CGMS

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NASA REPORT ON THE STATUS OF CURRENT AND FUTURE EARTH SATELLITE SYSTEMS

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Executive summary

NASA currently supports the operations of 21 Earth Science missions. Since CGMS-45 (June 2017), NASA's Earth Science program launched the Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) mission (jointly with Germany's GFZ German Research Centre for Geosciences), several U-class technology demonstration satellites, and one instrument (Total Solar Irradiance Sensor, TSIS-1) to the International Space Station (ISS), as well as continued development of several new missions. During this time, GRACE (a twin-spacecraft mission, which represented a long-standing partnership with Germany) ceased operations and the Tropospheric Emission Spectrometer (TES) instrument was turned off following a detailed assessment as part of the biennial Senior Review. CloudSat moved out of the A-Train because of hardware limitations, and some instruments in extended mission operations continue to have reduced capability, but still routinely provide valuable data. Although all NASA operated missions discussed in this report were conceived as research missions, the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications. NASA has also continued to support the development and deployment of direct operational application Earth sensing missions with the Landsat series for the USGS and the GOES and JPSS series for NOAA.

NASA's Earth Science Division (ESD) is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space for advancing Earth sensing science research. The program advances knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A balance of satellite measurements, science research, technology development and applications are all needed to address and observe a complex global Earth system. NASA's plans include the launch of 11 missions and 8 instruments (on host missions) in the future.

During this past year, the National Academies of Science, Engineering, and Medicine released their latest decadal survey for Earth Sciences, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, which provides guidance to the ESD on scientific questions to be addressed and observations to be made over the coming decade. NASA's Earth Science Division is in the process of responding to the survey, working in consultation with the community as it develops plans for the future.

NASA Report on the status of current and future satellite systems

1 INTRODUCTION

NASA currently supports the operations of 21 Earth Science missions (see Tables 1 to 3). Since CGMS-45 (June 2017), NASA's Earth Science Division launched the Total Solar Irradiance Sensor (TSIS-1) as a hosted payload on the International Space Station (ISS), the Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) in partnership with Germany's GFZ German Research Centre for Geosciences, and several U-class technology demonstration satellites. During this time, GRACE, a twin-satellite mission carried out together with our partners in Germany, came to an end after ~15 years of operation. Operations of the Tropospheric Emission Spectrometer (TES) instrument aboard the Aura satellite (launched in 2004), which had been limited because of hardware issues that led to intermittent performance outages and recovery processes, were completed following a recommendation of the biennial community-based Senior Review that assesses the performance of operating satellite missions that are beyond their "prime" period of operations. The CloudSat mission was moved out of the A-Train constellation to provide maximal protection to the other A-Train satellites in the event of additional satellite bus issues. The QuikSCAT and SORCE missions continue to show significant signs of aging and are operating in reduced data collection mode. Efforts for the Radiation Budget Instrument (RBI) were discontinued in response to cost and schedule challenges with the mission. Although all missions were conceived as research missions, the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications.

NASA's Earth Science Technology Office (ESTO) continues to support the development of U-class satellites as technology demonstrations; the RAVAN and ICECube satellites deployed prior to CGMS-45 continue to operate, and RainCube and TEMPEST-D satellites were launched to the International Space Station (ISS) on 21 May 2018 as technology demonstrations from the ESTO and Earth Venture programs, respectively.

NASA's Earth Science Program is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space. The program advances knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A balance of satellite measurements, science research, technology development and applications are needed to address a complex global Earth system. NASA's plans include the launch of 11 missions and 8 instruments (on host missions) in the future.

During this past year, the National Academies of Science, Engineering, and Medicine released their latest decadal survey for Earth Sciences, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, that provides guidance to the program on scientific questions to be addressed and observations to be made over the coming decade. In particular, it recommended that NASA's Earth Science

Division implement several new mission lines (Designated, Explorer, Earth-Venture Continuity), as well as initiate an incubator program that could help accelerate the capability for measurements that it did not feel were ready for near-term implementation from space. NASA's Earth Science Division is in the process of responding to the survey, working in consultation with the community, as it develops plans for the future.

NASA is also in the process of implementing a commercial satellite data buy program, having released a Request For Information (RFI) to US-based entities operating three or more satellites covering all longitudes. The plan, not yet completed, is for NASA to purchase limited data from those entities that met the terms of the RFI requirements and to then support several of NASA's currently supported investigators to assess the usefulness of the purchased data to address the research questions and applications objectives currently being pursued.

Note that this working paper focuses on those missions developed and/or operated by and for NASA's Earth Science Division (ESD); some of these missions are operated by NASA's partners, but are included here given ESD's significant leadership in their development. Two other divisions within NASA's Science Mission Directorate (SMD) have missions within their portfolios that may be of interest to CGMS members. The Heliophysics Division (HPD) studies the Earth's upper atmosphere, the sun, and the interactions between them, and is thus extensively involved with measurements that contribute to the knowledge of Earth's charged particle and magnetic environment, and thus all aspects of Space Weather. These activities are reported through the CGMS Space Weather Task Team. NASA's Joint Agency Satellite Division (JASD) builds satellites for the National Oceanic and Atmospheric Administration (NOAA) on a reimbursable basis. Since NOAA holds the requirements and resources for these missions, NOAA will report on them as part of its inputs to CGMS. Readers interested in those programs should consult the relevant working papers.

2 CURRENT SATELLITE SYSTEMS

The following tables summarize ESD's satellite systems:

Table 1: Current ESD LEO Satellites
Table 2: Current ESD HEO (or other) Satellites
Table 3: Current ESD Research and Development (R&D) Satellites

Table 1 - Current NASA LEO Satellites

Satellite	Operating Agency	ECT / Inclination	Mean Altitude	Launch Date	Data Access	Instruments and Details
Landsat-7	* USGS (support from NASA)	10:00 (D)	705 km	15-Apr-1999	EROS	**Science:** High-resolution image information of the Earth's surface (Follow on to Landsat series) **Instruments:** ETM+
Jason-2 (Op) (Ocean Surface Topography Mission)	* NOAA (support from NASA, EUMETSAT and CNES)	66-deg Non Sun-Sync	1336 km	20-Jun-2008	Handbook	**Science:** Sea surface topography (Follow on to Jason-1) **Instruments:** LRA, DORIS, POSEIDON-3, AMR, GPSP
Suomi-NPP (Op)	* NOAA (support from NASA)	13:30 (A)	833 km	28-Oct-2011	Suomi Data Direct Broadcast	**Science:** Atmospheric dynamics, water and energy cycle, clouds and aerosols, radiation, GHG, air/sea fluxes; also supporting operational weather forecasting & ozone monitoring **Instruments:** CrIS, CERES, VIIRS, ATMS, OMPS
Landsat-8	* USGS (support from NASA)	10:11 (D)	705 km	11-Feb-2013	EROS	**Science:** High-resolution image information of the Earth's surface (Follow on to Landsat series) **Instruments:** OLI, TIRS

Table 2 - Current NASA HEO (or other) Satellites

Satellite	Operating Agency	Orbit	Launch Date	Data Access	Instruments	Details: Applications
DSCOVR^	* NOAA (support from NASA)	Lagrange (L1)	11-Feb-2015	PlasMag (NOAA) EPIC NISTAR	PlasMag, EPIC, NISTAR	Solar Wind Plasma, Interplanetary 3-D magnetic field vectors UV and VIS radiance for derived total ozone, clouds, aerosols, and vegetation indices

** Although NASA does not officially "operate" these missions, NASA supports operations through the science instrumentation.*
^ Instrument operation continues through FY18 consistent with the Consolidated Appropriations Act, 2018.

