CGMS

CGMS-45 NASA-WP-01
v1, 15 June 2017

Prepared by NASA
Agenda Item: D.12
Discussed in Plenary

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

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Executive summary

NASA currently supports the operations of 20 Earth Science missions. Since the last CGMS-44 (June 2016), NASA's Earth Science program launched one Earth Venture Mission and two instruments to the International Space Station (ISS), and continued development of several new missions. During this time period, the Earth Observing – 1 (EO-1) mission completed passivation and some instruments in extended mission operations have experienced reduced capability, but continue to provide valuable data. Although all NASA operated missions listed 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 Program 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 needed to address a complex global Earth system. NASA's plans include the launch of 14 missions and 8 instruments (on host missions) in the future.

NASA Report on the status of current and future satellite systems

1 INTRODUCTION

NASA currently supports the operations of 20 Earth Science missions[1] (see Tables 1 to 3). Since the last CGMS-44 (June 2016), NASA's Earth Science program launched the 8-satellite CYGNSS constellation and two instruments (SAGE III and LIS) as hosted payloads on the International Space Station (ISS). During this time period, the Earth Observing-1 (EO-1) mission was decommissioned, and the RapidSCAT instrument on the ISS suffered an unrecoverable power anomaly; previously acquired data will continue to be made available, however, in accordance with NASA's data access policy. All active missions are currently producing data, but four missions (GRACE, QuikSCAT, SORCE and CloudSat) show significant signs of aging and are operating in reduced data collection mode. 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 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 14 missions and 8 instruments (on host missions) in the future.

Note that this working paper focuses on those missions developed and/or operated by and for NASA's Earth Science Division (ESD); note that 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. Reporting on these activities is 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.

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[1] 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 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	Mean Altitude	Launch Date	Data Access	Instruments and Details
Landsat-7	* USGS (support from NASA)	10:00	705	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	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	833	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)	10:15	705	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	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

** Though NASA does not officially "operate" these missions, NASA supports operations through the science instrumentation.*
^ Instrument operation continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President's FY18 Budget Proposal released May 23, 2017

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

Satellite	Operating Agency	ECT / Inclination	Launch Date	Data Access	Instruments	Details: Applications
QuikSCAT	NASA	6:00 (A) 803 km	19-Jun-1999	PO.DAAC	SeaWinds	Sea surface wind vectors
Terra	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

GRACE	NASA (support from DLR, GFZ)	89 Deg Inclination Non Sun-Sync 485 km	17-Mar-2002	PO.DAAC	MWA, Accelerometers, GPS	Earth mass distribution, with application to ground water, ocean currents and ice sheets, GPS (P,T,humidity)
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 Inclination Non Sun-Sync 640 km	25-Jan-2003	DISC	SIM, SOLSTICE, TIM, XPS	Total and spectral solar irradiance
Aura	NASA	13:45 (A) 705 km	15-Jul-2004	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 Inclination 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

CATS-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km	10-Jan-2015	ASDC	LIDAR	Atmospheric pollution, dust, smoke, and aerosols
SMAP	NASA	18:00 (A) 685 km	31-Jan-2015	ASF (radar) and NSIDC (cryosphere and land microwave)	L-Band Radar, L-Band Radiometer	Soil Moisture, Freeze-thaw state
CYGNSS	NASA	8 small satellites, 35 Deg Inclination, 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 Inclination Non Sun-Sync 407 km (ISS)	19-Feb-2017	ASDC	Spectrometer	Stratospheric ozone, aerosols, and water vapor
LIS-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	19-Feb-2017	Global Hydrology Resource Center DAAC	Optical Imager	Lightning

Failed Instruments

***** *HSB on Aqua*
* *AMSR-E on Aqua*
* *HIRDLS 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)*
** TES on Aura (flex cable degradation limiting to targeted observations, frequent stalls of the translator, and laser degradation)*
** SORCE - Battery degradation, Instruments turned off during orbit night*
** CloudSat - Battery degradation, Instruments turned off during orbit night*
** GRACE – Battery degradation, instruments turned off 40-60 days twice/year (during each maximum eclipse period)*
** QuikSCAT – Battery degradation, instruments turned off during eclipse period from November to January*

3 STATUS OF CURRENT LEO SATELLITE SYSTEMS

Jason-2 and Suomi-NPP continue to provide operational data within accuracy and latency requirements. The Jason-2 satellite experienced an anomaly with one of its primary gyros (Gyro #1). A redundant spare gyro (Gyro #3) was brought on-line to continue the mission while the Gyro 1 anomaly is investigated. The Jason-3 satellite is also operating nominally since its launch on January 17, 2016 to extend the ocean topography measurements initiated with the TOPEX mission in 1992 and continued through the Jason-1 and Jason-2 missions.

4 STATUS OF CURRENT HEO (OR OTHER) SATELLITE SYSTEMS

The Deep Space Climate Observatory (DSCOVR) was launched on February 11, 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. For the first time, we imaged the passage of the Moon in front of the sunlit disk of Earth (see below), and the passage of a total solar eclipse passing through the Pacific Ocean. 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 2 products from both EPIC and NISTAR are undergoing validation and will be archived at the Langley Atmospheric Science Data Center (https://eosweb.larc.nasa.gov).

Note that operation of the Earth-viewing instruments on DSCOVR continue through FY17 consistent with the FY2017 Consolidated Appropriations Act. They are identified for termination in FY18 in the President's FY18 Budget Proposal released May 23, 2017.

5 STATUS OF CURRENT R&D SATELLITE SYSTEMS

The 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 QuikSCAT, GRACE, CloudSat, and 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. SORCE and CloudSat are operating in nominal science mode and collecting data during daylight only. GRACE data include outages of 40-60 days during the periods (approximately twice/year) when the twin satellites experience their longest eclipses, and the GRACE-2 satellite also only produces data during the daylight portion of the orbit. The QuikSCAT mission also stands down from data collection during the eclipse period from November to January each year. The EO-1 mission, which exhausted its orbit maintenance fuel in 2011, was decommissioned in 2017 as planned based on the 2013 and 2015 Senior Review assessment of the reduced data utility. Instruments with reduced capability (noted in RED, Table 3) are QuikSCAT's SeaWinds (antenna no longer rotates so that the data are used primarily to cross-calibrate with other on-orbit scatterometers), Terra's ASTER (SWIR module is no longer functional), Aura's TES performs only Special Observations (no-longer performs Global Survey and has experienced frequent outages due to an intermittently stalled component), and Aqua's AMSU instrument lost two additional channels (channels 1 and 2) to add to the previous non-operational channels 4,5, and 7. Instruments that no longer provide data (noted in RED, Table 3) are Aqua's HSB and AMSR-E, Aura's HIRDLS, and SMAP's L-Band Radar. RapidScat-ISS suffered a power anomaly in 2016, which ended the mission. All other sensors are fully functional and are producing standard products that meet or exceed specifications.

