and GMI calibrations, improved precipitation type physics, a more comprehensive GMI database, and the production of a more consistent dataset across TRMM and GPM eras (1997-present). The algorithm changes led to improvements in frozen precipitation retrievals and retrievals over snow and ice land surfaces, and to more consistency between IMERG mid-to-high latitude precipitation estimates compared to other datasets.

Thousands of scientific application and operational users download GPM data every year and more than 1,200 peer-reviewed publications have resulted from GPM activities and data, 800 of which were published in the past three years. Some highlights include improved snow and hail climatologies, precipitation extremes characterization, more physically consistent latent heating profiles, and assimilation of all-sky GMI radiances into global models. The GPM-CO also provided strong value as a cross-calibrator to polar-orbiting sensors due to its non-sun-synchronous orbit.

The extended mission will continue following the above successes by improving the main precipitation algorithms and reprocessing for the final V8 data version. Some of the algorithm improvements will focus on persistent disparities and biases in precipitation retrievals over land and over frozen surfaces. New techniques, such as Machine Learning, and observational sources, such as passive microwave Smallsats (especially from NASA's TROPICS mission), will also be used toward algorithm and product improvement. The resulting higher-quality retrievals will enhance the new science to be achieved, which includes research on microphysical and physical properties of storms and the use of the long record to study global precipitation patterns, the water cycle, water resources, precipitation extremes, weather, and climate.

The GPM-CO data is irreplaceable since there is no other Ku-band radar in space and will not be until the launch of AOS Storm, nominally slated for 2029. The calibration-level quality of the GMI is also not provided by any other passive microwave sensor and it has the proven ability to bring consistency between older lower-frequency sensors to newer and planned higher-frequency instruments. The IMERG product is heavily utilized by all sectors and has strong international use, especially in regions that do not have access to ground measurements of rainfall or snow.

Weaknesses
No significant weaknesses.

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

Strengths
The NASA Science Mission Directorate (SMD) 2020-2024 Science Plan identifies six key Earth Science areas of science and application to which the GPM mission contributes to five: i)

coupling of the water and energy cycles; ii) ecosystem change; iii) extending and improving weather and air quality forecasts; iv) reducing climate uncertainty and informing societal response; and v) surface dynamics, geological hazards, and disasters.

The GPM-CO also acts as the main PoR for the NASA 2017 Decadal Survey observables associated with precipitation and convection until the launch of AOS Storm, which will host a wide-swath Ku- and Ka-band, Doppler radar provided by JAXA and a passive microwave radiometer, in 2029.

Weaknesses
None.

Standard data product quality: Excellent

Strengths
The GPM mission produces L1 through L3 data products. L1 products are orbital observations of brightness temperature from the GMI and partner radiometers and radar power from the DPR. These observations represent the gold standard in calibration and stability for both the passive and active CO sensors. L2 orbital retrievals involve surface precipitation from the GMI only, GMI+DPR, and partner radiometers and 3D precipitation structures from the DPR at high spatial resolution (e.g., 5 km for the DPR at nadir). L3 gridded products consist of monthly latent heating profiles and rainfall maps and 30-min, 0.1° merged precipitation fields from IMERG provided in NRT and post-real time. All of GPM's L1 through L3 data products are mature and of high quality (V7), with plans to be maintained or improved to V8 during the extended mission. Many of the data products are regularly validated with ground sensors, including from the ground validation supersite located at the NASA Wallops Flight Facility on the eastern shore of Virginia.

Weaknesses (Minor)
Assuming the GPM-CO is boosted to a higher altitude, this will cause changes in the calibration and resolution of the observations that will need to be accounted for in the algorithm stream. Assessment will also need to be done to account for changes to the data products and precipitation statistics. However, this was successfully done for TRMM when it changed its altitude from 350 to 403 km to conserve fuel in 2001 so this is considered as a minor weakness by the panel.

Technical Performance: Excellent/Very Good

Strengths
The GPM-CO spacecraft and DPR and GMI are in good working order. Station-keeping fuel should last to mid-2027 based on current estimates (this is earlier than in previous reports because of the unexpectedly active solar cycle) and until 2030 after an altitude boost from 407 km to about 430 km expected to be performed at the end of 2023. A similar boost maneuver was successfully performed by TRMM in 2001.

Weaknesses

One of five spacecraft reaction wheels failed in 2019 and another malfunctioned in April 2020 and was returned to service in February 2021. The GPM-CO safely transitioned to 3-wheel control during that time and is currently operating with four reaction wheels. There are plans to implement a patch during the extended mission to be able run science operations if just two reaction wheels remain. However, the mission team has deemed the likelihood of needing to operate in 2-wheel science mode as very unlikely (0% in 2023, < 9% in 2029).

Cost Performance

The Independent Cost sub-panel rated the GPM mission as 'Med/Low Risk'. We agree with the sub-panel's assessment and believe that mission-critical elements (i.e., the NRT system and an accelerated development of the 2-wheel science mode) should have been included in the in-guide request. However, we realize that mandated across-the-board cuts made this difficult to achieve.

The panel also notes that ROSES plays an important role in the production of specialized products (like hail retrievals) and enhanced understanding about precipitation and its impacts using GPM observations and products.

Operational, Applications, and Non-research Value

The National Interests sub-panel rated the GPM mission as 'High Utility'. We agree with the sub-panel's assessment and feel that GPM provides a strong contribution to operational and societal applications, especially related to high-impact weather events.

Other Comments

The proposal was clear and well written and the presentation by the science team addressed remaining aspects necessary for evaluating the mission extension.

A3.6 Mission: GRACE Follow-On

Mission Extension Conclusion

FY2024-2026
Continuation as currently baselined.

FY2027-2029
Continuation as currently baselined.

Overview

The Gravity Recovery and Climate Experiment Follow-On (GFO) mission, launched in May 2018 as a joint endeavor between NASA and the German Research Centre for Geosciences, has been tracking the global redistribution of water (including liquid water and ice) mass due to changing climate, growing urbanization, industry, agriculture, and tectonics. With more than 5600 (5 publications/week) peer-reviewed publications, the contribution of the mission to improved understanding of ice mass, land water storage, earthquake processes, sea level rise, and ocean mass variability is clearly documented.

GRACE-FO, as the name suggests was always designed, as a mission to continue the mass change time series started by GRACE and perhaps to take monthly mass changes until the NASA EOS MC is launched (2028 nominally). A 20 plus year record of ice mass changes and water storage changes allow us to separate natural variability of ice and water storage from climate warming and more acute anthropogenic changes on the Earth system, distinctions important for predicting the future of and managing fresh water sources. Extending the data record will offer opportunities for new scientific discovery. A consistent reprocessing of the existing data set will improve the precision of observations and improve scientific conclusions.

The case for extension is also pretty clear with extension enabling the link to the MC mission so as to create a long record for increased science value.

Scientific merits: Excellent

Strengths
The 5-year record of gravity from GFO extends the GRACE global monthly observations of mass change to 22 years and provides a unique time series for characterizing and studying mass change in the Earth system. GFO has improved our understanding of ice mass, land water storage, earthquake processes, sea level rise, and ocean mass variability by providing a global image of mass at monthly intervals. GFO has contributed to better understanding the effects of climate warming, e.g., decreasing ice thickness and extent, increasing frequency and severity of droughts and stress on fresh-water stores, increasing precipitation leading to flooding, and sea-level rise, to name a few. More than 5600 publications (5/week) have used the GFO products. It is particularly impressive that the scope of the scientific output has been sustained across a wide range of Earth System topics including geodesy, glaciology, hydrology, and more.

Weaknesses
None

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

Strengths
Monthly observations of global mass change from GFO map directly into NASA's Science Plan and the Decadal Survey 2017 for the themes (1) Climate Variability and Change, (2) Global Hydrological Cycles and Water Resources, and (3) Earth Surface and Interior. The decadal survey identifies *Mass Change* observations as critical for observing the Earth system, emphasizing the need for continuity between GRACE-FO and the future Earth Science Observatory (ESO) *Mass Change* mission.

The data analysis and observations from GFO address priorities *1*, *3* and *4* of the 2020–2024 SMD Science Plan. *Priority 1:* For Exploration and Scientific Discovery by "enabling discoveries and Earth system understanding in five Earth-Science focus areas (Coupling of the water and energy cycles, Extending and improving weather and air quality forecasts, Reducing climate uncertainty and informing societal response, Sea-level rise, Surface dynamics, geological hazards and disasters)".
"For Interconnectivity and Partnerships (*Priority 3*), the GRACE-FO team has been working for decades with its German mission partner GFZ, the German Space Operations Center DLR-GSOC. National interest in the data products is increasing including uptake from the US Drought Monitor and NOAA-NGS for updating their national gravity reference frame. "For Inspiration (*Priority 4*), GRACE-FO continues the GRACE-legacy of strong outreach and engagement activities with the public and media. High-impact research papers (e.g., on ice mass loss or groundwater decline) frequently make headlines in international online and print news."