Table 3 - Current NASA Research and Development (R&D) Satellites

Satellite	Operating Agency	ECT / Inclination	Mean Altitude	Launch Date	Data Access	Instruments	Details: Applications
QuikSCAT	NASA	06:00 (A)	803 km	19-Jun-1999	PO.DAAC	SeaWinds	Sea surface wind vectors
Terra (EOS AM-1)	NASA	10:30 (D)	705 km	18-Dec-1999	Terra Data Direct Broadcast	ASTER, MODIS, MOPITT, MISR, CERES	Atmospheric dynamics and chemistry, water and energy cycle, clouds, aerosols, radiation, GHG, carbon and water, air-land exchange

Aqua (EOS PM-1)	NASA	13:30 (A)	705 km	4-May-2002	EOSDIS Direct Broadcast	MODIS, AIRS, CERES, AMSU-A, AMSR-E, HSB	Atmospheric dynamics, water and energy cycle, clouds and aerosols, radiation, GHG, air/sea fluxes, precipitation
SORCE	NASA	40-deg Non Sun-Sync	640 km	25-Jan-2003	GES DISC	SIM, SOLSTICE, TIM, XPS	Total and spectral solar irradiance
Aura	NASA	13:45 (A)	705 km	15-Jul-2004	GES DISC	MLS, TES, HIRDLS, OMI	Chemistry and dynamics of atmosphere, O_3, GHG, aerosols
CALIPSO	NASA (support from CNES)	13:30 (A)	705 km	28-Apr-2006	ASDC	CALIOP, IIR, WFC	Aerosols and clouds vertical profiling
CloudSat†	NASA	13:30 (A)	705 km	28-Apr-2006	CloudSat DPC	CPR	Cloud vertical profiling
GPM Core	NASA (support from JAXA)	65-deg Non Sun-Sync	407 km	27-Feb-2014	PMM Data	GMI, DPR	Global precipitation, evaporation, water cycle
OCO-2	NASA	13:30 (A)	705 km	02-Jul-2014	GES DISC	Spectrometer	Carbon dioxide sources and sinks and solar-induced fluorescence
SMAP	NASA	18:00 (A)	685 km	31-Jan-2015	ASF (radar) NSIDC (cryosphere and land microwave)	L-Band Radar, L-Band Radiometer	Soil moisture, freeze-thaw state

CYGNSS (8 small satellites)	NASA	35-deg Non Sun-Sync	500 km	15-Dec-2016	PO.DAAC	GPS	Ocean surface winds for tropical storms and hurricanes
SAGE-III-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	19-Feb-2017	ASDC	Spectrometer	Stratospheric ozone, aerosols, and water vapor
LIS-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	19-Feb-2017	GHRC	Optical Imager	Lightning
TSIS-1-ISS Intl. Space Station Instrument only	NASA	51.6-deg Non Sun-Sync	407 km	15-Dec-2017	TBD	SIM, TIM	Total and spectral solar irradiance
GRACE-FO (Follow-On)	NASA/GFZ	89-deg inclination Non Sun-Sync	490 km	21-May-2018	TBD	Accelerometer, GPS RO	Earth mass distribution, with application to ground water, ocean currents and ice sheets; vertical temperature and humidity profiles of the atmosphere.

† CloudSat exited the A-train constellation in February 2018 by lowering its altitude. A final orbit for renewed science operations orbit has not yet been defined.

Failed / Decommissioned Instruments
** HSB on Aqua*
** AMSR-E on Aqua*
** HIRDLS and TES on Aura*
** L-Band Radar on SMAP*

Reduced Function Instruments
** SeaWinds on QuikSCAT (no antenna rotation, only used for cross-calibration)*
** ASTER on Terra (SWIR module not functioning)*
** AMSU on Aqua (channels-1, 2, 4, 5 and 7 failed)*
** SORCE - Battery degradation, Instruments turned off during orbit night*
** CloudSat - Battery degradation, Instruments turned off during orbit night*
** QuikSCAT – Battery degradation, instruments turned off during eclipse period from November to January*

3 STATUS OF CURRENT LEO SATELLITE SYSTEMS

After the onset of repeated gyro anomalies, **Jason-2** lowered its orbit by ~27 km in July 2017, transitioning to a long-repeat orbit. This marked the beginning of a geodetic mission phase similar to that of Jason-1 near the end of its mission, designed to improve bathymetry and mean sea surface models. Gyro anomalies have continued, triggering five safeholds in the last year, and resulting in data outages from a few days to more than one month. Investigations into mitigation strategies are ongoing. The **Jason-3** satellite continues to operate nominally, extending the ocean topography measurements initiated with the TOPEX mission in 1992 and continued through the Jason-1 and Jason-2 missions. The Suomi National Polar-orbiting Partnership (**Suomi-NPP**) satellite experienced a solar array anomaly in April 2018 that reduced its power output by ~1/3, but nominal science operations continue, with more than adequate power margin.

4 STATUS OF CURRENT HEO (OR OTHER) SATELLITE SYSTEMS

The Deep Space Climate Observatory (**DSCOVR**) was launched on 11 February 2015 to the Sun-Earth Lagrange-1 (L1) point, 1.5 million kilometers from Earth towards the Sun, to provide continuous solar wind measurements for accurate space weather forecasting, and to observe the full, sunlit disk of Earth from a unique vantage point. The DSCOVR mission is a joint venture between NOAA, NASA and the U.S. Air Force. NASA built the spacecraft and operates the two Earth science instruments, the Earth Polychromatic Imaging Camera (**EPIC**) and the NIST Advanced Radiometer (**NISTAR**).

EPIC produces RGB color images of the sunlit disk of Earth, typically at least 11 times per day. The DSCOVR vantage point at L1 has afforded opportunities for some unique images. All EPIC color images are publicly available through the web page http://epic.gsfc.nasa.gov.

In addition to the RGB images, numerous science products are derived from EPIC. These include total column ozone and erythemal irradiance. Aerosol products include UV aerosol index, aerosol optical depth, single scattering albedo, and aerosol and cloud optical depth of aerosol layers above clouds. Two volcanic SO2 algorithms have been developed to retrieve volcanic SO2 columns from EPIC UV radiances. EPIC cloud products include Cloud Mask (CM), Cloud Effective Pressure (CEP), Cloud Effective Height (CEH), and Cloud Optical Thickness (COT). Surface Reflectance products include spectral bidirectional reflectance factors (BRF, aka surface reflectance) and bidirectional reflectance distribution function (BRDF). Vegetation products include Leaf Area Index (LAI) and diurnal courses of Normalized Difference Vegetation Index (NDVI), Sunlit Leaf Area Index (SLAI) and Fraction of incident Photosynthetically Active Radiation (FPAR) absorbed by vegetation.