5.1 Formation Flying

It is still worth noting that a number of NASA satellites (and one non-NASA satellite) are flying in close proximity to each other in orbits with equatorial crossing times in the 1330 range. By flying in close proximity, the satellite instruments can provide the benefits on nearly-simultaneous measurements even though they are spread across multiple platforms from multiple providers; this constellation (known as the A-Train) 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 and CALIPSO (2006), the Japanese GCOM-W1 "SHIZUKU" satellite (2012), and the Orbiting Carbon Observatory-2 (2014). Between these satellites, a broad range of complementary techniques using different wavelengths and viewing geometries are used. It is particularly valuable in studying atmospheric chemistry and physics because of the need to comprehensively measure physical state and trace gas and particular composition. The constellation is actively managed to assure appropriate separation even in the presence of collision avoidance maneuvers (see next sub-section). There is a strong emphasis in the NASA program on science that makes synergistic use of the A-Train instruments. A major international A-Train workshop California in 2017 that brought together a wide variety of scientific users from many countries of the data from the A-Train satellites.

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 in order 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.

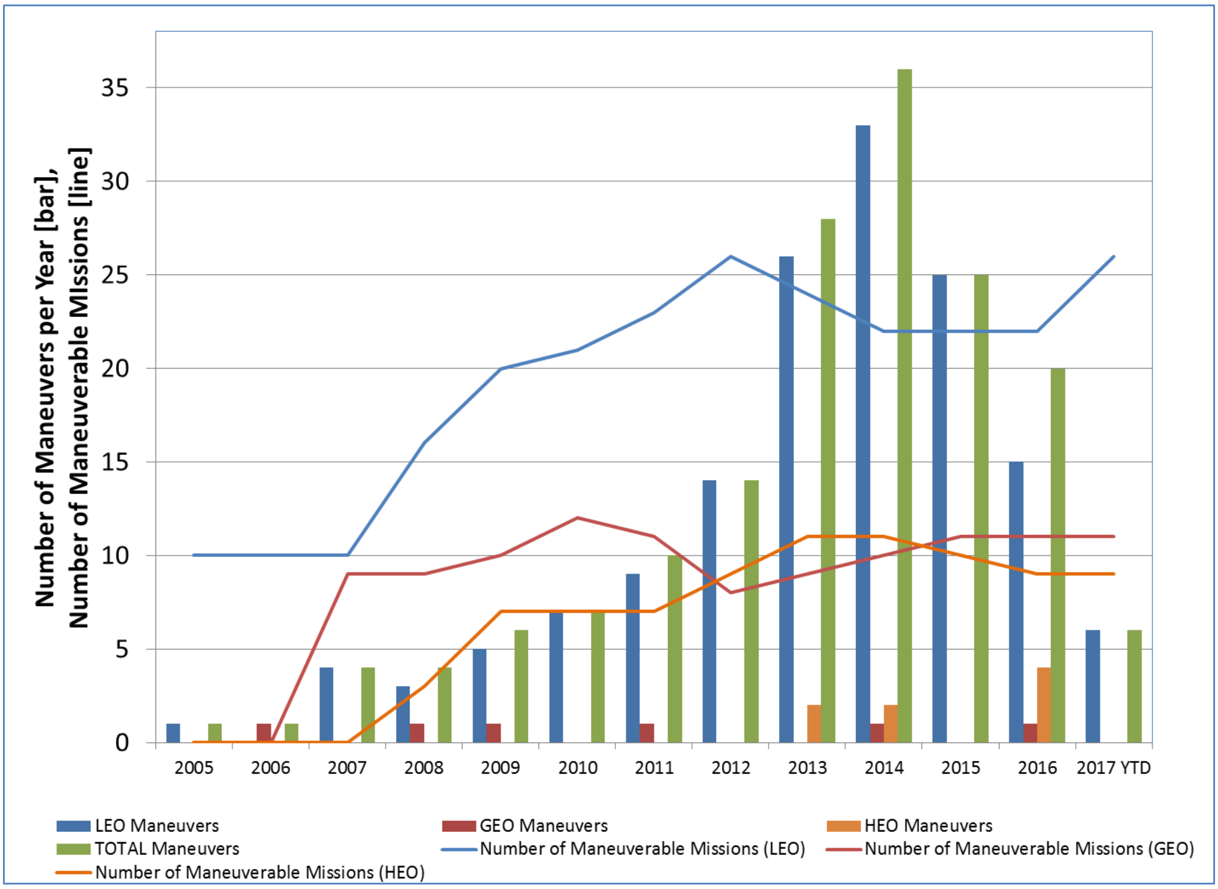

Figure 1: *History of collision avoidance maneuvers.*

5.3 Measurement Continuity and Transition to Follow-on Missions

5.3.1 Global Precipitation Measurement (GPM) Mission

Co-led by NASA and JAXA, the Global Precipitation Measurement (GPM) mission is the successor to the Tropical Rainfall Measuring Mission (TRMM), providing next-generation global observations of rain and snow every three hours. The mission consists of a GPM Core Observatory satellite and a constellation of additional research and operational satellites provided by a consortium of international partners, including the Centre National d'Études Spatiales (CNES), the Indian Space Research Organization (ISRO), the National Oceanic and Atmospheric Administration (NOAA), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and others. The GPM Core Observatory, launched on February 27, 2014, also extends the coverage from TRMM to higher latitudes—between approximately 65° north latitude (e.g., the Arctic Circle) and 65° south latitude (e.g., the Antarctic Circle), and carries the first space-borne Ku/Ka-band Dual-frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI) that serves as a reference standard for the rest of the satellite constellation.

The DPR instrument, which provides three dimensional measurements of precipitation structure over 78 and 152 mile (125 and 245 km) swaths, consists of a Ka-band precipitation radar (KaPR) operating at 35.5 GHz and a Ku-band precipitation radar (KuPR) operating at 13.6 GHz. The GMI instrument is a conical-scanning multi-channel microwave radiometer covering a swath of 550 miles (885 km) with thirteen channels ranging in frequency from 10 GHz to 183 GHz. The GMI uses a set of frequencies that have been optimized over the past two decades to retrieve heavy, moderate and light precipitation using the polarization difference at each channel as an indicator of the optical thickness and water content. These data are freely available through NASA's Precipitation Measurement Missions Data Access site at: https://pmm.nasa.gov/data-access.