Weaknesses
None

Standard data product quality: Excellent

Strengths
The data quality is very high and well maintained. Although GFO's mass measurements inherently can't be validated against ground measurements, the mission team has done a careful job analyzing data uncertainty, and the many successful science uses of the data implicitly speak to the high data quality. The data are regularly compared with SLR, satellite altimetry, terrestrial water storage models, and GNSS observations.

As a justification to the ranking of 'Excellent' for the data products, the data quality itself is excellent for science applications. For the extended mission, a full reprocessing that will include better accelerometer calibrations, will result in improvements for science data projects. Preliminary results indicate that the planned reprocessing will yield noise reductions on the current RL06.1 of 15%.

The GFO Science Data System (SDS) team will continue routine production, validation, and delivery of the L1 and the L2 and L3 data products under the proposed in-guide budget. Data from the mission is provided at L1 to L4 data products. This increases the community of GFO users beyond the L2 expert data users and opens the possibility for even more users to synthesize

the observations. The popularity of these higher-level data products is evidenced in the fact that 70% of the GFO users download the L3 & 4 mass change products.

In terms of Calibration /Validation, the GFO data have no equivalent for direct validation.

As the satellite ages, the magnitude of the differential drag between the two satellites will change due to solar activity and satellite orbital altitude degradation. The accelerometer calibration must be continually updated. To date, these calibrations have maintained the quality of the data products since the mission launch.

Weaknesses
None

Technical Performance: Excellent/Very Good

Strengths
After five years of operations, ample margins in power and propellant remain. The battery capacity is better than 90% of the capacity at launch for both satellites.

Weaknesses
Estimated propellant loss due to leaking thrusters are stated in the proposal to not be a problem until 2028 or later. These are not being monitored directly but using another satellite with the same CGPS that is experiencing the same problem. At the panel presentation, the project scientist reported that "the Airbus 2023-Q1 report finds reduced leak rates during Jan/Feb-2023 … with AOCS parameter changes; a longer period in this 'relaxed AOCS' mode is required to fully assess the impact on lifetime". "AOCS" is the Attitude and Orbit Control System. The project plans to operate in this AOCS mode for an additional 6 months to quantify fuel use and leak rates (starting as soon as in July or August 2023). Currently everything is working nominally but the effect of these leaks on the data quality will need to be monitored and considered in the next extension review.

Cost Performance
NASA has specified a funding guideline for 2025-2029 that is 24% lower than the annual funding provided during the primary missions. The team has adjusted their budget reductions and distributed them evenly across project management, systems engineering, safety and mission assurance (S&MA), flight systems engineering, and mission operations with the goal of minimizing impacts to science.

The MOU with German Research Centre for Geosciences (GFZ) that provides all routine telemetry, tracking, and command capabilities at no cost to NASA has been extended through December 31, 2026. The GFZ contribution will be necessary for operations beyond December 2026. The NASA Office of International and Interagency Relations (OIIR) will be asked to coordinate another extension of the MOU in advance of the 2026 Senior Review.

Please note that the budget for the extended mission was derived from experience from the GRACE extended mission and the initial five years of the GRACE-FO mission. The issues that

may affect the budget in the future include the GRACE-FO-2 SuperSTAR Accelorometers (ACC), solar cycle 25 and CGPS (Cold Gas Propulsion System) leaks that may require more effort and expertise than in the final years of GRACE.

Operational, Applications, and Non-research Value

The panel defers to the sub-panel assessment.

Other Comments

The quality of the proposal was excellent. It thoroughly addressed the metrics that the expert panel was asked to assess. The scientific contributions of the mission deftly synthesized the massive literature and clearly distilled the community accomplishments to the most notable results.

Likewise, the presentation and the responses to the questions from the review team were answered to the satisfaction of the panel. Good Job!

A3.7 Mission: ICESat-2

Mission Extension Conclusion

FY2024-2026
Continuation with augmentations to the current baseline.

FY2027-2029
Continuation with augmentations to the current baseline.

Overview

ICESat-2 employs ATLAS, a photon-counting lidar system, to monitor ice sheet mass loss and sea-ice changes in the polar regions. At lower latitudes, ICESat-2 measures canopy height to estimate large-scale biomass. Launched in October 2018, ICESat-2 has met all prime mission requirements by December 2021 and, since then, has continued to operate nominally.

The extended ICESat-2 mission will generate a decadal-scale record of key essential climate variables with high spatiotemporal resolution and accuracy. ICESat-2 observations have already provided significant new insights into the seasonal and interannual variations of the cryosphere. However, a long-term record is needed to identify climate system trends, assess the mechanisms driving cryospheric changes, and improve predictive ice sheet models. ICESat-2 will also provide observations for numerous other scientific inquiries and applications, such as estimating snow depth, shallow bathymetry, ocean surface elevation, and wave features.

The ICESat-2 mission produces a wide range of data products distributed through the National Snow and Ice Data Center. Additionally, various open-source software packages, cloud-based tools, and custom data products are developed to ensure the broad use of ICESat-2 data. The ICESat-2 mission resulted in 315 peer-reviewed papers and has 6,200 data users (April 2023).

The ICESat-2 spacecraft is in excellent condition and operating on primary components across all subsystems. The operating laser shows only slow degradation, suggesting that a single laser may operate for 18-24 years. With a spare laser on board, ICESat-2 can operate nominally until the mission's End of Lifetime (EOL), which is currently estimated in January 2036.

There was strong agreement in the panel about the excellent performance of the mission and the benefits of its continuation. The panel suggests a modest augmentation of the in-guide budget to support the continuing the development of the ICESat-2 atmospheric products that could bridge the gap between the cloud-optimized lidar observations after the decommissioning of CALIPSO.

Scientific merits: Excellent

Strengths
ICESat-2 was designed as an advanced follow-on mission of NASA's ICESat satellite laser altimetry to measure sea-ice freeboard, ice-sheet elevation, and vegetation height. The mission established stringent science requirements to obtain robust estimates of ice loss. ICEsat-2 employed the ATLAS photon-counting lidar system with six beams organized in beam pairs to facilitate accurate elevation change detection. ICESat-2 has met all prime mission requirements

by December 2021 and, since then, has continued to operate nominally, collecting observations with unprecedented accuracy from orbit (better than 0.03-meter vertical and 2-meter horizontal).

ICESat-2 science achievements include the estimation of Greenland and Antarctic mass loss, the first year-around measurement of sea-ice freeboard, and mapping of above-ground biomass in the northern boreal zone. ICESat-2 observations revealed critical processes on seasonal and short-term interannual levels.

For the first time, the ICESat-2 mission extension will provide a long-term (decadal-scale) record of glacier and ice-sheet elevation changes and sea ice freeboard with high spatiotemporal resolution and unprecedented accuracy. Moreover, because of its high accuracy and global coverage, ICESat-2 will facilitate the generation of unbiased long-term elevation change data records from various sensors (radar altimetry, stereoscopic DEMs, etc.) by filling spatiotemporal gaps and providing a reference for data validation and correction.

The extended mission will also allow long-term monitoring of the hydrosphere, biosphere, and geosphere by studying landscape evolution, coastal erosion, sea-level and inland water-level changes, and other processes.

The unique nature of ICESat-2 accurate observations was acknowledged by the National Interests Panel, which gave a Very High Utility rating to ICESat-2, noting that "Most agencies or groups have a very high reliance on ICESat-2 for accurate elevation data to be used in all sorts of earth models and derived data products". During the extended mission, ICESat-2 will continue contributing to the national objectives by monitoring ice sheets' contribution to sea level rise and coastal sea level changes, providing data to support icebreaker operations, and developing new products for shallow bathymetry mapping.

Weaknesses

No significant weaknesses are identified

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

Strengths

The proposed mission extension contributes to at least four of the strategy elements (SE) of NASA SMD's 2020-24 Science plan by continuing to support a growing, application-oriented user community; broadly distributing ICESat-2 products and following Open Science practices; developing striving international collaborations and actively engaging with other federal agencies, e.g., NOAA, NGA. ICESat-2 is at the forefront of community engagement in product development and distribution by supporting open-source data generation tools (SlideRule), cloud computing resources (CryoCloud), and ICESat-2 Hackweeks. This activity is critically important as some of the more traditional, widely available platforms, such as Google Earth Engine, were developed to handle raster data sets and cannot effectively store and process lidar point clouds.

Although the ICESat-2 mission was developed to address priorities of the 2007 Decadal Survey, the observations also support many of the 2017 Decadal Survey priorities related to science questions and Targeted Observables (TOs), listed in the proposal.

Weaknesses

None

Standard data product quality: Excellent

Strengths

The ICESat-2 mission developed an entire new suite of higher-level products to serve the needs of different communities. This is an impressive improvement over the very limited set of ICESat altimetry products. The structure and documentation of ICESat, ICESat-2 and ESA radar altimetry data products is very similar, supporting easy combination of the different data sets and user engagement.