NISTAR is designed to measure the absolute irradiance reflected and emitted from nearly the entire sunlit face of Earth seen from the L1 point. An accurate measurement of the irradiance provides insight into Earth radiation balance and helps quantify any changes in the radiation budget over time. Level 1a, Level 1b, and Level 2 data from both EPIC and NISTAR are available at the Langley Atmospheric Science Data Center (https://eosweb.larc.nasa.gov). Level 2 data sets include those for aerosols, total ozone, sulfur dioxide, clouds, total vertical columns of O_3 and SO_2, surface reflectivity, and Aerosol Index.

Note that operation of the Earth-viewing instruments on DSCOVR continue through FY18 consistent with the Consolidated Appropriations Act, 2018. They are identified for termination in FY19 in the President's FY19 Budget Proposal released 12 February 2018.

5. STATUS OF CURRENT R&D SATELLITE SYSTEMS

NASA's science data sets continue to be extended with many satellites operating well beyond their design life. Some satellite missions are producing data from healthy instruments as the operations teams work around their aging satellite bus limitations. Signs of battery aging have been observed on **CloudSat**, **QuikSCAT** and the Solar Radiation and Climate Experiment (**SORCE**), all of which require intensive battery management and/or duty-cycling of instruments, which can reduce both quality and spatial/temporal coverage of the datasets. Furthermore, CloudSat experienced a failure of one of its reaction wheels (RW #1) in June 2017, and subsequently lost the ability to reliably command another (RW #4) in December. Since that time, the satellite has been in a safe sun-point spin mode, and is not collecting science data. Options for returning to science operations are currently being studied. The QuikSCAT mission continues to stand down from data collection during the eclipse period from November to January each year. The current plan is to decommission QuikSCAT during the coming year. SORCE is operating in nominal science mode, collecting data during daylight only. The Gravity Recovery and Climate Experiment (**GRACE**) mission ended in October 2017 with a battery cell failure on the GRACE-2 spacecraft, which reduced the overall power to an insufficient level. Both of the GRACE satellites have since re-entered the Earth's atmosphere.

Instruments with reduced capability (noted in RED, Table 3) are QuikSCAT's SeaWinds (the antenna no longer rotates so data are used primarily to cross-calibrate with other on-orbit scatterometers), Terra's ASTER (the SWIR module is no longer functional), and Aqua's AMSU (channels 1, 2, 4, 5, and 7 are no longer operational). Aura's TES instrument was decommissioned at the end of January 2018, as planned, based on the 2017 Senior Review assessment of its reduced functionality. Other instruments that no longer provide data (also noted in RED, Table 3) are Aqua's HSB and AMSR-E, Aura's HIRDLS, and SMAP's L-Band Radar. CATS-ISS suffered a power anomaly in October 2017, which ended the mission. All other sensors are fully functional and are producing standard products that meet or exceed specifications.

5.1 Formation Flying

Several of the satellites in Table 3 fly in close proximity to each other at ~705 km altitude and ascending equator crossing times of ~13:30. Known as the A-train, this constellation was built up over more than a decade from the initial launch (Aqua in 2002) through the launches of PARASOL (2004, decommissioned 2013), Aura (2004), CloudSat (2006, exited 2018), CALIPSO (2006), the Japanese GCOM-W1 "SHIZUKU" satellite (2012), and the Orbiting Carbon Observatory-2 (2014). The constellation is actively managed to ensure appropriate separation even in the presence of collision avoidance maneuvers (see next sub-section). In light of its reaction wheel problems, CloudSat exited the A-train in February 2018, by lowering its orbit, to reduce the risk of collision to the other constellation members.

This proximity provides nearly-simultaneous measurements even though they are spread across multiple platforms from multiple providers. The broad range of complementary techniques used across these platforms, with different wavelengths and viewing geometries, are particularly valuable in studying atmospheric chemistry and physics because of the need to comprehensively measure physical state and trace gas and particle composition. There is a strong emphasis in the NASA research program that makes synergistic use of the A-Train instruments.

5.2 Collision Avoidance Monitoring

Once new missions are launched, NASA must continually monitor their positions to avoid collisions with other satellites. Changing solar activity has led to more uncertainty in collision analysis calculations and consequently intensified analysis and planning activities to determine collision avoidance maneuvers. A history of collision avoidance maneuvers is shown in Figure 1. Active monitoring of close approach events has steadily increased since 2008. In addition, potential conjunctions between operational, maneuverable satellites have increased, necessitating communication between the satellite operators to coordinate avoidance maneuver planning. In addition to increasing the resources dedicated to collision assessment, NASA continually improves the agency’s orbital debris procedures, and invests in analysis tool improvements.