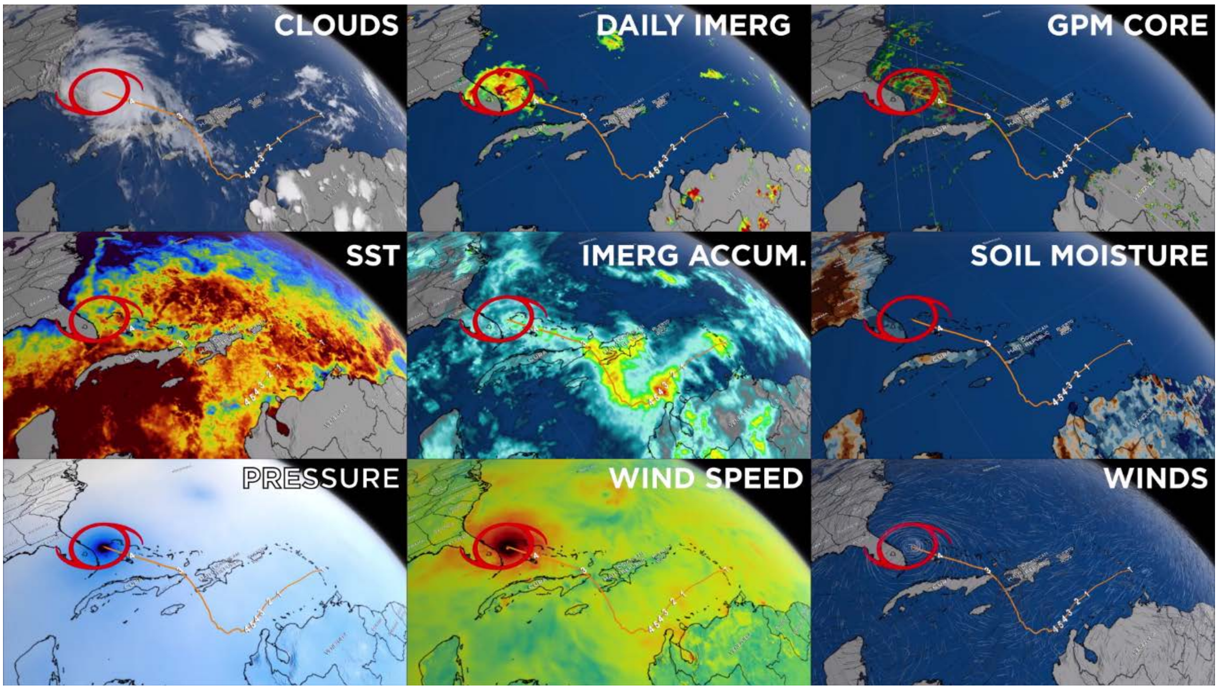

Figure 2: *(a) Measurements from the GPM Core Observatory, when combined with those from the rest of the satellite constellation and model runs, provided insights into Hurricane Matthew's rapid intensification and fast decline as it tracked through the Caribbean and United States from late September to early October 2016.*

5.3.2 Cyclone Global Navigation Satellite System (CYGNSS)

NASA's Cyclone Global Navigation Satellite System (CYGNSS) -- a constellation of eight microsatellites that will take detailed measurement of wind speeds inside hurricanes -- successfully completed the development and on-orbit commissioning phases of its mission on March 23 and moved into the science operations phase (Phase E). The spacecraft have now begun their science instrument calibration and validation and are on track to deliver the first science data in May, just in time for the start of the 2017 Atlantic hurricane season.

The eight CYGNSS spacecraft were launched into low-inclination (35 degree), low-Earth orbit over the tropics on December 15, 2016. All spacecraft have completed their on-orbit engineering tests and are performing to specification. The Southwest Research Institute (SwRI) office in Boulder, Colorado, hosts the mission operations center, which commands the spacecraft, collects the telemetry, and transmits the data to the science operations center, based at the University of Michigan in Ann Arbor.

CYGNSS recently demonstrated its ability to observe surface winds in major storms during its flyover of Tropical Cyclone Enawo, on March 6, just hours before the storm made landfall over Madagascar. Enawo had maximum sustained winds estimated at 125 mph by the Joint Typhoon Warning Center around the time of the CYGNSS overpass. The satellites' measurements responded as expected to changes in the wind speed as they approached and passed over the storm center, showing strong and reliable sensitivity throughout.

The CYGNSS mission is led by the University of Michigan. SwRI led the engineering development and manages the operation of the constellation. The University of Michigan Climate and Space Sciences and Engineering department leads the science investigation, and the Earth Science Division of NASA's Science Mission Directorate oversees the mission.

For more information about CYGNSS, visit: http://www.nasa.gov/cygnss/.