Current status and planned development of standard data products:

The algorithm development during the prime mission phase concentrated on the L1, L2, and L3 products supporting core mission objectives (cryosphere, vegetation). Thus, these L1, L2, and most L3A products reached a high level of maturity. Further improvements of these products fall into two categories, (1) reprocessing of L2 data to improve bias monitoring and calibration, which also impacts the higher-level products, and (2) improvement of some of the L3A algorithms (sea ice). Significant development focuses on deriving higher-level (L3B) gridded products, e.g., ice sheet elevation, mass change, and vegetation height grids. The update of the lower-level products (L1, L2, L3A) and the development of gridded products (L3B) supporting core mission objectives will continue during the extended mission. Cost reduction will be achieved by reducing the frequency and extent of field validation campaigns and bringing the PPD effort to GSFC. The mission expects to be able to maintain data quality after implementing these changes.

The in-guide request also includes funding for developing a new, shallow-bathymetry product, endorsed at the Mission Extension Review in February 2022.

Weaknesses

(minor) The support for developing the non-core product, except shallow bathymetry, will be significantly reduced to facilitate the budget reduction. It is not clear why the bathymetry product was prioritized over other products that are better aligned with the priorities of the 2017 Decadal Survey.

Technical Performance: Excellent

Strengths

The ICESat-2 spacecraft is in excellent condition and operating on primary components across all subsystems. The operating laser shows only slow degradation, suggesting that a single laser may operate for 18-24 years. With a spare laser on board, ICESat-2 can operate nominally until the mission's End of Lifetime (EOL), which is currently estimated in January 2036. The only non-green ATLAS subsystem is the Laser Reference System (LRS) Stellar Side. The mission developed and implemented a mitigation strategy to fulfill the Precision Pointing Determination (PPD) requirement without the LRS and achieved a pointing performance of ~3 m compared to the geolocation requirement of 6.5 m. Performance modeling indicates that ICESat-2 would still meet pointing and geolocation requirements after the loss of one Star Tracker.

Weaknesses
No major weaknesses are identified

Cost Performance

The panel suggests a modest over-guide to fund the continuing development of the ICESat-2 atmospheric products. When CALIPSO is decommissioned in August 2023, there will be a gap in cloud-optimized lidar observations until the launch of AOS at the end of the decade. Although ICESat-2 does not have the same capabilities of CALIPSO, it could provide important cloud and aerosol profiling information to the community.

Operational, Applications, and Non-research Value

The panel concurs with the sub-panel assessment.

Other Comments

None**.**

A3.8 Mission: OCO-2

Mission Extension Conclusion

FY2024-2026
Continuation with augmentations to the current baseline.

FY2027-2029
Continuation as currently baselined.

Overview

OCO-2 was launched in July 2014 into a sun-synchronous orbit and has provided nearly continuous measurements of the dry-air, column averaged value of CO_2 (X_{CO2}) since Sept 2014. The measurements of X_{CO2} are obtained with a measurement precision that exceeds the original baseline mission science precision requirement of 0.3% or 1.2 ppm on regional spatial scales. These measurements of X_{CO2} are obtained in three observing modes: nadir (mainly over land), sun-glint (mainly over the Atlantic and Pacific oceans), and target (mainly over validation sites). In addition, a solar-induced chlorophyll fluorescence (SIF) product has been provided for the terrestrial biosphere. The OCO-2 observations of X_{CO2} and SIF have provided valuable new insights into seasonal and geographic variations in the exchange of carbon between the atmosphere, the world's oceans, and terrestrial biosphere. The first major ENSO event since the launch of OCO-2 occurred in 2015-2016; data from OCO-2 guided the community's understanding of unexpected responses of the global carbon cycle throughout this event. Recently, the OCO-2 team has provided a policy relevant estimate of National Net Emissions and Terrestrial Carbon Stock Changes (with uncertainties) for the world's countries, over the time-period 2015-2020: this product is termed GST (global stocktakes).

Extension of the OCO-2 mission would provide an opportunity for the response of the global carbon cycle to the second major ENSO event since the launch of OCO-2 to be quantified and would allow for a start at using OCO-2 data to assess trends in the oceanic and terrestrial carbon sinks. Currently, the magnitude of interannual variations in the strengths of these two sinks exceeds the size of any possible trend. A six-year extension would allow the GST product to be provided for 2021 to 2026. Finally, OCO-2 is the flagship mission for space-borne measurements of column CO_2: the data are of exceptionally high quality, the science team has executed a very rigorous calibration and validation effort, and the ground footprint (3 km^2 at nadir) is smaller than any other current or known future, space-borne column CO_2 observational effort.

The instrument is in excellent condition. There is enough propellant to allow for operations until 2040. The detectors are exhibiting slow degradation that is well monitored, understood, and quantitatively accounted for in production of the data products. The Attitude Control System (ACS) had to be adjusted in June 2019 to work in "gyroless-mode" due to indications that "the Honeywell miniature inertial measurement unit (MIMU) was reaching end of life unexpectedly early". "The loss of the MIMU does not impact the ability of the ACS to meet all performance requirements. As a result, new requirements on observation scheduling were established to ensure that the star tracker assembly (STA) is never occulted by the Earth or Sun."

Scientific merits: Excellent

Strengths

To date OCO-2 data have been used in about 400 publications, a significant number of which have been published in high profile journals. Data from OCO-2 have been used to show stronger seasonality in net ecosystem exchange over South Asia than simulated by state-of-the-art terrestrial biogeochemical models, a larger role of sparsely vegetated semi-arid regions (such as the interior of Australia) in global CO_2 flux interannual variability, measure significant and spatially-extensive early cold season release of CO_2 to the atmosphere from the boreal ecosystem in northern Eurasia, and that heat and drought caused by the 2015/2016 El Nino were primary contributors to the record increase in atmospheric CO_2 concentrations around the world.

Data from OCO-2 have been used since 2020 to constrain regional sources and sinks of CO_2 that are reported annually by the very influential Global Carbon Budget (GCB) project. Data from OCO-2 have recently been used to quantify emissions of CO_2 from large point sources such as coal-fired power plants across the globe. Finally, data from OCO-2 are now used to define fluxes and stocks of CO_2 on the national level, which is an important, unique source of information for evaluating the efficacy of pledges made to reduce emissions of greenhouse gases under the Paris Climate Agreement.

From a scientific perspective, obtaining OCO-2 observations during another ENSO event, such as the one that has developed between the time the proposal was submitted and is being reviewed, is exceedingly important. Similarly, extension of the mission long enough to separate interannual variability in uptake of CO_2 by the oceans and terrestrial biosphere, from long-term trends, is also very important. An extended mission would lead to a reduction in random errors and enable detection of emission trends from large point sources, such as coal-fired power plants. Both X_{CO2} and SIF data from OCO-2 are central to a new effort to understand the relation of aridity and dryness stress on ecosystems. If the world continues to follow the "wet get wetter and dry get drier" paradigm, that seems to be a good summary of the response of the global hydrological cycle to rising levels of GHGs, then continuation of this effort during an extended mission may have great importance for society.

An accurate understanding of dryness stress on ecosystems is critical to managing of OCO-2 data, both X_{CO2} and SIF, in analyses conducted by the Global Change Biology (GCB) community is just getting started: synergies between space-based and ground-based measurements of CO_2 are greatly facilitated by the embrace of OCO-2 data by the GCB community. Finally, having another five-year period to the global surface air temperature (GSAT) record would be of great benefit to the Paris Climate Agreement.

Weaknesses

The proposal outlines a series of programmatic objectives of the In-Guideline budget effort for either a 3- or 6-year extension, such as:

1.5.3 Maintenance and Refinement of Instrument Calibration1.5.4 Updating Gas Absorption Cross-Sections for O_2 and CO_2

1.5.5 Retrieval Algorithm Improvements

1.5.6 Exploiting New Data Product Validation Opportunities

Much of these activities seem to be inconsistent with the In-Guideline work force described in Section 2 of the proposal. For example, Section 2 of the proposal seems to indicate no further improvement of the retrieval algorithm, under the In-Guideline effort.

During the panel review interview, the mission Principal Investigator (PI) clarified that the community would continue to use Version 11 of the retrieval algorithm, due to the cost involved with reprocessing that data under the In-Guideline funding profile.

Also, during the interview process, it became clear that a significant amount of the proposed work with OCO-3 data has already been completed. Perhaps this section of the proposal (that is, exploration of synergies with OCO-3) was a carry-over from the prior Senior Review proposal. Regardless, the Panel was disappointed to see that this portion of the proposed effort has been completed and was submitted for publication on 19 December 2022: https://amt.copernicus.org/preprints/amt-2022-329/

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

Strengths
OCO-2 addresses areas of ecosystem change and reducing climate uncertainty and informing societal response of the NASA 2020 Science Mission Directorate strategic plan and the accomplishments of OCO-2 were highlighted in the 2017 Decadal Survey as an "*illustrative example*" for the realization of *"scientific progress resulting from the specific missions*".

Weaknesses
The OCO-2 team might want to encourage the use of their L1 radiance product by data assimilation centers in the U.S., as well as assure that the U.S. EPA is aware of their GSAT product, because OCO-2 did not fare particularly well in the National Interests ranking (9th of the 12 ranked missions).

Standard data product quality: Excellent/Very Good

Strengths
The data product provided by the OCO-2 team is far and away the most accurate and precise measurement of X_{CO2}. The GSAT product is of paramount importance to the achievement of the goal of the Paris Climate Agreement.