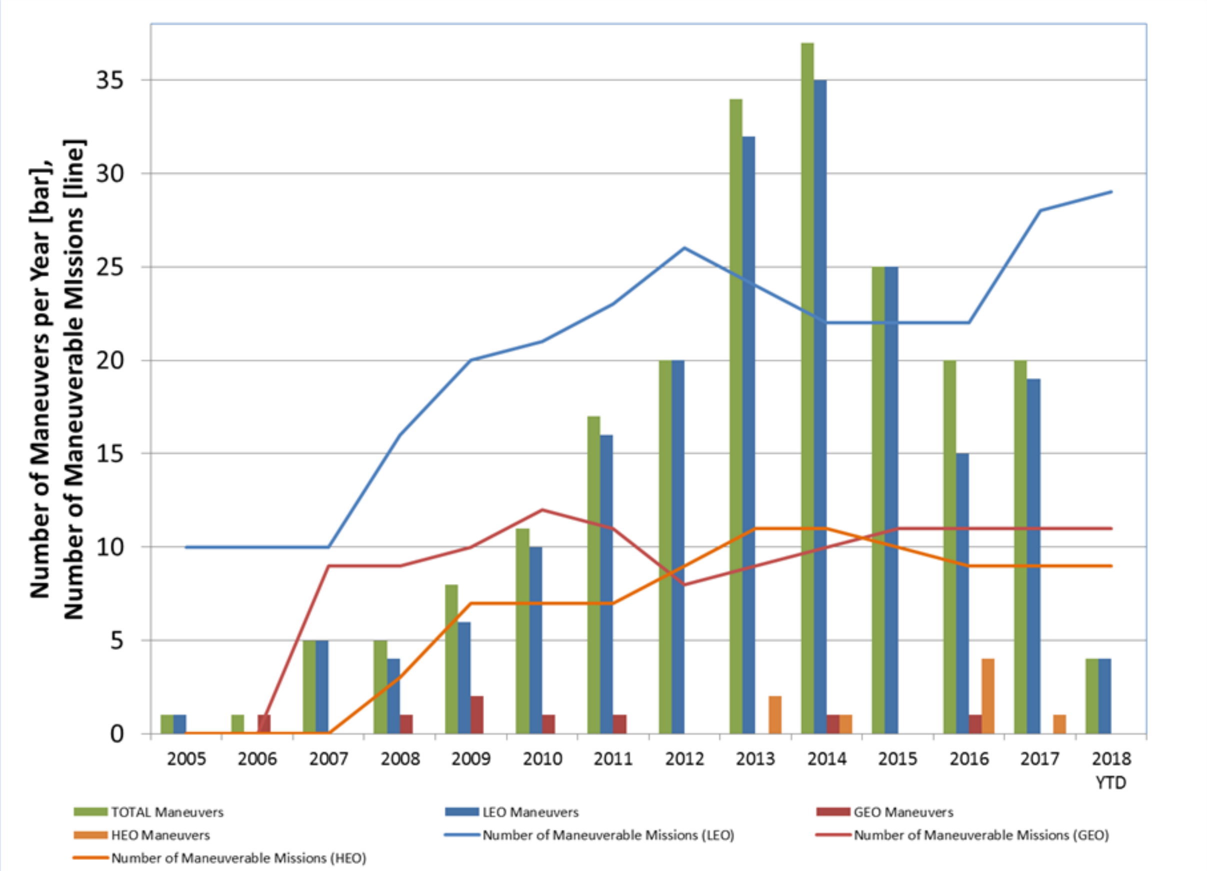

Figure 1: *History of collision avoidance maneuvers.*

5.3 Measurement Continuity and Transition to Follow-on Missions

5.3.1 Orbiting Carbon Observatory-2 (OCO-2)

Space based remote sensing is now providing new tools for studying atmospheric carbon dioxide (CO2), methane (CH4) and their contributions to the global carbon cycle. The Orbiting Carbon Observatory-2 (**OCO-2**) is the first NASA mission designed to measure atmospheric carbon dioxide (CO2) with the precision, accuracy, resolution, and coverage needed to quantify CO2 fluxes (sources and sinks) on regional scales over the globe. OCO-2 was successfully launched on 2 July 2014, and was inserted at the head of the 705-km Afternoon Constellation (A-Train) on 3 August 2014. OCO-2 completed it nominal 2-year science mission on 16 October 2016 with a healthy spacecraft and instrument and began its first extended mission.

In 2019, NASA plans to deploy the OCO-2 flight spare instrument on the International Space Station (ISS) as the Orbiting Carbon Observatory-3 (**OCO-3**) mission. The instrument is currently in the final stages of its pre-launch testing. While the OCO-2 and OCO-3 spectrometers are nearly identical, differences in the OCO-2 and OCO-3 orbits and observing capabilities will provide new insights into the role of CO2 in the global carbon cycle.

5.3.2 Gravity Recovery and Climate Experiment Follow-On (GRACE-FO)

The Gravity Recovery and Climate Experiment Follow-On (**GRACE-FO**) mission, a partnership with Germany's Research Centre for Geosciences (GFZ) was launched 22 May 2018. GRACE-FO will continue the observations from the recently-completed GRACE mission. GRACE-FO will also test and demonstrate an experimental instrument using lasers instead of microwaves for the between-satellite ranging, which promises to improve the precision of separation distance measurements on future generations of GRACE satellites by a factor of up to 20, thanks to the laser's higher frequencies.

5.3.3 Total and Spectral Solar Irradiance Sensor on the ISS (TSIS-1-ISS)

NASA's Solar Radiation and Climate Experiment (**SORCE**) launched in 2003 to provide total solar irradiance (TSI) data, data essential to quantify Earth's energy budget. The mission carries four instruments including a Spectral Irradiance monitor (SIM) and a Total Irradiance Monitor (TIM). While SORCE continues to collect data, NASA has developed and launched the next generation TSI-observing Satellite - The Total and Spectral Solar Irradiance Sensor-1 (**TSIS-1**) – to advance previous measurements.

TSIS-1 was successfully launched to the International Space Station (ISS) on 15 December 2017 and was integrated onto the ISS Express Logistics Carrier 3, Site 5. TSIS-1 completed its commissioning activities on 8 March 2018 with the acquisition of the first Spectral Irradiance Monitor (SIM) spectrum. Validation activities are underway, along with comparisons to spectra from SORCE SIM. At the time of this report a full assessment of data quality is unavailable. However, all systems are working within expected ranges. The TIM first-light occurred on 11 January 2018. Data are consistent with the SORCE TIM and TCTE TIM within measurement uncertainties. Like the SIM, all TIM elements are operating nominally. Data will be released to the GSFC DISC no later than six months following commissioning. Because TSIS-1 tracks the Sun, predicting observation times and flagging data quality depend on knowledge of solar availability within the glint-free instrument fields-of-view. A serendipitous result of continuous solar tracking is the construction of a raster image of the ISS structural obscurations using the TSIS-1 Fine Sun Sensors (FSS) that are used for active tracking. As the Sun passes behind the ISS structural elements the FSS is reduced. These signals are combined with pointing direction to construct obscuration maps. The maps are used to fine tune the instrument observation times as a function of the solar beta angle and to flag instrument data quality when there is partial occultation or additional solar glint from the ISS structure.

To ensure data continuity while improving measurements, increasing efficiency and reducing size, NASA is now funding the Compact Solar Spectral Irradiance Monitor Flight Demonstration (CSIM-FD) project to validate a SIM instrument on a 6U CubeSat platform. The SORCE mission is 1.57 meters tall and 1.16 meters in diameter, TSIS measures 1.2x1.2x2.4 m, and CSIM-FD is just 10x20x30 cm. The SIM on CSIM is similar to that flown on both SORCE and TSIS and will allow direct data comparisons of the two other instruments once CSIM is in orbit, no earlier than late 2018.

5.4 Cyclone Global Navigation Satellite System (CYGNSS)

The Cyclone Global Navigation Satellite System (**CYGNSS**) constellation of eight satellites was successfully launched on 15 December 2016 into a low inclination (tropical) Earth orbit. Each satellite carries a four-channel bistatic radar receiver that measures GPS signals scattered by the ocean. Measurements of ocean wind speed can be made under all levels of precipitation due to the low frequency at which GPS operates, and frequent sampling of tropical cyclone intensification and of the diurnal cycle of winds is made possible by the large number of satellites.

The mission was transitioned to Phase E (continuous on-orbit science operations) in March 2017 and delivery of provisional science data products to NASA's PO.DAAC data distribution center began in May 2017. Release of non-provisional science data products to the PO.DAAC began in November 2017. CYGNSS ocean wind speed measurements were made of all major storms during the 2017 Atlantic hurricane season. NOAA hurricane hunter aircraft were flown along flight paths coincident with CYGNSS overpasses during 25 of its eyewall penetrations to provide sources of “ground truth” intercomparison. In addition to science investigations utilizing CYGNSS ocean wind speed measurements, investigations have expanded to include measurements over land. Land measurements are sensitive to near surface soil moisture and to flood inundation in wetland regions.

5.5 Successful CubeSat Technology Satellite Demonstrations

Emerging CubeSat opportunities are transforming the way how new space technologies are demonstrated and validated, through small, standardized satellites and fast-track, low-cost access to space. Once in orbit, CubeSats are able to carry the *in situ* sensors or remote-sensing instruments into the realistic spaceflight environment that is similar to those in future science missions, for lifetime, stability, and endurance tests. NASA’s In-Space Validation of Earth Science Technologies (InVEST) program was established to validate and reduce the risk of new technologies for future Earth science missions. In addition, NASA established an agency-wide Small Spacecraft Technology Program (STP) to enhance/expand the capabilities of small spacecraft through spaceflight demonstration and testing.