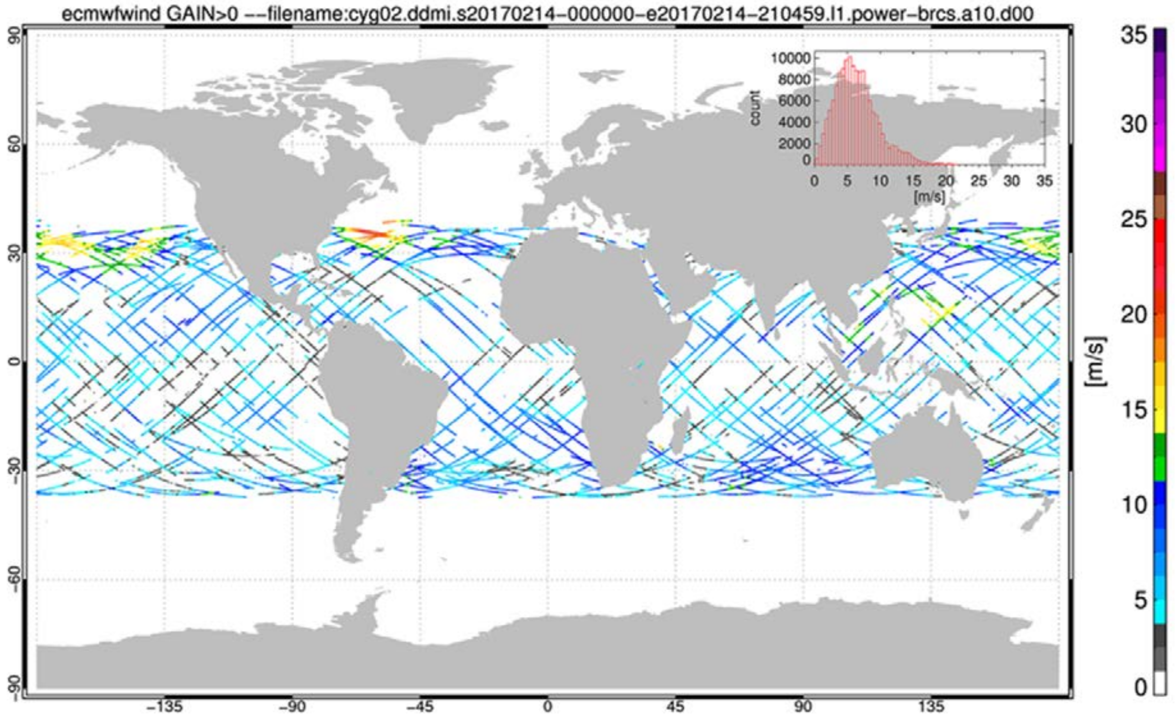

Figure 3: *This map shows the coverage of ocean surface wind measurements made by one of the eight spacecraft that make up the CYGNSS constellation over the course of 4 orbits (approximately 6 hours) on February 14, 2017. The blue values indicate relatively low wind speeds, while the yellow, orange, and red values indicate increasingly higher wind speeds. The highest wind speeds in this image (orange and red) are associated with a powerful extratropical cyclone that moved off the East Coast of North America.*

5.4 Orbiting Carbon Observatory-2 (OCO-2)

The Orbiting Carbon Observatory-2 (OCO-2) is the first NASA mission designed to measure atmospheric carbon dioxide (CO_2) with the precision, accuracy, resolution, and coverage needed to quantify CO_2 fluxes (sources and sinks) on regional scales over the globe (Crisp et al. 2004; 2015). OCO-2 was successfully launched on July 2, 2014, and was inserted at the head of the 705-km Afternoon Constellation (A-Train) on August 3, 2014. Its 3-channel imaging grating spectrometer has been returning almost one million soundings over the sunlit hemisphere each day since September 6, 2014. On monthly intervals, between 7 and 21% of these soundings are sufficiently cloud free to yield spatially resolved estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2}, with unprecedented precision and accuracy. OCO-2 completed its 2-year prime mission in October 2016 and began its first extended mission.

OCO-2 carries and points a three-channel, imaging grating spectrometer that collects high-resolution ($\lambda/\Delta\lambda$ ~19,000), co-boresighted spectra of reflected sunlight within the molecular oxygen (O_2) A-band at 0.765 microns (µm) and within CO_2 bands at 1.61 and 2.06 µm (Crisp et al., 2017; Eldering et al. 2017). Co-boresighted spectra from the three channels constitute a sounding. Each spectrometer records 8 spatially resolved soundings across a narrow (0.8°) swath three times each second, yielding surface footprints that extend 2.25 km down-track and < 1.3 km cross-track. Soundings are analyzed with a state-of-the-art, remote sensing retrieval algorithm to yield spatially resolved estimates of X_{CO2}.

The OCO-2 orbit follows a reference ground track that is displaced ~ 217.3 km to the east of the World Reference System-2 (WRS-2) track followed by the Aqua platform. This orbit track was selected to overfly the reference ground tracks of the CloudSat Cloud Profiling Radar instrument and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, to maximize overlap between the measurements collected by these three narrow-swath instruments. From this orbit, OCO-2 circles the Earth 14.5 times each day, collecting observations as it traverses the sunlit hemisphere from south to north (ascending). The mean local time of the ascending node of this sun synchronous orbit is 1:36 PM.

For routine operations, the observatory points the instrument's field of view (FOV) at the local nadir or near the "glint spot," where sunlight is specularly reflected from the surface. Nadir observations yield higher spatial resolution over land. Glint measurements have greater sensitivity than nadir observations over dark ocean surfaces. The glint-nadir observing strategy was optimized throughout the prime mission to improve the data quality and yield. Each month, glint and nadir observations yield millions of soundings that are sufficiently cloud-free to produce full-column estimates of X_{CO2} with single sounding random errors near 0.5 ppm at solar zenith angles as large as 70°. The observatory can also scan the instrument's field of view over pre-selected stationary surface targets to collect thousands of soundings as the spacecraft flies overhead. Typical targets include vicarious calibration sites, such as Railroad Valley, Nevada, X_{CO2} validation targets, such as Total Carbon Column Observing Network (TCCON) stations, which are used to establish and maintain the end-to-end performance of the OCO-2 products (Wunch et al. 2016).

For details on additional products derived from the OCO-2 spectra, including other atmospheric and surface properties such as surface albedo, aerosols, temperature, wind speed (over ocean) and total column water vapor (O'Dell et al., 2012; Eldering et al., 2017), as well as solar-induced chlorophyll fluorescence (SIF), see CGMS-45 NASA-WP-02.

5.5 Lightning Imager Sensor on the ISS (LIS-ISS)

On February 19, NASA's Lightning Imaging Sensor (LIS) was successfully launched to the ISS aboard the SpaceX Cargo Resupply Services-10 (SpaceX CRS-10) mission. The LIS was delivered to the ISS in the Dragon trunk as a hosted payload on DoD’s Space Test Program-Houston 5 (STP-H5) package and robotically installed in an external Earth viewing location. From this vantage point, LIS continuously detects (i.e., the amount, rate, and radiant energy), both day and night, 90% or more of the lightning that falls within its field of view, extending to 54 degrees north and south latitude.

The LIS-ISS is an exact copy – the backup flight spare in fact – of the LIS that operated for an impressive 17 years on the Tropical Rainfall Measuring Mission (TRMM). Therefore placing LIS-ISS provides a great opportunity to not only extend this 17-year record of tropical lightning measurements but also to expand that coverage to higher latitudes missed by the previous mission. The LIS observations, being well characterized from the TRMM mission, will support cross platform calibration and validation with the new Geostationary Lightning Mapper (GLM), an instrument based on LIS heritage that was launched November 2016 on NOAA’s newest weather satellite, GOES-16. However, one of the most important science objectives of this mission will be to better understand the processes which cause lightning, as well as the connections between lightning and subsequent severe weather events, as this understanding will contribute to improving weather forecasts and saving lives and property in the United States and around the world. Real-time data, available for the first time with this mission, will be made available to interested users in partnership with NASA’s Land, Atmosphere Near rea-time Capability for EOS (LANCE) program.