The SIF product is a wonderful complement to X_{CO2}.

Weaknesses
The review panel was concerned that "spectral residuals show systematic features above the instrument noise that likely contribute to sub-ppm regional biases in X_{CO2} [of the version 11 retrieval algorithm]" (page 1-17) and that there is no apparent plan to address this potential very important deficiency of the primary OCO-2 data product under the in-guideline budget over the FY 24 to FY 26 period of time.

Also, as a minor weakness, the review panel thought the usage of the OCO-2 SIF product for drought management may have been somewhat over-stated in the proposal for real applications. The panel felt that this concern was not adequately addressed during the in-person interview, but time for this interview was also brief. Finally, the discussion of how future retrievals of X_{CO2} might be improved due to revision of the Bidirectional Reflectance Distribution Functions (BRDF) and treatment of polarization over snow were not thoroughly addressed to convince the panel that this revision would lead to the significant improvement of the product.

Technical Performance: Excellent/Very Good

Strengths
The calibration & validation efforts for assessing hardware performance seem excellent. The establishment and OCO-2 support of the Total Carbon Column Observing Network (TCCON), as well as vicarious ground-based calibration sites, together with the solar and lunar observing modes have led to an exceptionally well quantified record of detector performance.

Weaknesses
The possible loss of data collection due to the solid-state recorder becoming full, if data downloads occur only on weekdays under the in-guideline budget, is a concern.

The possible loss of support for U.S. based TCCON stations under the in-guideline budget request is also a concern.

Cost Performance

The review panel was concerned that so many important matters such as continued improvement of the retrieval algorithm, support for TCCON, and possible loss of data due to the SSR becoming full could not be addressed under the in-guideline budget. Given the amount of time OCO-2 has been in orbit, collecting excellent data, it had been thought that perhaps some efficiency of operations could have occurred, such that most (or perhaps all) of these matters could be addressed in some manner under the in-guideline budget.

The suggested augmentation is limited to only the request for Assessment & Authorization (A & A) activities related to the new NASA cybersecurity requirements.

Since most of the tasks related to OCO-3 described in Section 1.5.3 appear to have been accomplished, perhaps the personnel effort that had been planned for this effort could be either redirected to algorithm improvement or support for the U.S.-based TCCON effort.

Operational, Applications, and Non-research Value

The panel defers to the sub-panel assessment.

Other Comments
None

A3.9 Mission: SAGE III

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation as currently baselined.	Continuation as currently baselined.

Overview

The SAGE III instrument on the International Space Station (ISS) uses a solar (and lunar) occultation technique to measure vertical profiles of ozone, aerosol, water vapor, and other trace gases (e.g., nitrogen dioxide) from cloud top to ~70 km. The solar occultation technique has several advantages. It can retrieve trace gases and aerosol extinctions with high vertical resolution (~0.7 to 1.0 km). Because of the strong signal from the Sun (higher signal-to-noise ratio) and self-calibrating feature of the occultation technique, SAGE III can provide measurements with high accuracy and long-term stability compared to other satellites using nadir viewing, limb scattering, or emission techniques. Data from SAGE III are suitable for monitoring long-term trends in stratospheric composition.

Another advantage of SAGE III is that it implicitly measures aerosol extinction coefficients at multiple wavelengths while other satellite instruments with limited wavelengths need to make assumptions of the aerosol properties (e.g., particle size distribution) in order to convert their native measurement to an extinction product. The extension of the SAGE III/ISS mission will enable the continuation of the climate data record for ozone, aerosols as well as water vapor. It will also help to improve retrievals from other instruments and bridge future missions. The overall scientific merit of the mission is excellent/very good. It is highly relevant to NASA Science Goals and the 2017 Decadal Survey. The Panel strongly supports the extension of SAGE-III for 2024-2026 with the in-guide budget. The project should succeed even though the budget is somewhat tight.

Scientific merits: Excellent/Very Good

Strengths

The SAGE III/ISS mission uses the solar (and lunar) occultation technique to measure vertical profiles of the surface (or cloud top) to ~70 km, for sunlit latitudes between about 60N and 60S. The solar occultation technique has several advantages. It can retrieve trace gases and aerosol extinctions with high vertical resolution (~0.7 to 1.0 km). Because of strong signal from the Sun (higher signal-to-noise ratio) and self-calibrating feature of the occultation technique, SAGE-III/ISS can also provide measurements with high accuracy and long-term stability compared to other satellites using nadir viewing, limb scattering, or emission techniques. The SAGE-III/ISS datasets are suitable for long-term trend studies as well as research studies of large-scale dynamics, radiative forcing, and climate change processes related to the extra-polar ozone layer.

Weaknesses

The spatial and temporal coverages of SAGE-III/ISS are limited. Data are not suitable for studies of polar regions.

Relevance to NASA Science Goals & 2017 Decadal Survey: Excellent/Very Good

Strengths
The mission is relevant to all 4 NASA Science Mission Directorate (SMD) priorities (exploration and scientific discover; innovation; interconnectivity and partnership; and Inspiration), and two focus areas (extending and improving weather and air quality forecast; reducing climate uncertainty and informing societal response) suggested by the 2017 Decadal Survey

Weaknesses
No major weakness

Standard data product quality: Excellent/Very Good

Strengths
Compared to other limb viewing satellites used to measure vertical profiles of ozone, aerosols and other trace gases, SAGE III measurements intrinsically can provide O3 and aerosol profiles with better accuracy/precision, higher vertical resolution, and long-term stability.

Furthermore, SAGE III does not require an assumption of particle size distribution to retrieve aerosol extinctions (e.g., aerosol retrieval is not sensitive to larger wildfires and volcanic eruptions).

The ozone, water vapor, aerosol extinctions (at multi-wavelengths), and nitrogen dioxide data products from solar measurements have been validated and data quality is high. The data have been used and contributed to many scientific studies, for example: 2022 World Meteorological Organization (WMO)/ United Nations Environment Programme (UNEP) Ozone Assessment; World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 6 (CMIP6); Data assimilation (Goddard Earth Observing System [GEOS] Constituent Data Assimilation System [CoDAS]); the impact of PyroCb and volcanic aerosols on the atmosphere.

Weaknesses
Some lunar data (NO_2, NO_3) have not been fully validated, although they are not core data products. Further improvements of some data products will be delayed due to budget reduction.

Technical Performance: Excellent

Strengths
The SAGE III instrument is healthy and can continue to collect science data beyond FY29 as long as the ISS continues to host it. The SAGE III/ISS payload includes two Contamination Monitoring Packages (CMPs), which can provide valuable information regarding the contamination environment directly to ISS program and external payload teams to avoid contamination of the aperture optics. The advantage of CMPs has been demonstrated by alerting major leak events from ISS visiting vehicles.

Weaknesses

The budget reduction would impact mission operation which could potentially reduce data collection efficiency slightly (e.g., a few percent). The lack of coordination with colleagues external to SAGE III for validation using ozone sondes, under the in-guide budget, was deemed to be a weakness.

Cost Performance

The in-guide budget reduction will be distributed between the mission operations and data processing teams. This could affect data collection efficiency (still meets mission requirements) and delay some algorithm improvements. The overall cost evaluation is medium low risk.

Due to budget reduction, the SAGE III mission decided to defund the external validation effort in coordination with NOAA and NIWA. The review panel suggests the mission team to continue the coordination of validation efforts/activities through budget reallocation or ROSES funding.

The review panel was concerned that so many important matters such as providing Quicklook data and assessing the effects of excess stratospheric H_2O and aerosols from the HTHH volcanic eruption on the accuracy of the O_3 retrieval are not planned for the in-guide budget. Given the amount of time SAGE III has been on ISS, collecting excellent data, it had been thought that perhaps some greater efficiency of operations could have occurred, such that these matters could be addressed in some manner under the in-guideline budget.

Operational, Applications, and Non-research Value:

The panel defers to the sub-panel assessment.

Other Comments

None

A3.10 Mission: SMAP

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation with augmentations to the current baseline.	Continuation with augmentations to the current baseline.

Overview

The SMAP soil moisture data are unique in terms of both accuracy and coverage and have had significant impacts in the areas of hydrology, ecosystems and carbon cycling, weather and climate, and hazard predictions. With the exception of the synthetic aperture radar (which failed shortly after launch) and some minor concerns about non-volatile memory, the instruments are mostly in good health. The low errors of the data products are consistent across the mission record. Thus, mission extension should lead to continued scientific utility. The ability to sample a greater range of climate variability and extremes during a longer mission should help to further increase the utility of SMAP for science applications, particularly given the utility of SMAP data for several different hazards that are the result of extreme conditions (floods, droughts, wildfire, food security). Furthermore, if successful, the proposed effort to enable soil moisture retrieval under forests would significantly enhance the dataset utility. In addition, SMAP mission extension will extend the L-band record to the NISAR and once successfully launched ESA CIMR satellites, potentially enabling a multi-decadal record that would have significant utility for trend analysis and study of extremes. The panel supports continuation of the mission – with an augmented budget only to support A&A activities and continuation of the near-real-time products.