Four small satellites that may be of interest to CGMS members are currently in Earth orbit. Three were selected in response to solicitations from the InVEST program under NASA’s Earth Science Technology Office (ESTO) and one was selected in response to the Earth Venture Instrument (EVI-2) call in 2014 to demonstrate new technologies in orbit.

Earth’s energy balance is a key factor in climate. To more-accurately understand how much energy is being reflected back into space, the Radiometer Assessment using Vertically Aligned Nanotubes (**RAVAN**) project was funded through InVEST. RAVAN launched on 11 November 2016 into an orbit that is nearly circular, sun-synchronous, and close to 600km. The compact, low-cost mission – flown on a 3U CubeSat platform – contains radiometer technology accurate to NIST traceable standards, which serves as a pathfinder for constellations that are affordable in sufficient numbers to measure Earth's radiative diurnal cycle and absolute energy imbalance to climate accuracies (globally at 0.5 W/m2 absolute) for the first time. RAVAN is still in orbit after meeting all of its mission validation objectives. The key technologies that have been demonstrated and validated to TRL 7 include a gallium fixed-point black body phase-transition calibration source, and a vertically aligned carbon nanotube (VACNT) absorber. VACNTs are the blackest known substance, making them ideal radiometer absorbers with order-of-magnitude improvements in spectral flatness and stability over the existing state-of-the-art. Operations continue with the goal of achieving accuracy, precision, and stability needed for climate measurements.

The InVEST-funded **ICECube** 3U CubeSat built and developed by Goddard Space Flight Center and Wallops Flight Facility is currently in orbit performing the space validation of an 883 GHz submillimeter wave radiometer for ice cloud remote sensing. Global cloud ice and properties are critical for quantifying the role of clouds in the Earth system, important for climate and weather research. Submillimeter (submm) wave remote sensing is capable of penetrating clouds to measure cloud ice mass and microphysical properties in the middle-to-upper troposphere, filling the sensitivity gap not covered by visible/infrared (IR) and low-frequency microwave sensors.

Launched on 18 April 2017 and deployed from the ISS on 16 May 2017 of that year, ICECube has met its primary mission objectives of validating the radiometer technology in space and remains in orbit to further test and prove the technology. This successful demonstration should enable a host of science applications while reducing the risks and costs of future Earth Science missions.

In addition, NASA has recently launched two other validation missions to the ISS. One of these missions was funded by NASA's Earth Science Technology Office, while the other was selected for technology demonstration in response to the Earth Venture Instrument (EVI-2) call in 2014. They were both launched as part of OA-9 from Wallops Flight Facility on 21 May 2018 with deployment from the ISS scheduled for soon thereafter.

The Radar-in-a-CubeSat (**RainCube**), developed by NASA's Jet Propulsion Laboratory and funded through InVEST, consists of a fully operational 6U CubeSat platform with a miniaturized Ka-band precipitation radar as its payload. The RainCube payload has a performance defined to emulate the nadir azimuth of the Ka-band channel of GPM's DPR: for the InVEST technology demonstration the requirements are 250 m vertical resolution, 10 km horizontal resolution, and sensitivity of 20 dBZ. RainCube adopts a novel system architecture, high purity pulse compression and a highly constrained lightweight deployable antenna to achieve these performance goals within the mass, volume and power constraints imposed by the 6U class form factor. For this technology demonstration, RainCube is a single nadir-looking instrument, similar to CloudSat's Cloud Profiling Radar.

The Temporal Experiment for Storms and Tropical Systems Technology Demonstration (**TEMPEST-D**), developed by Colorado State University and selected as part Earth Venture Instrument (EVI-2) for technology demonstration, will validate technology to reduce the risk, cost and development time for a potential future TEMPEST mission. TEMPEST-D will provide observations at five millimeter-wave frequencies from 89 to 183 GHz using a single instrument that is well-suited for the 6U-class architecture. The key objectives of TEMPEST-D are to demonstrate cross-calibration with at least one other orbiting radiometer to 2 Kelvin inter-satellite precision or better and to demonstrate feasibility of orbital drag maneuvers to control a 6U-class spacecraft altitude to 100 m or better.

5.6 Research Missions for Operational Use

Although all missions were conceived as research missions, the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications. Our interagency partners have rated most NASA missions as High Utility for operational applications, with Terra, Aqua, and Suomi-NPP rated Very High. All missions have met their original success criteria and are meeting the objective for sustained measurements on decadal time scales. This objective is met not only due to the satellites' longevity, but also to the sustained calibration/validation program and the data systems tools which enhance data quality and access.

Continued operation of the missions is determined through a review process, called the "Senior Review", which evaluates the continuing science value. Operational uses of the missions are considered in the review, but science remains the defining factor for continuation. The most recent Senior Review, completed in 2017 (final report released 22 June 2017, and available at http://science.nasa.gov/earth-science/missions/operating/) reviewed 13 of NASA's missions currently in operation to determine if they are still producing valuable science datasets for research, and should be extended for another three years. The next Senior Review will take place in 2020.

6. FUTURE SATELLITE SYSTEMS

NASA's Earth Science Program is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space. The program advances knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A balance of satellite measurements, science research, technology development and applications are needed to address a complex global Earth system. Table 5 summarizes NASA's future plans for the launch of 11 missions and 7 instruments (on host missions).

6.1 Earth Systematic Missions (ESM)

NASA's ESM includes a broad range of multi-disciplinary science investigations aimed at developing a scientific understanding of the Earth system and its response to natural and human-induced forces and changes. The ESM program develops Earth observing research satellite missions, manages the operation of NASA facility research missions once on orbit, and produces standard mission products in support of NASA and national research, applications, and policy communities. The current flight missions[1] in formulation or development contained in the ESM program most relevant to CGMS members are the Ice, Cloud, and Land Elevation Satellite (**ICESat-2**) and Surface Water Ocean Topography (**SWOT**) missions.

The Agency continues with formulation and development of other missions, such as NASA-ISRO Synthetic Aperture Radar (**NISAR**), Pre-Aerosols, Carbon and Ecosystems (**PACE**[2]), and the Climate Absolute Radiance and Refractivity Observatory Pathfinder (instrument on the ISS (**CLARREO PF-ISS**[2]). NASA is also continuing its partnership with the U.S. Geological Survey (USGS) in extending the Landsat series with Landsat-9.

6.2 Earth System Science Pathfinder (ESSP)

ESSP provides an innovative approach to Earth science research by providing frequent, regular, competitively selected opportunities that accommodate new and emerging scientific priorities and measurement capabilities. These opportunities represent a series of relatively low-to-moderate cost, small-to-medium sized missions[3]. They are competitively selected, principal investigator led missions that focus on scientific objectives to support a selected subset of studies of the atmosphere, oceans, land surface, polar ice regions, or solid Earth. NASA currently funds the Earth Venture-class (EV) missions, and several other missions and instruments in pre-formulation under ESSP. The EV missions are part of a competitive program to select small instruments, small satellites, or airborne science campaigns to complement the strategic NASA Earth science missions.