The LIS science and operations are managed from the newly established LIS Payload Operations Control Center (LIS POCC) located at the National Space Science and Technology Center (NSSTC) in Huntsville, Alabama. The LIS data handling involves a partnership between the LIS Science Team and the Global Hydrology Resource Center, one of NASA’s Distributed Active Archive Centers (DAACs), and is leveraged upon the well-established and robust processing, archival, and distribution infrastructure used for TRMM that was adapted for the ISS mission.

LIS-ISS saw first light on February 27 when it was powered-on and successfully completed a two week checkout and commissioning. It is now undergoing a two to three month assessment to carefully evaluate the processing and data products prior to publically releasing this data to the science community. LIS data users should see little or no change from TRMM LIS in terms of data products, formats, software or access. However, in addition to maintaining the legacy data format, LIS products will also be cast in more modern formats such as HDF-5 and netCDF.

5.6 Stratospheric Aerosol and Gas Experiment III on the ISS (SAGE III-ISS)

The Stratospheric Aerosol and Gas Experiment III (SAGE III) on the ISS mission was launched on 19 February 2017. It is the fourth in a series of SAGE instruments which date back to 1979. Its primary objective is to monitor the vertical distribution of aerosols, ozone, and other trace gases in the Earth’s stratosphere and troposphere to enhance our understanding of ozone recovery and climate change processes in the stratosphere and upper troposphere. SAGE III-ISS will provide data necessary for assessing long-term changes in ozone, aerosols and other trace gases, modeling geophysical variability, understanding how to combine various methods for measuring aerosols, and the assimilation and reconstruction of fields of long-lived species. The instrument was successfully installed on the outside of ISS on 7 March. Instrument commissioning activities are underway and initial ozone profile retrievals are in excellent agreement with an earlier SAGE-derived ozone climatology.

5.7 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 biennial science 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 2015 (final report released on June 22, 201gcom5 and available at http://science.nasa.gov/earth-science/missions/operating/) reviewed 10 of NASA's missions currently in extended operations to determine if they are still producing valuable science datasets for research, and should be extended for another 2 years. The next Senior Review is in progress with results being released in June 2017.

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 summarize NASA's future plans for the launch of 9 missions and 6 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[2] in formulation or development contained in the ESM program most relevant to CGMS members are the Ice, Cloud, and Land Elevation Satellite (ICESat)-2, Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), Total and Spectral Solar Irradiance Sensor on the ISS (TSIS-ISS), Compact Spectral Irradiance Monitor (CSIM), and Surface Water Ocean Topography (SWOT) missions.

The Agency continues with the formulation, and development of other Decadal and climate missions such as NASA-ISRO Synthetic Aperture Radar (NISAR), Pre-Aerosols, Carbon and Ecosystems (PACE[3]), and the Climate Absolute Radiance and Refractivity Observatory Pathfinder (instrument on the ISS (CLARREO PF-ISS[3]). NASA is also continuing its partnership with the U.S. Geological Survey (USGS) in extending the Landsat series with Landsat-9.

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

The Total and Spectral Solar Irradiance Sensor on the ISS (TSIS-1-ISS), the latest NASA mission to measure solar irradiances, includes two instruments: the Total Irradiance Monitor (TIM) measuring total solar irradiance (TSI) and the Spectral Irradiance Monitor (SIM) measuring solar spectral irradiance. The TSIS TIM and SIM were designed, built, and will be operated by the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP). TSIS-ISS is currently scheduled for a November 2017 launch on a Space X Falcon 9 rocket from the Kennedy Space Center in Florida followed by deployment on the ISS on the Express Logistics Carrier 3, site 5 (ELC 3-5).

As a 5-year mission, TSIS-1-ISS constitutes the follow-on to the Solar Radiation and Climate Experiment (SORCE) launched on a Pegasus XL vehicle on January 25, 2003 and the Total Solar Irradiance Calibration Transfer Experiment (TCTE) launched on a Minotaur-1 rocket from NASA Wallops Flight Facility on November 19, 2013. The TSIS TIM will provide continuity of TSI measurements currently provided by the SORCE and TCTE TIM instruments. TSIS SIM will provide continuity of SSI measurements currently provided by the SORCE SIM, delivering Level 3 science products within 24 hours of data acquisition.

The TSIS SIM is a new design incorporating lessons learned from the SORCE SIM. The TSIS SIM measurement requirements are listed in Table 4 and are derived from analysis of the variability in spectral irradiance measured by the SORCE SIM and incorporating the needs of the atmospheric and solar physics modeling communities. The unprecedented accuracy (0.2%) of the TSIS SIM instrument will be of great value to the Global Space-based Inter-Calibration System (GSICS) initiated by WMO and CGMS. The SIM SSI measurements will establish a new standard for monitoring instrument performances, conducting operational inter-calibration of satellite instruments, and, in favorable cases, providing recalibration of archived data.

[2] 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/.
[3] Development continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President's FY18 Budget Proposal released May 23, 2017.

Table 4. TSIS SIM Measurement Requirements

Parameter	Requirement
Measurement Range ($W\ m^{-2}\ nm^{-1}$) Spectral (200-2400 nm)	10^{-4} to 10^{-1}
Relative Stability (per year) $200 \leq \lambda \leq 400$ nm $400 < \lambda \leq 2400$ nm	 0.05% 0.01%
Measurement Precision Spectral (200-2400 nm)	 0.01%
Measurement Accuracy Spectral (200-2400 nm)	 0.2%
Reporting Frequency (per day) Spectral (200-2400 nm)	2
Spectral Resolution (nm) $\lambda \leq 280$ nm 280 nm $< \lambda \leq 400$ nm $\lambda > 400$ nm	 2 5 45

The TSIS SIM instrument is designed to reduce the uncertainty of on-orbit instrument degradation corrections and to improve noise performance. Reduction of degradation correction uncertainty focuses on reduced contamination of the wavelength dispersive optics inside the instrument, namely, the Féry prisms. Contamination control is realized by ensuring ultra-clean operating conditions through both the pre-launch and on-orbit timeframes by exploiting a multiple modular isolation approach for specific instrument subsystems. TSIS SIM also has three redundant channels, compared to two channels on SORCE SIM to reduce uncertainties in the tracking of long- term instrument degradation. Improved noise performance in the TSIS SIM is realized through implementation of a better thermal design and a larger dynamic range enabled by improved electronics. Calibration and validation of the TSIS SIM at the required 0.2% level of absolute irradiance accuracy is realized using the LASP Spectral Radiometer Facility (SRF). The SRF uses NIST Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) sources, intensity stabilized lasers, and an absolute cryogenic electrical substitution radiometer as a standard calibrated detector to perform subsystem and system level characterizations and calibrations across the TSIS SIM operating spectrum.