Scientific merits: Excellent

Strengths

The SMAP radiometer provides a unique and valuable set of global-scale soil moisture products, which are relevant to a wide variety of scientific fields. Because soil moisture is a first-order control on plant and microbial function, SMAP soil moisture datasets enable improved estimation of coupling between the carbon and water cycles. In the last three years, SMAP has been used to map hot spots of irrigation effects on gross primary productivity (GPP, photosynthesis) and to map soil moisture thresholds for down-regulation of photosynthesis. Beyond photosynthesis fluxes, both SMAP soil moisture and level 4 carbon flux products (which are derived from assimilation of SMAP level 2 soil moisture) have been used in a range of studies of soil respiration and soil carbon dynamics under climate variability, particularly in high-latitude ranges. A second key application of SMAP soil moisture data is the understanding and estimation of the land surface's coupling to the energy cycle and soil moisture influence on weather and air quality. In the last three years, assimilation of soil moisture has been shown to affect estimation of low-level jets (which are often drivers of mesoscale convective systems) over the Great Plains, the North American monsoon system, convective rainfall, and daytime ozone concentrations. The SMAP soil moisture data have also improved our understanding of the hydrological cycle. In the last three years, SMAP observations have been used to provide the

first wall-to-wall, remote sensing-based maps of diffuse recharge and shallow ground water tables. SMAP soil moisture has also been shown to improve high-resolution MODIS evapotranspiration estimates. Lastly, SMAP soil moisture is of significant utility for studying a range of climate-dependent human hazards. SMAP data utility has been demonstrated for wildfire risk estimation, flood inundation mapping, and drought monitoring (including flash droughts, which are often particularly costly). In the last three years, research has also shown that SMAP soil moisture can be used to predict food security changes within a three-month lead time. Lastly, SMAP observations improve public health risk estimation of several vector-borne diseases.

Overall, the SMAP data have contributed to a wide range of scientific advances. Since launch, more than 150 papers have been published using SMAP data. Increased utility of the data is expected as the current eight-year record becomes longer after extension and covers a wider range of climate conditions (including more extreme events).

SMAP soil moisture data are unique in their accuracy and coverage. Although Soil Moisture and Ocean Salinity (SMOS) observations also estimate soil moisture, SMAP data are more accurate. Additionally, while SMOS has been extended to 2025, it will be a 16-year-old mission by that time, and it's unclear how long SMOS will continue to operate. While the CYGNSS mission is also starting to develop soil moisture data products, these are far less mature and currently of significantly lower quality than SMAP, and they do not have global coverage.

During the extension phase, SMAP will focus on five planned algorithm improvements. Two of these will focus on synergies between SMAP and other L-band missions: creating a combined SMAP-SMOS product and preparing the algorithm development necessities for a combined SMAP-NISAR product on the latter's launch. Both would provide a useful synergy that extends the SMAP record and reduces revisit. Additionally, three other tasks would target specific location types, including dynamic soil roughness estimation and accounting (which is likely to be particularly significant in agricultural regions), use of a dynamic water body mask, and extension of SMAP algorithms to forested regions.

Beyond the official SMAP data products, additional observables such as freeze/thaw, vegetation optical depth, ocean salinity, and ocean winds have the potential to enable further scientific applications derived from SMAP observations. Freeze/thaw observations are not available from other sources, and ocean salinity datasets have greater spatial resolution and revisit than other sources such as Aquarius and are well-validated. The ocean salinity product is becoming increasingly used. Furthermore, the ocean winds data from SMAP have been extensively used by the community and are becoming a reference dataset for algorithm development for other sensors. Vegetation optical depth (VOD), which is proportional to vegetation water content, is emerging as a dataset with a range of potential applications in ecohydrology, agricultural yield estimation, phenology, and drought-driven tree mortality studies. Because of its L-band sensor, vegetation optical depth from SMAP has greater penetration through the canopy than previously available X-band datasets. Therefore, it potentially better represents the integrated effect of water stress. The VOD datasets would be further studied during the extension phase.

Weaknesses
The freeze/thaw data products have not led to the same transformative science advances as the soil moisture products have. The mission may want to consider increasing outreach to possible scientific and/or operational users of those products.

Value of the data record with the additional 3-6 years of data and overall data continuity
Continuation of SMAP operation past 2028 will allow overlap between SMAP data and those from the ESA Copernicus Microwave Imaging Radar (CIMR) mission, which will also include an L-band radiometer. If CIMR is successfully launched, the SMAP mission extension could ultimately enable a many-decade passive L-band record that would be substantially more useful for trend analysis than any one mission can provide in isolation.

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

Strengths
SMAP's soil moisture observations address four of the six goals of the SMD Science Plan regarding ecosystem change (which is influenced by soil moisture change) and coupling of water and energy cycles. The improved characterization of the land surface and water-carbon-energy coupling also helps SMAP soil moisture products to address two other SMD science goals: reducing climate uncertainty and informing societal response and 'extending and improving weather and air quality forecasts'. The 2017 Decadal Survey listed soil moisture as a targeted observable (and SMAP as the Program of Record). The soil moisture targeted observable addresses a wide-ranging number of science goals, including four designated as most important, six designated as very important, and several others listed as important. These span primarily the global hydrological cycles and water resources, climate variability and change, and weather and air quality panels, but also include science goals from the marine and terrestrial ecosystems panel. Additionally, sea surface salinity is also a decadal survey targeted observable, addressing three science goals designated as most important, one very important, and more listed as important.

Weaknesses
None

Standard data product quality: Excellent/Very Good

Strengths
The SMAP mission maintains a network of vetted and continuous cal/val sites to validate the level two soil moisture, level two freeze/thaw, and level four net ecosystem exchange products. The baseline soil moisture random errors are low (0.036 m^3/m^3) and below the mission performance target, with very low bias and high correlation. In addition, the soil moisture errors are relatively stable across the mission's record, and the mission has plans for continued improvements to the algorithms. The validation exercises necessary to test these enhancements are mature and the support requested is likely adequate both for validation of new changes and maintenance of the existing high data quality. Concerns expressed at a previous senior mission review about the data quality in agricultural areas have been ameliorated with the SMAP team's incorporation of a dual-channel algorithm as the baseline algorithm. This approach has enabled

better accounting for interannual variability in vegetation cover, leading to improvements, particularly in agricultural areas, in soil moisture data quality. The higher resolution SMAP/Sentinel-1 product has somewhat higher errors than the baseline SMAP product, but they are only slightly outside the mission target (0.046 vs 0.04 m^3/m^3). Lastly, the proposed investigation to extend the SMAP soil moisture products to at least some forested environments could significantly increase coverage of the data products. As for higher-level products, the L4 surface and root-zone soil moisture products are also low and have been shown to benefit from SMAP assimilation over most of the world. The improvement of the error of the level 4 net ecosystem exchange product across the SMAP mission period is significant and less than half of the target performance threshold.

Weaknesses
The 9 km and 36 km spatial resolution of most of the soil moisture data products remains limited. While the mission has invested in a combined SMAP/Sentinel-1 product released at 3 km, the value of that dataset is somewhat limited by the long 12-day temporal revisit of Sentinel-1, particularly given the failure of Sentinel-1B in January 2022. However, a potential radar restart (if the restart is successful and if the radar algorithms and data operate are as successful as the radiometer-only data has been, both of which are uncertain) would significantly reduce this weakness.

Technical Performance: Excellent/Very Good

Strengths
The radiometer instrument is in excellent health and continues operating as expected, without significant hardware risks. Although the high-power amplifier on the synthetic aperture radar instrument failed shortly after launch in 2015, the SMAP team has identified a possible method for restarting it without risk to the radiometer. A successful restart would likely enable significant new science because of the greater data product resolution enabled by the SAR. Further testing and a Reconfiguration Review are necessary before the possibility of a restart is definite, however. The panel suggests the mission continue to work towards a possible restart in a timely manner. Other components of the spacecraft (e.g., power, telecommunications, antenna spin, etc.) also appear to be in good health. Sufficient fuel remains for any necessary debris avoidance maneuvers and to maintain the spacecraft in the nominal orbit.

Weaknesses
Individual blocks of the non-volatile NAND flash memory used by the SMAP mission occasionally fail. Although most memory blocks remain useable, the failure of these blocks can interrupt mission operations, which has happened on seven occasions through 2022. A NAND non-volatile memory block corruption is believed to have been one of two primary causes for a safing anomaly that prevented data collection for two months. Although the SMAP team is implementing additional monitoring and recovery mitigations, this is a recurring issue that has already had non-trivially effects on science operations.

Cost Performance

We defer to the sub-panel assessment. Since the SMAP science goals have previously been met

by a competed ROSES science team, this will be necessary again during a mission extension phase. Additionally, as described below, the panel was concerned about the potential loss of the NRT product and is supportive of an augmentation to support its continued production.