The first Earth Venture Instrument investigation (EVI-1), selected in 2012, the Tropospheric Emissions: Monitoring of Pollution (**TEMPO**) mission, will be the first space-based sensor to monitor major chemical air pollutants across North American hourly during daytime. It will share a ride on a commercial communications satellite in geostationary orbit as a hosted payload.

The second set of investigations (EVI-2) selected in 2014 were the Global Ecosystem Dynamics Investigation (**GEDI**) and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (**ECOSTRESS**). ECOSTRESS will provide critical insight into plant-water dynamics and how ecosystems change with climate via high spatiotemporal resolution thermal infrared radiometer measurements of evapotranspiration from the ISS. GEDI uses lidar to provide the first global, high-resolution observations of forest vertical structure to characterize the effects of changing climate and land use on ecosystem structure and dynamics to enable radically improved quantification and understanding of the Earth's carbon cycle and biodiversity.

The EVI-3 selection in 2016 included the MAIA and TROPICS missions, which are both low-Earth orbit investigations. Observations of small atmospheric aerosols from

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[1] In general, only missions determined to have a strong meteorological component are included in this document. For a full list of NASA missions, visit: https://www.nasa.gov/missions/.
[2] Development continues through FY18 consistent with the Consolidated Appropriations Act, 2018.
[3] In general, only missions determined to have a strong meteorological component are included in this document. For a full list of NASA missions, visit: https://www.nasa.gov/missions/.

the Multi-Angle Imager for Aerosols (**MAIA**) will be combined with health information to determine the toxicity of different particulate matter types in airborne pollutants over the world's major cities. The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (**TROPICS**) investigation will develop and launch a constellation of CubeSats to study the development of tropical cyclones through rapid-revisit sampling.

The most recent selections (EVI-4) made in early 2018 were the Polar Radiant Energy in the Far Infrared Experiment (**PREFIRE**) and the Earth Surface Mineral Dust Source Investigation (**EMIT**). PREFIRE will fly a pair of small CubeSat satellites to probe a little-studied portion of the radiant energy emitted by Earth for clues about Arctic warming, sea ice loss and ice-sheet melting. EMIT will be mounted to the exterior of the International Space Station to determine the mineral composition of natural sources that produce dust aerosols around the world, and help answer the essential question of whether these types of aerosol warm or cool the atmosphere.

6.3 In-Space Validation of Earth Science Technologies (InVEST) Program

NASA has primarily relied on sounding rockets, high-altitude balloons, and international space station (ISS) as a vehicle to validate new technologies prior to use in a science mission. This validation step is necessary because of stringent spaceflight conditions imposed on instrument components and systems, some of which cannot be fully tested on the ground or in airborne systems. These tests sometimes may not be even sufficient as the sounding-rocket or balloon flights are often short and do not address endurance and extreme aspects of the spaceflight environment. While the spaceflight validation is critical for the risk and cost reduction of future science missions, NASA has also recognized the need to invest in new approaches to shorten the development cycle of space technologies.

In addition to the small missions already being flown – RAVAN, TSIS-1, ICECube, RainCube, and TEMPEST-D – NASA has other validation missions planned. One of these missions was funded by NASA's Earth Science Technology Office, while the other was selected for technology demonstration in response to the Earth Venture Instrument (EVI-2) call in 2014.

The HyperAngular Rainbow Polarimeter (**HARP**) CubeSat, being developed by University of Maryland, Baltimore County and selected through InVEST, will perform a technology validation of a wide field of view (FOV) imaging polarimeter for characterizing aerosol and cloud properties as required by the Aerosol-Cloud-Ecosystem (ACE) mission concept. HARP uses modified Philips prisms to split 3 identical images into 3 independent imaging detector arrays. This technique achieves simultaneous imagery of the 3 polarization states and is the key innovation to achieve high polarimetric accuracy with no moving parts. The spacecraft consists of a 3U CubeSat with 3-axis stabilization designed to keep the polarimeter pointing nadir. HARP is scheduled to launch late in 2018 as part of an ISS resupply mission, with deployment from the ISS shortly thereafter.

The Compact Solar Spectral Irradiance Monitor Flight Demonstration (**CSIM-FD**) has been funded through the Earth Science Technology Office and is being developed by

CU Boulder/LASP to validate science-quality solar spectral irradiance (SSI) measurements for at least 18 months utilizing a 6U CubeSat platform. When launched, no earlier than late 2018, CSIM-FD will use the same methods as TSIS' Spectral Irradiance Monitor instrument to make concurrent measurements. This will allow direct data comparisons to TSIS and SORCE, but on a much smaller platform.

Table 5 - Future NASA Research and Development (R&D) Satellites

Satellite	Space Agency	Orbit Information	Launch Date (NET)	Instruments	Details: Applications
ECOSTRESS-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	June 2018	Thermal radiometer	Plant-water dynamics
ICESat-2	NASA	92-deg inclination Non Sun-Sync	September 2018	ATLAS	Ice-sheet thickness, sea-ice thickness, vegetation height, carbon and biomass
CSIM	NASA	Sun-Sync, 10:30 (D) 575 km	September 2018	Absolute ESR detector (VACNT bolometer)	Solar spectral irradiance
GEDI-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	November 2018	LIDAR	Forest vertical structure
TROPICS	NASA	LEO constellation	2020	Microwave radiometer	Precipitation, temperature, humidity, imagery, cloud ice
CLARREO PF-ISS Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	2020	Spectrometer	Reflected solar Earth radiance
Landsat-9	NASA/USGS	98.2-deg inclination Sun-Sync, 10:00 (D) 650 km	2020	OLI-2, TIRS-2	High-resolution imagery of the Earth’s surface (follow-on in the Landsat series)

TSIS-2	NASA	TBD	≥2020	Absolute ESR detector (NiP bolometer)	Solar spectral irradiance
TEMPO Hosted Payload Instrument only	NASA	Geosynchronous	>2020	UV and VIS spectrometer	Atmospheric pollution over the Americas; tropospheric ozone, ozone precursors, aerosols, and clouds
SWOT	NASA/CNES	77.6-deg inclination Non Sun-Sync 891 km	2021	Ka-Band Radar Interferometer, AMR, GPSP, LRA, Poseidon Altimeter	Oceanography (wide swath ocean surface topography) and hydrology (lake levels, river discharge)
GeoCarb Hosted Payload Instrument only	NASA	Geosynchronous	2022	Grating spectrometer	Concentrations of carbon dioxide, methane, and carbon monoxide and solar-induced fluorescence
NISAR	NASA/ISRO	98-deg inclination Sun-Sync, 6AM-6PM 747 km	2022	L-band, S-band SAR (repeat-pass interferometry, polarimetry)	Earth surface deformation, ecosystems and biomass change, ice motion
PACE (Pre-ACE)	NASA	98-deg inclination Sun-Sync 675 km	2022	OCI, Polarimeters	Aerosols, clouds, ocean color
MAIA Hosted Payload Instrument only	NASA	Sun-Sync 600-850 km	TBD	Multi-angle imager	Atmospheric aerosols
PREFIRE	NASA	Near-polar 470-650 km	2022	Grating spectrometer	Energy exchange between surface and atmosphere in the Arctic
EMIT Intl. Space Station Instrument only	NASA	51.6-deg inclination Non Sun-Sync 407 km	2024	Imaging spectrometer	Mineral composition of natural dusts; thermal impacts on atmosphere