6.1.2 Compact Spectral Irradiance Monitor (CSIM)

NASA continues to explore and support new approaches and technologies to measure the solar spectral irradiance (SSI) at a higher level of accuracy than the Solar Radiation and Climate Experiment (SORCE) and equal to or better than the Total and Spectral Solar Irradiance Sensor on the ISS (TSIS-1-ISS) mission. The Compact Spectral Irradiance Monitor (CSIM) instrument, designed for accommodations on a CubeSat or micro-bus, will acquire the same SSI measurements currently being made by the SORCE Spectral Irradiance Monitor (SIM) and the TSIS SIM. CSIM was designed and built and will be operated by the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) with a proposed launch date in the first six months of 2018. The performance requirements for the CSIM instrument are identical to those for the TSIS SIM, slated to launch to the ISS in November 2017.

CSIM covers a continuous wavelength range of 200-2400 nm and meets the required SI-traceable accuracy and on-orbit stability but with reduced size and cost. The CSIM and accompanying electronics were designed to fit into a 6U CubeSat while also meeting its reduced power requirements, all while adopting new SSI sensor technology. CSIM, like TSIS SIM, will undergo extensive radiometric absolute spectral calibrations in the LASP Spectral Radiometry Facility (SRF) in early 2017 to achieve the same calibration and stability performance of TSIS SIM (see Table 4). Like the SORCE and TSIS TIM and SIM, CSIM SIM uses redundant channels to track and correct the solar-exposure related degradation. While TSIS SIM is a three-channel instrument designed to maintain on-orbit long-term stability at least five through full inter-channel cross calibrations activities, CSIM is a two-channel instrument (like SORCE SIM) for which analysis has shown the long-term stability can be maintained for several years. The primary measurement channel will be used to obtain the twice-daily solar spectral irradiance. The secondary channel will then be used less frequently (~10% duty cycle) to correct the solar exposure degradation in the primary channel.

Launch and on-orbit operation of the CSIM will produce a number of advances in future satellite SSI measurements. First, CSIM will demonstrate the viability of a 6U CubeSat SSI monitor to benefit the long-term SSI climate data record by providing short development cycles at reduced costs that can offer rapid response to augment larger missions where the risk of launch delays and measurement gaps are real. Second, it will raise the TRL of several new technologies that can be applicable to other instruments. Third, the timing of this flight may potentially allow overlap with the SORCE SIM instrument and the TSIS SIM instrument resulting in improved accuracy of the SSI climate record and providing an end-of-mission calibration for SORCE SIM. Operational overlap between the TSIS SIM and CSIM instrument is particularly interesting because the calibration of both instrument is tied to the same calibration facility. With more than 6 months of operational overlap, the data trends for each instrument can be compared and provide a unique opportunity to validate the technique for degradation tracking using redundant channels. Finally, the CSIM can mitigate a potential data gap between SORCE and TSIS SIM instruments should a significant delay occur in the TSIS program.

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[4]. 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

[4] 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/.

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 early 2016 included the MAIA and TROPICS missions, which are both low-Earth orbit investigations. Observations of small atmospheric aerosols from 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.

6.2.1 Tropospheric Emissions: Monitoring of Pollution (TEMPO) Instrument

The NASA Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument will measure atmospheric pollution over Greater North America, from Mexico City to the Canadian tar/oil sands, and from the Atlantic to the Pacific, hourly and at relatively high spatial resolution. TEMPO spectroscopic measurements in the ultraviolet and visible wavelengths provide a measurement suite that includes the key elements of tropospheric air pollution chemistry. Measurements are from geostationary orbit capture the inherent high variability in the diurnal cycle of emissions and chemistry. A small spatial footprint will resolve pollution sources at a sub-urban scale. Together, this temporal and spatial resolution will improve emission inventories, monitor population exposure, and enable effective emission-control strategies.

TEMPO takes advantage of a geostationary (GEO) host spacecraft to provide a modest cost mission that measures the spectra required to retrieve O_3, NO_2, SO_2, CH_2O, $C_2H_2O_2$, H_2O, aerosols, cloud parameters, solar-induced fluorescence, and UVB radiation. TEMPO thus can measure the major elements, directly or by proxy, in the tropospheric O_3 chemistry cycle. Multi-spectral observations provide sensitivity to

O_3 in the lowermost troposphere, which should significantly improve our understanding of North American air quality in unmonitored locations. TEMPO will quantify and tracks the evolution of aerosol loading and provide near-real-time air quality products that will be made widely and publicly available. TEMPO will the first North American trace gas measurements from GEO, providing hourly observations during the sunlit portion of the day.

The TEMPO instrument is currently under construction at Ball Aerospace and is scheduled for completion in early 2018. While the host spacecraft has not yet been selected, the TEMPO launch is anticipated by early 2021. TEMPO, with its view of North America, is one part of an international Atmospheric Composition Virtual Constellation (AC-VC) which includes the ESA TROPOMI satellite (with global afternoon coverage from LEO), the Korean GEMS instrument sampling from GEO over Asia, and the ESA Sentinel-4 with a GEO view of Europe.

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

Satellite	Space Agency	Orbit Information	Launch Date (NET)	Instruments	Details: Applications
GRACE-FO (Follow-On)	NASA/GFZ	89 Deg Inclination Non Sun-Sync 490 km	2018	Gravity, GPS	Earth mass distribution, with application to ground water, ocean currents and ice sheets, GPS (P,T,humidity)
ICESat-II	NASA	92 Deg Inclination Non Sun-Sync 478 km	2018	ATLAS	Ice sheet thickness, sea ice thickness, vegetation height, carbon and biomass
TSIS-1-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	<Mar 2018	Absolute ESR detector (NiP bolometer)	Solar spectral irradiance
ECOSTRESS-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	<Mar 2018	Thermal Radiometer	Plant-water dynamics
CSIM	NASA	TBD	<Nov 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 (ISS)	<Mar 2019	LIDAR	Forest vertical structure
TROPICS	NASA	LEO Constellation	Summer 2019	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 (ISS)	2020	RS	Reflected Solar (RS) Earth radiance
Landsat-9	NAS/USGS	Sun-Synchronous 650 km	2020	OLI-2, TIRS-2	High-resolution image information of the Earth's surface (Follow on to Landsat series)
TSIS-2-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 KM (ISS)	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.
GeoCarb Hosted Payload Instrument only	NASA	Geosynchronous	2021	Grating Spectrometer	Concentrations of carbon dioxide, methane, and carbon monoxide and solar-induced fluorescence
RBI* Hosted Payload Instrument only on JPSS-2	NASA	98.7 Deg Inclination Sun-Sync 833 km	2021	Scanning Radiometer	Measures Earth's reflected sunlight and emitted thermal radiation
SWOT	NASA/CNES	78 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)
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	Sun-Synchronous 650 km	2022	Spectrometer, Polarimeter	Aerosols, ocean color
MAIA	NASA	LEO	TBD	Multi-angle Imager	Atmospheric aerosols