Operational, Applications, and Non-research Value

We defer to the sub-panel assessment, which pointed out the high operational utility of the SMAP products. In addition, the panel was concerned about a potential loss of the near-real-time product for operational and applications use. This includes concern about the loss of the data for the Air Force use detailed in the proposal. Furthermore, the panel was also concerned about the implication of the loss of the NRT data for the multiple data assimilation/numerical weather prediction users that can potentially significantly benefit from assimilating SMAP data (both over land and ocean). These entities, by nature, move only slowly towards choosing to assimilate new products and are currently in the process of evaluating SMAP data for potential assimilation. Removing the NRT product may halt these evaluations. Thus, funding the NRT efforts may significantly increase the future utility of SMAP data, and would irrevocably harm these prospects if not funded.

Other Comments

The proposal had limited information about the freeze/thaw and sea surface salinity products generated by the mission, requiring follow-up discussion to evaluate.

A3.11 Mission: Terra

Mission Extension Conclusion

FY2024-2026	FY2027-2029
Continuation as currently baselined.	Continuation as currently baselined.

Overview

Terra was launched in December of 1999 and includes five instruments: ASTER, CERES, MISR, MODIS, and MOPITT. With the exception of the SWIR bands on ASTER, instrument health is excellent, and all five instruments continue to provide high quality data with substantial value to the science, applications, and operational user communities. Data usage and scientific impacts are both extremely high and continue to grow, which demonstrates the value of Terra.

There are five key benefits to continuing the Terra mission:

- First, extension of the multi-decadal data record from all five instruments is vitally important to both the science and national interests community. Each of the instruments on-board Terra provide critical and unique time series related to ongoing changes in the Earth system.

- Second, the morning overpass time is an important and unique aspect of Terra. Data from Terra complements data from other missions and provides information related to the diurnal cycle, especially for land and atmospheric process studies.

- Third, the ongoing MLT drift of Terra provides exciting opportunities for new science and algorithm refinements focused on diurnal variation and that leverage large solar zenith angles for parameter retrievals (e.g., aerosols).

- Fourth, from a national interests perspective, data from Terra are exploited by a very large community of end-users and agencies for a suite of important applications including weather forecasting, air quality monitoring, and fire monitoring (among others), all of which have substantial societal value.

- Fifth, MISR, ASTER, and MOPITT all provide unique measurements that are not available from other missions.

Overall, given the age of the mission, the health of the spacecraft and instruments is excellent, and the Terra team provided a compelling case that high quality data will be collected up to passivation.

Scientific merits: Excellent

Strengths
As described in the summary, the 23-year record of observations from Terra provides a unique and highly valuable time series for characterizing and studying change in the Earth system. No other data sets with similarly high radiometric quality are available with the same length of record. The morning MLT overpass of Terra provides a suite of information related to diurnal variability in land, ocean, and atmospheric processes that is not available from other missions. Both of these attributes make Terra unique and extremely valuable. ASTER provides unique data related to LST/emissivity, surface topography/digital elevation, volcano and event monitoring; CERES provides unique information related to long-term changes and variability in Earth radiation budgets; MISR provides unique multi-angular data sets for estimating atmospheric aerosols and cloud properties; MODIS provides a large suite of standard products related to land, oceans and atmospheres that are heavily used in the science and applications community; MOPITT provides unique time series related to event-based changes (e.g., from fires), seasonality, and trends in atmospheric CO. Simply put, Terra provides unique, high-quality, long-term measurements that have immense value to both the science and applied/operational/national interests communities.

For the most part, the proposal prioritized continuation of data collection and operational production of data products. Important new science in the extended mission is related to the MLT drift, which will provide new opportunities to observe land, ocean, and atmospheric properties and processes at large solar zenith angles and earlier in the diurnal cycle.

An additional ~3 years of data will extend the unique data record provided by Terra. In an era of climate change and variability, each additional year can provide substantial value. For example, with an incipient El-Nino currently developing, continued data collection and provision of data products over the next 3 years will enable a large variety of studies to study ENSO-related variability in oceans, terrestrial ecosystems, and the atmosphere.

Weaknesses
There were few weaknesses identified by the panel. One issue that was raised is that the panel expressed some concern that the project team may be underestimating the challenges and degradation in data products related to changes in the MLT. However, this was a relatively minor concern.

Value of the data record with the additional 3-6 years of data and overall data continuity
Overall, there is substantial value to acquiring an additional ~3 years of data from Terra. Outside of Advanced Very High Resolution Radiometer (AVHRR), Terra provides the longest continuous record of global Earth system observations from any single mission, but with much higher overall radiometric quality and supporting a much larger set of applications and science questions. ASTER, MOPITT, and MISR are all unique. Because of inherent variability in the Earth system, each additional year of data provides substantial scientific value for characterizing trends, change, and variability in the Earth's oceans, atmosphere, and terrestrial ecosystems. Note that the need for continuity is especially relevant given the nascent El-Nino, which will provide an important opportunity to study variability in coupled ocean-atmosphere/climate

processes, along with associated impacts on terrestrial ecosystems.

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

Strengths
Extension of the Terra mission is highly aligned with NASA ESD research objectives and focus areas. MODIS, CERES, ASTER, MOPITT, and MISR all contribute fundamental data that support process-based understanding of variability and change in the Earth's climate system, in atmospheric composition and chemistry (specifically aerosols and CO), weather, and atmospheric dynamics. The core goal of the Terra mission proposal is to extend collection and production of systematic data records required by the scientific community. In doing so, the mission extension will support a wide variety of investigations to understand the earth's water and energy cycles, measure ecosystem changes, improve weather and air quality forecasts, reduce climate uncertainty, and understand surface dynamics, geological hazards, and disasters. Specifically, the mission extension will provide global quantitative measurements of Earth's atmosphere, land, cryosphere, and oceans through 87 core data products that provide information related to a diverse and comprehensive suite of Earth system properties and processes including: cloud cover and height, cloud droplet effective radius, sea surface temperature, top of atmosphere energy balance; aerosols, aerosol optical depth, CO and PM2.5, primary productivity in terrestrial and marine ecosystems, surface energy balance, drought and evaporative stress, convective plumes, polar winds, high resolution digital elevation models, ice sheet dynamics, sea ice dynamics, and flood extent, among many others. Both individually, and in combination with observations collected from other missions, data from Terra's suite of five instruments provide core measurements that are essential to NASA's ESD research objectives.

Similar comments apply to Terra's contributions to Decadal Survey priorities for observables. One or more instruments onboard Terra contributes to 15 'top-level' science goals (11 of which are identified as "most important" or "very important" in the Decadal Survey), and all five instruments are identified as part of the NASA's Program of Record included in Appendix A of the Decadal Survey.

Weaknesses
No significant weaknesses

Standard data product quality: Excellent

Strengths
The vast majority of the 87 core data products generated by the five instruments onboard Terra are high quality. Almost all (with the exception of a few newly developed products) have been refined multiple times via successive Collections and validated using community established standards and protocols. The instruments are all healthy and are continuously monitored for anomalies and to maintain calibration as detector and on-board electronics degrade over time. Overall, given the age of the mission, degradation of data quality is modest and is well characterized and accounted for. Science teams continue to refine products, but most adjustments are minor aside from updates that are already in process (e.g., Collection 7 for MODIS). With the exception of a few newer products, the large majority of products only

require maintenance with relatively automated production.

Weaknesses
One challenge and priority for the proposed mission extension will be analysis, maintenance, and/or adjustments to algorithms to maintain the quality, consistency, and continuity of long-term data records as the Terra's MLT slowly shifts earlier through the end-of-mission. The project team expressed strong confidence that existing algorithms are sufficiently robust to maintain high-quality data records as the MLT drifts. However, given the importance of the long-term record provided by Terra to studies of Earth system variability and change it's essential that, if extended, the mission team monitor impacts on data products to ensure their integrity. Note that this is not really a weakness, per se. However, the panel wanted to reinforce the importance of monitoring data products for systematic changes (and increases in uncertainty) arising from the MLT drift.

Technical Performance: Excellent

Strengths
Based on the information included in the proposal, with the exception of the SWIR bands on ASTER, the hardware status and performance of all instruments onboard Terra are excellent. The solar diffuser for MODIS is degrading with age, but associated drift in calibration is being effectively monitored and corrected. Life expectancy for all instruments is more than sufficient to provide good quality data up to the end of planned data collection.

Weaknesses
The proposal makes multiple allusions to increased risk of data loss or degradation in the event of unforeseen instrument anomalies due to staff cuts. However, the team indicated that risk of data loss is quite modest (~1%), which seems acceptable.

Cost Performance

Costs were appropriate. The team expressed strong confidence that they would be able to meet all project goals for both data acquisition and production of data products within in-guide funding levels.

Operational, Applications, and Non-research Value

The science panel concurs with the assessment of the National Interests panel. The operational, applications and non-research communities use data from Terra extensively and derive substantial value for a wide range of use-cases with high societal value.

Other Comments

The proposal was complete and thorough. Given the limited time period before passivation and the heavy reliance of the operational and applications user communities on Terra, the panel strongly concluded that effort and focus is needed to transition these communities from Terra to available alternatives, if/as available.

A3.12 Mission: TSIS-1

Mission Extension Conclusion

FY2024-2026
Continuation with augmentations to the current baseline.

FY2027-2029
Continuation as currently baselined.