6.4 2nd Decadal Survey for Earth Science and Applications from Space

The US National Academies of Science, Engineering, and Medicine released their new Decadal Survey for NASA's Earth Science program, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, in early 2018. In this report, the Academies laid out a blueprint for how NASA might implement its Earth science program over the next decade, focusing on observations that it considers to be the highest priority in order to meet the scientific objectives required. The Academies used multiple disciplinary panels to collect inputs (over 200 white papers from the community) and then make recommendations on scientific priorities, and then used a steering committee to narrow the potential observations down to a limited set that they thought was achievable within a realistic budget scenario for the coming decade. In doing this, they broke these observations down into a variety of categories (designated, explorer, incubator, addition of a new Earth Venture Continuity line) that could be implemented with different solicitation approaches and cost constraints. Five designated observations were identified (aerosols, clouds/convection/precipitation, surface biology and geology, mass change, surface deformation) that could be initiated as larger, but still cost constrained missions. Seven observations, three of which they felt could be initiated through the new explorer line were identified as well (greenhouse gases, ice elevation, ocean surface winds and currents, ozone & trace gases, snow depth and snow water equivalent, terrestrial ecosystem structure, and atmospheric winds). The incubator program involved preparatory work (e.g., technology development/airborne demonstration) for three potential measurements (atmospheric winds, planetary boundary layer, and surface topography and vegetation). There was a strong focus on competition in implementing these new observations. The report also included guidance on the relative level of investments between NASA's flight, research, applied sciences, and technology programs.

7. ADDITIONAL TOPICS OF RELEVANCE TO CGMS

7.1 Using GNSS Radio Occultation Data for Research and Operations

COSMIC Status

Launched in 2006, the joint U.S./Taiwan Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) six-satellite mission has been a great success, demonstrating the value of Global Navigation Satellite System (GNSS) radio occultation (RO) profile data for numerical weather prediction, climate monitoring, and space weather forecasting and ionospheric research. NASA and the National Science Foundation (NSF) are currently funding the University Corporation for Atmospheric Research (UCAR) COSMIC Program (UCAR/COSMIC) to 1) process COSMIC and all other RO mission data in post-processed and re-processed modes and serve them to the research community; 2) process COSMIC data in a near real-time mode and make them available to the operational community; 3) conduct research to improve GNSS RO inversion science and techniques; and 4) conduct research, education, and outreach activities to support science applications of RO data. NASA also funds a GNSS RO science team.

The primary science instrument on the COSMIC satellites is a GPS RO receiver developed by NASA's Jet Propulsion Laboratory (JPL). By precisely tracking the phase and amplitude of the dual-frequency GPS L-band radio signals as a COSMIC satellite rises or sets behind Earth, the receiver acquires high-rate limb measurements that can be processed into vertical profiles of bending angle, refractivity, temperature and water vapor in the neutral atmosphere, and total electron content (TEC), electron density profiles, and scintillation information in the ionosphere. Since launch UCAR and JPL have been monitoring and improving the receiver firmware, which has led to more than 6.7 million high-accuracy and high vertical resolution soundings for use by the research and operational communities (see Figure 1). Currently only two out of the original six satellites (Flight Models, FMs #1, #6) are providing up to 700 profiles per day.

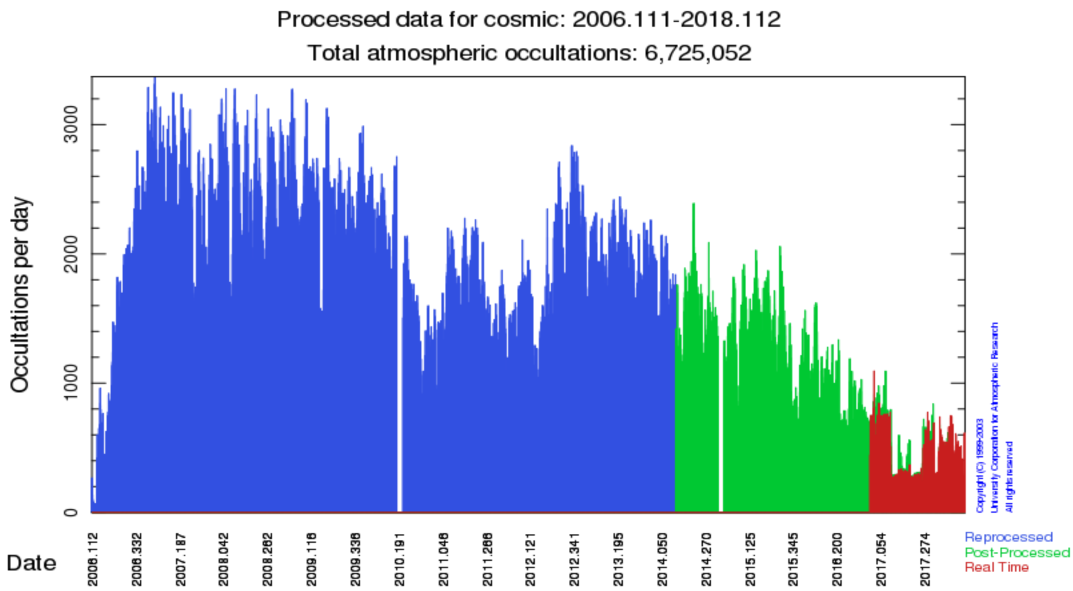

Figure 1. Daily COSMIC neutral atmosphere profile count throughout the mission. The red color shows the soundings from near real-time UCAR processing. The green color shows the soundings from post-processing, which often is able to generate more sounding profiles but lags several months behind the near real-time products. The blue color shows the soundings from re-processing, which are processed every 3 years with up-to-date software.

7.2 Commercial Data Buy

NASA has begun an activity to purchase and analyze commercial satellite data from private sector entities that have satellites in orbit providing data. In 2017, NASA released a Request for Information (RFI) for satellite providers with available data from three or more satellites to describe their data, and based on the responses, NASA would look to purchase data (with associated metadata) from those meeting the requirements of the RFI. At the time of this paper's release, NASA is still in the process of reviewing responses received from companies that have met those terms, but procurements are not yet in place. NASA is also looking to provide added support for a number of currently-funded researchers who would then be positioned to evaluate the ability of the purchased data to meet NASA's research and/or applied sciences goals. It is expected that the evaluation process would take approximately one year, and will result in a detailed assessment which will be used to guide NASA's future plans for data purchases.