* Development continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President’s FY18 Budget Proposal released May 23, 2017.

7 ADDITIONAL TOPICS OF RELEVANCE TO CGMS

7.1 Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)

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) data for numerical weather prediction, climate monitoring, and space weather forecasting and ionospheric research. The primary science instrument on the COSMIC satellites is a GPS RO receiver developed by NASA's Jet Propulsion Laboratory (JPL). By accurately tracking the phase and amplitude of the dual-frequency GPS L-band radio signals as a COSMIC satellite rises or sets behind Earth (see Figure 4), 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. NASA and the National Science Foundation (NSF) are currently funding the University Corporation for Atmospheric Research (UCAR) COSMIC Program (UCAR/COSMIC) to 1) process and serve COSMIC and other RO mission data to the operational (via the Global Telecommunications System) and research communities; 2) conduct research to improve GNSS RO inversion science and techniques; and 3) conduct research, education, and outreach activities to support science applications of RO data. NASA also funds a GNSS RO science team.

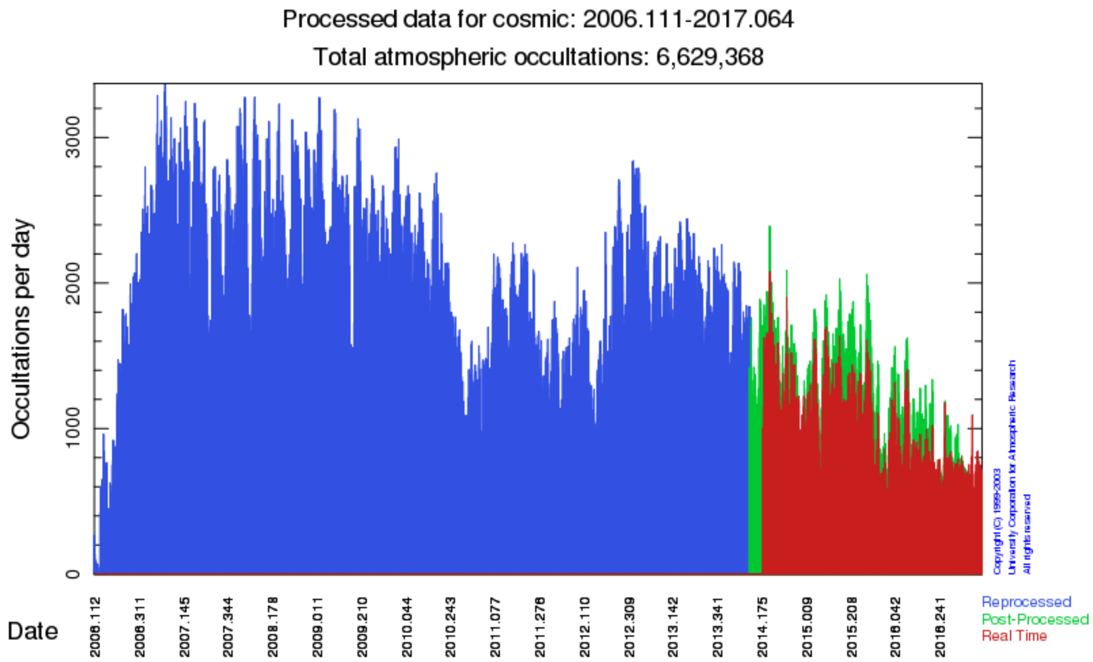

Figure 4: *Daily COSMIC neutral atmosphere profile count throughout the mission. The red color shows the soundings from near real-time UCAR processing. The green color shows the soundings from post-processing, which often is able to generate more sounding profiles but lags several months behind the near real-time products. The blue color shows the soundings from re-processing, which are processed every 3 years with up-to-date software.*

UCAR/COSMIC currently processes COSMIC data into atmospheric and ionospheric products for data users in near real-time, three months after real-time with the latest inversion algorithms, and also periodically every three years with up-to-date and consistent software to provide the most accurate and stable products for use in climate studies (see http://www.cosmic.ucar.edu). Since shortly after launch on April 14, 2006, COSMIC has provided as many as 3,200 atmospheric profiles per day, and to date has accumulated more than 6.6 million profiles. During the first half of April 2017 two out of the original six satellites (Flight Models, FMs #1, #6) were providing up to 700 profiles per day. Taiwan's National Space Organization (NSPO) lost contact with flight model #1 on April 16, 2017 due to loss of attitude control. Temporary loss of contact with COSMIC spacecraft has occurred many times throughout the mission, so it is a reasonable expectation to regain contact with FM #1 in the near future. Flight model #6 is currently providing approximately 200 profiles per day. Flight models #2, #3, #4, and #5 are not expected to provide any more useful data.