Overview

The Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) mission has two instruments onboard the International Space Station (ISS): total irradiance measurement (TIM) and spectral irradiance measurement (SIM). TIM provides the total solar irradiance (TSI) at all wavelengths as 6-hr averages, while SIM provides the spectral solar irradiance (SSI) in 200 – 2400 nm every 12 hours. During its primary mission from March 2018 to March 2023, TSIS-1 achieved all of its primary mission objectives, including the delivery of the level-3 data products of TSI at the absolute accuracy of 0.01% and SSI at the absolute accuracy of 0.02%. These data products have been used for a wide range of scientific research and applications, by providing reference datasets for (a) calibration or inter-calibration of other satellite measurements of moonlight and reflected sunlight, and (b) climate research and prediction that require accurate time series of TSI and SSI data to understand climate variability (such as temperature) and atmospheric composition (such as ozone). The TSIS-1 mission fulfills the critical need of long-term continuity of the Program of Record for TSI and SSI, as recommended by the 2017 Decadal Survey. TIM and SIM are both healthy, and their continuation in 2024-2029 will lead to the extension of the 44-year TSI and 20-year SSI data sets, ensure a successful overlap between TSIS-1 and TSIS-2 (slated for launch in Feb. 2025), and observe a full range of solar variabilities during Solar Cycle (SC)-24 and SC-25. Its extension plan also asks for an augment to extend the spectral coverage of SSI measurements from 2400 nm to 2800 nm. The extension will continue its delivery of level 3 data products, outstanding contribution to the Climate Data Record of TSI and SSI that are of interest to many agencies (such as NOAA and ESA) as well as NASA's research programs and missions (such as AERONET, TEMPO, CERES, CLARREO-Pathfinder, etc.) and the climate research community. The panel suggests that the mission should be continued with the proposed modest augmentations to the current in-guide baseline for the FY 2024-26 period and be further continued as currently baselined for FY 2027-29 period.

Scientific merits: Excellent

Strengths
The TSIS-1 mission achieved all its primary mission objectives with excellence. Its data products of TSI and SSI have contributed significantly to the establishment of reference data products in the climate research community for constraining the radiative energy budget in the Earth system modeling, including those as part of the past and future climate modeling intercomparison projects (CMIP). These data products are also uniquely used in the inter-calibration of different satellite sensors and ground-based instruments in the solar spectrum, which is fundamental for the stability and accuracy of the retrieval (often level-2 and level-3) products from these satellite sensors (such as CERES, OMI, AERONET, etc.). These data

products have helped the science community to better understand the changes of atmospheric composition (such as ozone and aerosols) and climate variability (such as temperature and water vapor) because of natural variation of solar radiation. The review panel evaluated the scientific merits of TSIS-1 satellite mission overall as excellent.

Considering that both TIM and SIM are in healthy condition, the proposed extension of TSIS-1 will continue its excellence in scientific merits and service to the Earth sciences community because of its uniqueness in achieving the measurements of TSI and SSI with high accuracy and stability. The review panel concurred that there are compelling reasons for the extension of the TSIS-1 mission to complete the measurements of TSI and SSI in two solar cycles and have significant overlap with the future TSIS-2 mission to ensure that the continuity and stability of TSI and SSI data can be continued by TSIS-2 beyond 2025. The extension will help to better improve the modeling of solar cycle and the prediction of solar energy inputs to our home planet, thereby improving the fidelity in the prediction of regional and global climate from the present to the end of 21st century. The review panel supports that, as part of the TSIS-1 extension and augmentation efforts, the SIM should conduct the measurements from 2400 nm to 2800 nm, enabling the possibility to obtain new and insightful characterization of solar radiation in that spectrum. By filling the gap to provide accurate measurements of solar irradiance data in this spectrum range, TSIS-1 mission can help improve the understanding and modeling of radiative effects of water vapor, aerosols (such as dust), and other gases in the atmosphere, which contributes to the further advancement of climate prediction and satellite algorithm retrievals. Overall, the panel agrees that by pairing instruments measuring both TSI and SSI in one platform, TSIS-1 is unique in generating one of the most important datasets for studying climate change and atmospheric composition, providing the total and spectral solar irradiance datasets that define the top boundary conditions for the Earth system modeling and many satellite or ground-based retrieval algorithms.

Weaknesses

A minor weakness is that the engagement with the scientific community could be further enhanced. For example, efforts of TSIS-1 project team and science team so far have appeared to focus nearly exclusively on the quality assurance and control (QA/QC) of TSI and SSI data records. This focus might be needed in the beginning of the primary mission time, but considering the maturity, stability, and robustness of the TSIS-1 instruments and datasets as well as the TSIS's heritage from SOURCE, additional efforts to bring the data users into the mission investigation and science teams would be beneficial. This could be accomplished via continued organization of and participation in sessions at meetings like AMS and AGU (atmosphere section), which may further broaden the scientific impact of the TSIS-1, improve the data utility from data users' point of view, and increase the number of TSIS-1 data users.

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

Strengths

Extension of TSIS-1 is highly relevant to the ESAS2017 and ESD's focus areas. Direct solar irradiance measurement from space is a key Program of Record as stated in ESAS2017. The extension will enable multi-decadal records of TSI and SSI for climate studies with ever-improved accuracies and stabilities. The TSI and SSI are two key datasets needed to address key science questions in ESD focus areas related to atmospheric composition and climate variability

and change.

In addition, the NOAA Climate Records for TSI and SSI are primarily based on Solar Radiation and Climate Experiment (SORCE) and TSIS-1 observations. The Intergovernmental Panel on Climate Change (IPCC) recognizes that measuring TSI and SSI is essential for understanding how solar radiation is deposited in the atmosphere and at the surface.

Weaknesses
None.

Standard data product quality: Excellent

Strengths
Level-3 TSI and SSI are two premier datasets with robust quality assurance (QA)/quality control (QC) for scientific use. The products have been assessed and the uncertainties in the product well established via independent measurements (and on-board degrading cross check) in a systematic and statistically robust way representing a broad array of conditions. Quality of data products is high and continues to be maintained.

Weaknesses
None.

Technical Performance: Excellent

Strengths
Both SIM and TIM are in excellent health. As of 7 March 2023, 86% of the daily and 73% of the six-hourly TIM level-3 data are available, meeting mission threshold requirements. As of 7 March 2023, 86% of the daily and 73% of the six-hourly TIM level-3 data are available, meeting mission threshold requirements. The primary causes of the data gaps are to safeguard the instrument during ISS operations and tackle an issue related to heater saturation, both of which are inherent to the operational environment on ISS.

Cavity degradation in TIM is ~ 12 ppm / year, meeting threshold stability requirements. The most frequently used shutter is SIM Channel A shutter and is currently at ~50% of the tested life; SIM Channel B and SIM Channel C are used less frequently than SIM Channel A, ~12% and ~1%.

The TSIS-1 Thermal Pointing System (TPS) has two high-rate fine sun sensors (HFSS-A and B), and a gimbal pointing system. HFSS-B was contaminated on March 19, 2022, during the 67S docking (Soyuz MS-21). Corrections for the HFSSB anomaly have been applied for the SIM data products (but none needed for TIM), and the current and future operations use HFSS-A for the TPS solar pointing.

Weaknesses
A minor weakness is that the optical degradation occurring in the UV at 220 nm appears to be

somewhat large (10%) in 5 years for SIM Channel A. This degradation, however, is corrected by comparisons with Channel B (bi-weekly) and Channel C (every six months).

A minor weakness involves the loss of the temperature sensor on the SIM Channel B prism which is located in the same mechanism that holds the prisms for Channels A & C. This temperature is used to evaluate the index of refraction which impacts the wavelength calibration. By use of the temperature sensors in the other two prisms and temperature correlations prior to this failure, the Channel B prism temperature is determined. Using this method, no change in the sensitivity degradation is observed thus confirming this process.

Cost Performance

The extension requests a budget that is a 24% reduction from its primary mission budget. The reduction includes reduced frequency in progress reports, slightly less support for operation staff, calibration updates, ground software support staff, and travel. The request budget will support civil servants' efforts for project management at the level of 1.9 FTE in FY24 and 1.8 in FY25-FY29, as well as contractual efforts for project operations at the level of 1.4 WYE (work-year-equivalent) in FY24 and 1.3 WYE in FY25-FY29.

As in-kind support, based on previous allocations, the TSIS-1 Project Scientist and Deputy Project Scientist expect to receive ~$369 K/year for labor and procurement needs, in FY2024 and beyond.

The extension also proposes an over-guide budget that includes an extra of $200K per year for FY25-FY29 to acquire the measurements in 2400-2800 nm range. While supportive of the new science associated with this wavelength range, the panel found that the justification for this fund request could be improved by providing a bit more description of the details on how this fund will be spent.

The budget is flat for the most part. One comment from the budget panel is that it remains unclear how inflation will impact planned activities.

Operational, Applications, and Non-research Value:

Based on the sub-panel assessment, TSIS-1 data is regarded as some utility. During the National Interests Panel, the USGS considered the TSIS-1 data as critical. TSIS-1 is ranked by the National Interests Panel as the 10th most important of 12 ESD missions.