7.3 Competed Research and Suborbital Investigations

7.3.1 The Science of Terra, Aqua and Suomi-NPP Solicitation / Terra and Aqua Transition to the 2017 Senior Review

The Suomi National Polar-orbiting Partnership (Suomi NPP, formerly the NPOESS Preparatory Project) satellite was launched on 28 October 2011, to extend more than 30 high-quality time series data records initiated by earlier NASA satellites (most notably Terra and Aqua, launched in 1999 and 2002, respectively, as well as Aura, launched in 2004. Its observations should allow scientists to extend a continuous record of satellite data of sufficient quality to detect and quantify global environmental changes. The NASA time series of global observations is continued for certain data records by the on-orbit Suomi NPP program sensors (https://jointmission.gsfc.nasa.gov).

Suomi NPP serves as a bridge between NASA's Earth Observing System (EOS) of satellites and the next-generation Joint Polar Satellite System (JPSS), a National Oceanic and Atmospheric Administration (NOAA) program that will collect data for both weather and climate (the first JPSS satellite, JPSS-1, launched on 18 November 2017). NASA is bridging the mission capabilities to continue a set of the Earth System Data Records begun with the EOS missions using the Suomi NPP mission data.

Released on 14 February 2017 in Research Opportunities in Space and Earth Science (ROSES)-2017, A.37 The Science of Terra, Aqua and Suomi NPP provided an opportunity for scientists to undertake studies using data and derived products from Terra and Aqua and their measurement sensors, as well as the Suomi NPP satellite and its measurement sensors. It represented a continuation of the research aspects of the previously solicited EOS and Suomi NPP Instrument Teams for these satellites, and emphasized opportunities for scientists to analyze and exploit EOS and Suomi NPP data. It also provided an opportunity to develop new products by combining multi-sensor and multi-platform data, or by developing innovative approaches to data retrievals. This program element offered investigators an opportunity to conduct integrative research using the data and products resulting from these satellites (Terra, Aqua, Suomi NPP).

This program element recognized the advances already made by investigations solicited in prior NASA Research Announcements and ROSES program elements, which focused in the areas of sensor calibration, algorithm development and refinement, data product validation, and scientific data analysis. As the EOS and Suomi NPP missions continue to mature and continue in the extended mission phase, less emphasis was placed upon algorithm refinement and more emphasis was directed to multi-sensor product development accompanied by active utilization of these data and products in scientific research, modeling, synthesis, and diagnostic analysis to answer Earth science questions.

Following historical program subelements, five types of research proposals were solicited, and they are described in Sections 2.1-2.5 of the solicitation (available at https://nspires.nasaprs.com/external/). This program element blends subelements from historical program elements in some cases, and identifies subelements specific to Suomi NPP in other cases. Specifically, this program element requested proposals for:

- 2.1 Science Data Analysis
  - 2.1.1 Multi-Platform and Sensor Data Fusion
- 2.2 Algorithms – New Data Products
- 2.3 Algorithms – Existing Data Product (Terra and Aqua) and EOS Continuity Data Product (Suomi NPP) Refinement (directed to subelement 2.1)
- 2.4 Real- or Near-Real-Time Data Algorithms
- 2.5 NASA Suomi NPP Science Team Leader and Terra, Aqua, Suomi NPP Discipline Leads

The algorithm/data maintenance activities in the proposals selected under a 2013 ROSES element (A.46, Terra and Aqua – Algorithms – Existing Data Products) program element were transitioned to the Senior Review in 2017 as planned (during the 2009-2013-2017 period competitions), as were Terra and Aqua core algorithm/data product maintenance activities. The Terra and Aqua algorithm/data product maintenance proposals submitted to the Senior Review in 2017 did not include modest-to-major algorithm/data product refinement or research. As such, the A.37 program element welcomed proposals to refine and improve algorithms/data products included in the 2017 Senior Review proposals for Terra and Aqua beyond the level of core algorithm/data product maintenance. This program element also welcomed proposals related to development or refinement of EOS continuity data products (work began in 2013), either alone or in conjunction with refinement of an algorithm/data product for Terra and Aqua.

The outcome for The Science of Terra, Aqua, and Suomi NPP program element was the selection of 67 proposals on 15 Jan 2018 for a total of $44.6M/three years. EOS continuity data products recommended for Suomi NPP are listed below in Table 6.

The standard data products, pulled directly from the solicitation, included those for land, ocean, and atmosphere (the latter tied to observations from imaging, sounding, and ozone column/profiling). Information on these products may be found at the following website:

- Land: https://lpdaac.usgs.gov/, http://nsidc.org/daac/ and http://modis.gsfc.nasa.gov/data/.
- Ocean: http://oceancolor.gsfc.nasa.gov/ and https://modis.gsfc.nasa.gov/data/.
- Atmosphere (MODIS derived): http://modis-atmos.gsfc.nasa.gov/products.html and http://disc.sci.gsfc.nasa.gov/.
- Atmosphere (AIRS/AMSU/TES derived): https://airs.jpl.nasa.gov and https://eosweb.larc.nasa.gov.
- Atmosphere (MLS/OMI derived): https://mls.jpl.nasa.gov/data/ and https://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI.

Table 6: EOS Continuity Data Products Recommended for Suomi NPP

Land	Ocean	Atmosphere (MODIS)	Atmosphere (OMI/MLS)	Atmosphere (Sounder Profiles)
Surface Reflectance	Sea Surface Temperature	Aerosol Product	Total Column Ozone	Atmospheric Temperature
Snow Cover	Aerosol Angstrom Exponent	Cloud Product	Ozone Concentration	Atmospheric Moisture
Land Surface Phenology and Vegetation Indices	Aerosol Optical Thickness	Cloud Mask	Aerosol Concentration	Surface Temperature
Fire and Thermal Anomalies	Subsurface Chlorophyll a Concentration		NO_2 Total Column	Cloud Properties
Sea Ice Cover and Ice Surface Temperature	Diffuse attenuation at 490 nm		Sulfur Dioxide Total Column	
BRDF/Albedo	Photosynthetically Available Radiation		Aerosols Total Column	
Incident downward shortwave radiation and PAR	Particulate Organic Carbon			
	Remote Sensing Reflectance			

The Terra and Aqua standard data products were transitioned to the Senior Review during the 2009-2013-2017 period competitions. The Suomi NPP EOS continuity algorithm work began in 2013 and continued in 2017.

7.3.2 U.S. Participating Investigator (USPI) Program

NASA solicits proposals for the U.S. Participating Investigator (USPI) investigations on a foreign space mission that address the Earth Science Research Program objectives listed in the NASA Science Plan every 2 years. The current solicitation is for Earth science investigations that contribute and facilitate access to foreign space agencies' assets. The proposer's role in the foreign space mission can include, but is not limited to, instrument design, modeling, and simulation of the instrument's operation and measurement performance; calibration of the instrument; and/or development of innovative data analysis techniques. A proposer may also serve as a member of a foreign space mission science or engineering team and participate in science team activities such as mission planning, mission operations, data processing, data analysis, and data archiving. The investigation must also include a meaningful contribution to the development of products, including, but not limited to, algorithm development and/or testing, calibration/validation, and/or requirements definition (especially as may be carried out in Observing System Simulation Experiments).

The current solicitation focuses on involvement in the mission during its development phase. Missions to launch during or after 2020 are encouraged to maximize work done during the development phase. Awards will be for a maximum of five years. Proposals are due on 12 July 2018 with announcement of awards expected during the autumn of 2018.

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