Other Comments

None

APPENDIX 4

Acronyms and Abbreviations

TERM	DEFINITION
3D	three dimensional
A&A	Assessment and Authorization
ACC	accelerometers
ACS	Attitude Control System
AEB	Brazilian Space Agency
AERONET	AErosol RObotic NETwork
AGU	American Geophysical Union
AI	Aerosol Index
AIRS	Atmospheric Infrared Sounder
ALTIUS	Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere
AM	ante merīdiem
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ANY	Australian New Year's
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System (AOCS)
AOS	Atmosphere Observing System
AQ	air quality
ARSET	Applied Remote Sensing Training
ASCAT	Advanced Scatterometer
ASDDC	Atmospheric Science Data Center
ASF	Alaska Satellite Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Advanced Topographic Laser Altimeter System
AVHRR	Advanced Very High Resolution Radiometer
AWS	Amazon Web Services
BoE	Basis of Estimates
BRDF	Bidirectional Reflectance Distribution Functions
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMS	Copernicus Atmosphere Monitoring Service
CARA	Conjunction Assessment Risk Analysis
CDC	Centers for Disease Control and Prevention
CDR	climate data record
CERES	Clouds and the Earth s Radiant Energy System
CGPS	Cold Gas Propulsion System
CIMR	Conical Imaging Microwave Radiometer
CIRIS	Compact Infrared Radiometer in Space
CLARREO	Climate Absolute Radiance and Refractivity Observatory18
CMAQ	Community Multi-scale Air Quality
CMIP	Coupled Model Intercomparison Project
CMP	Contamination Monitoring Package

CNES	Centre National d'Études Spatiales
CO	Core Observatory
CoDAS	Constituent Data Assimilation System
COVID	coronavirus disease
CPC	Climate Prediction Center
CRIS	Cross-track Infrared Sounder
Crop-CASMA	Crop Condition and Soil Moisture Analytics Tool
CSA	Canadian Space Agency
CTIM	Compact Total Irradiance Monitor
CTS	Cornell Technical Services
CYGNSS	Cyclone Global Navigation Satellite System
DA	data analysis
DAAC	Distributed Active Archive Center
DDM	delay Doppler maps
DLR	Deutsches Zentrum für Luft- und Raumfahr
DPR	Dual-frequency Precipitation Radar
DSCOVR	Deep Space Climate Observatory
ECCOE	EROS Calibration/Validation Center of Excellence
ECMWF	European Centre for Medium Range Weather Forecasts
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ENSO	El Niño – Southern Oscillation
EOL	end of lifetime
EOS	Earth Observing System
EPA	Environmental Protection Agency
EPIC	Earth Polychromatic Imaging Camera
EPS	Electrical Power Subsystem
EROS	Earth Resources Observation and Science
ESA	European Space Agency
ESD	Earth Science Division
ESDIS	Earth Science Data and Information System
ESMO	Earth Science Mission Operations
ESO	Earth Science Observatory
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FAS	Foreign Agricultural Service
FDS	Fire Dynamics Simulator
FY	fiscal year
GCB	Global Change Biology
GEDI	Global Ecosystem Dynamics Investigation
GEMS	Geostationary Environment Monitoring Spectrometer
GEOS	Goddard Earth Observing System
GES DISC	Goddard Earth Sciences Data and Information Services Center
GFZ	GeoForschungsZentrum (German Research Center)
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer

GMI	GPM Microwave Imager
GNSS	Global Navigation Satellite System
GNSS-R	GNSS-Reflectometry
GPM	Global Precipitation Measurement
GPM-CO	GPM Core Observatory
GPS	Global Positioning System
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GSAT	global surface air temperature
GSICS	Global Space-based Inter-Calibration System
GST	global stocktakes
HFSS	high-rate fine sun sensors
HRDLS	High Resolution Dynamics Limb Sounder
HSB	Humidity Sounder for Brazil
HT-HH	Hunga Tonga–Hunga Ha'apai
HW	hardware
HyTI	Hyperspectral Thermal Imager
IBTrACS	International Best Track Archive for Climate Stewardship
ICESat-2	Ice, Cloud and land Elevation Satellite-2
IF	intermediate frequency
IGES	Institute for Global Environmental Strategies
IGS	International GNSS Service
IMERGE	Integrated Multi-satellitE Retrievals for GPM
INCUS	Investigation of Convective Updrafts
IPAD	International Production Assessment Division
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
ISS	International Space Station
IT	information technology
JAXA	Japan Aerospace Exploration Agency
JEDI	Joint Effort for Data assimilation Integration
JPSS	Joint Polar Satellite System
K	thousand
km	kilometer
KMNI	Koninklijk Nederlands Meteorologisch Instituut
L	Level
L1	The first Sun-Earth Lagrange point
LEO	low Earth orbit
LIS	Lightning Imaging Sensor
LRS	Laser Reference System
M	million
MAIAC	multi-angle implementation of atmospheric correction
MC	Mass Change
med	medium
METI	Ministry of Economy, Trade and Industry
MIMU	Miniature Inertial Measurement Unit
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
MODAPS	MODIS Adaptive Processing System
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurement Of Pollution In The Troposphere
MOS	mission operations systems
MOU	memorandum of understanding
NACHOS	Nanosat Atmospheric Chemistry Hyperspectral Observation System
NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NCEP	National Centers for Environmental Prediction
NDMC	National Drought Mitigation Center
NEN	Near Earth Network
NESDIS	National Environmental Satellite, Data and Information Service
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NIR	near infrared
NISAR	NASA-ISRO Synthetic Aperture Radar
NIST	National Institute of Standards and Technology
NISTAR	NIST Advanced Radiometer
NIWA	National Institute of Water and Atmospheric Research
nm	nanometer
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPP	NPOESS Preparatory Project
NPS	National Park Service
NRT	near real time
NSIDC	National Snow and Ice Data Center
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
NSO	Netherlands Space Office
NWC	National Water Center
NWS	National Weather Service
NZ	New Zealand
OBC	on-board computer
OBPG	Ocean Biology Processing Group
OCO-2	Orbiting Carbon Observatory-2
OIIR	Office of International and Interagency Relations
OMI	Ozone Monitoring Instrument
OMPS-Limb	Ozone Mapping and Profiler Suite-Limb

OPC	Offshore Precipitation Capability
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PAR	photosynthetically active radiation
perf	performance
PI	Principal Investigator
PO.DAAC	Physical Oceanography Distributed Active Archive Center
PPBE	Planning, Programming, Budgeting, and Execution
PPD	Precision Pointing Determination
ppm	parts per million
PREFIRE	Polar Radiant Energy in the Far-InfraRed Experiment
PSC	polar stratospheric clouds
QA	quality assurance
QC	quality control
QMT	questions to mission team
ROSES	Research Opportunities in Space and Earth Science
RT	realtime
RTS	random telegraph signal
RY	real year
S&MA	Safety and Mission Assurance
SAGE III	Stratospheric Aerosol and Gas Experiment III
SAR	synthetic aperture radar
SBEM	space-based environmental monitoring
SBG	Surface Biology and Geology
SC	solar cycle
SCG	Storm-Centric Gridded
SDOS	Science Data Operations System
SDS	Science Data System
SERVIR	random telegraph signal
SIF	solar induced chlorophyll fluorescence
SIM	spectral irradiance measurement
SIPS	Science Investigator-led Processing Systems
SLI	Sustainable Land Imaging
SMAP	Soil Moisture Active/Passive
SMD	Science Mission Directorate
SMOS	Soil Moisture and Ocean Salinity
SN	Space Network
SNoOPI	Signals of Opportunity P-band Investigation
SORCE	Solar Radiation and Climate Experiment
SpaceX	Space Exploration Technologies Corporation
SR	Senior Review
SSI	spectral solar irradiance
STA	star tracker assembly
SW	shortwave
SWIR	shortwave infrared
SWOT	Surface Water Ocean Topography
TAA	Terra, Aqua, and Aura

TBD	to be determined
TC	tropical cyclone
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TES	Tropospheric Emission Spectrometer
TIM	total irradiance measurement
TO	Targeted Observable
TPS	Thermal Pointing System
TRMM	Tropical Rainfall Measuring Mission
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
TROPOMI	TROPOspheric Monitoring Instrument
TSI	total solar irradiance
TSIS	Total and Spectral Solar Irradiance Sensor
UFS	Unified Forecast System
UMIP	USACE Model Interface Platform
UNEP	United Nations Environment Programme
US	United States
USA	United States of America
USACE	US Army Corps of Engineers
USAF	United States Air Force
USAID	US Agency for International Development
USDA	US Department of Agriculture
USFS	United States Forest Service
USGS	US Geological Survey
UV	ultraviolet
V	version
VAAC	Volcanic Ash Advisory Center
VIIRS	Visible Infrared Imaging Radiometer Suite
VOD	vegetation optical depth
WCRP	World Climate Research Programme
WFS-M	Weather System Follow-On Microwave
WMO	World Meteorological Organization
WOTIS	Waters of the United States
WYE	work-year-equivalent
yr	year
YSLF	young seas with limited fetch