COSMIC is an interdisciplinary satellite mission that is addressing some of the most intriguing questions in Earth sciences today. COSMIC provides among the highest vertical resolution atmospheric measurements available. COSMIC data have had a significant positive impact on operational NWP, ranking among the top five in impact among all observing systems by some metrics (Cardinali and Healy, 2014). COSMIC data have the potential to produce a positive impact on the prediction of the track and intensity of tropical cyclones from genesis to landfall (Kuo et al., 2008; Vergados et al. 2014). COSMIC has increased our understanding of the genesis and evolution of atmospheric phenomena such as the El Niño Southern Oscillation (ENSO) and the Madden–Julian oscillation (MJO) (Scherllin-Pirscher et al., 2012; Tian et al., 2012; Zeng et al., 2012), is used for monitoring the structure and spatial and temporal variation of the atmospheric boundary layer (Sokolovskiy et al., 2007; Ao et al., 2012, Ho et al., 2015), and has shown promise in detecting tropospheric ducts (Sokolovskiy, et al., 2014). For climate studies, COSMIC is observing Earth's atmosphere with unprecedented long-term stability, vertical resolution, coverage, and accuracy. RO datasets are being used to quantify the structural uncertainty arising in RO processing (Ho et al., 2009) to investigate temperature trends in the upper troposphere and stratosphere (Steiner et al., 2009). For space weather research, COSMIC data are being used to study ionospheric climatology, improve physical models, and study coupling between the lower and upper atmosphere (Lei et al., 2007; Pedatella and Maute, 2015). COSMIC is also a pathfinder technology mission. UCAR and JPL have worked in partnership to advance RO tracking and inversion methods in the troposphere (Sokolovskiy et al., 2010) and to optimize use of new GPS signals such as L2C (Sokolovskiy et al., 2014). Since launch over 600 TB of COSMIC data have been downloaded from the UCAR website, which has led to over 440 high quality research publications between 2006 and 2015 (source: Web of Science). To date, UCAR/COSMIC has registered over 3,800 data users from 88 countries.

The U.S./Taiwan 6-satellite COSMIC-2/FORMOSAT-7 equatorial constellation is planned for launch no earlier than December 2017, continuing the partnerships established with COSMIC. This equatorial mission will greatly improve sampling density of RO profiles in the tropics, but due to the 24° inclination angle of the satellites will not provide data above 40° latitude. The COSMIC-2 polar constellation will provide data above 40° latitude, but is not yet fully funded. The primary instrument on COSMIC-2 is the TriG instrument developed at NASA/JPL, supplied by the US Air Force. The TriG tracks both GPS and GLONASS GNSS constellations. UCAR in conjunction with NOAA is developing the ground data processing system for COSMIC-2.

7.2 Recently Selected Research and Suborbital Investigations

7.2.1 Geostationary Carbon Cycle Observatory (GeoCarb)

NASA recently selected the Geostationary Carbon Cycle Observatory (GeoCarb), as the second complete mission in the NASA Earth Ventures series (CYGNSS is the first mission in the series, launched in December 2016). GeoCarb is the first NASA satellite designed to collect spatially resolved observations of the column averaged mole fractions of carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and solar-induced chlorophyll fluorescence (SIF) at high spatial resolution (5 to 10 km) from geostationary orbit (GEO).The primary goals of GeoCarb are to monitor plant health and vegetation stress throughout the Americas, and to monitor the sources, sinks of atmospheric CO_2, CH_4, and CO with unprecedented detail.

7.2.1.1 New Observing Capabilities of GeoCarb

The GeoCarb mission is scheduled for a 2021 launch as a hosted payload on an SES Government Solutions satellite. It will be deployed in a GEO orbit above 85° West longitude. From this vantage point, its high resolution imaging spectrometer will produce maps of the column averaged dry air mixing ratios of CO_2 (X_{CO2}), CH_4, (X_{CH4}), CO (X_{CO}) and SIF at a spatial resolution of 5-10 km multiple times each day (Figure 5). These data will cover the major urban and industrial regions in the Americas, large agricultural areas, and the expansive South American tropical forests and wetlands. GeoCarb maps will be analyzed to resolve the variability in CO_2, CH_4, and CO fluxes and to provide critical insight into the relationship between the carbon cycle and climate change. By demonstrating that GeoCarb can be flown as a hosted payload on a commercial satellite, the mission will strengthen NASA’s partnerships with the commercial satellite industry and provide a model that can be adopted by NASA’s international partners to expand these observations to other parts of the world.

The Principal Investigator (PI) of the GeoCarb mission is Professor Berrien Moore of the University of Oklahoma. U.S. mission partners include the Lockheed Martin Advanced Technology Center in Palo Alto, California; SES Government Solutions Company in Reston, Virginia; the Colorado State University in Fort Collins; and NASA's Ames Research Center in Moffett Field, California, Goddard Space Flight Center in Greenbelt, Maryland, and Jet Propulsion Laboratory in Pasadena, California. International collaborators include the University of Melbourne in Australia, the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) and Laboratoire de Météorologie Dynamique (LMD) in France, as well as Agencia Espacial Mexicana (AEM) and several research universities in Mexico.

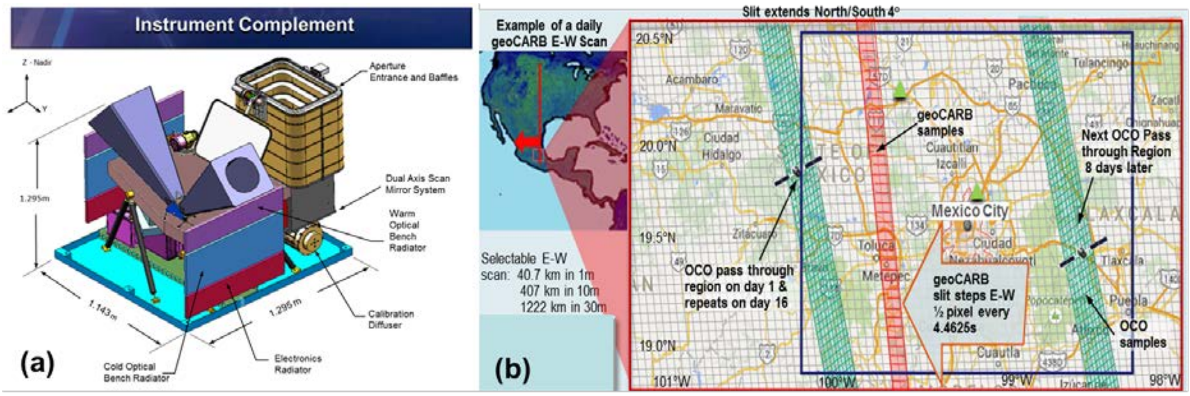

Figure 5: *(a) The GeoCarb instrument is an imaging grating spectrometer designed to measure reflected sunlight in near- and shortwave infrared absorption bands of O_2 (765 nm) CO_2, (1610 and 2060 nm), CH_4 and CO (2300 nm), using methods pioneered by OCO-2. (b) From GEO, GeoCarb can scan its slit from east to west to provide continental scale imaging of X_{CO2}, X_{CH4}, X_{CO} and SIF at high spatial resolution. The grid pattern produced by GeoCarb sampling is superimposed on a map that also shows OCO-2 tracks (green) for comparison. The red shading indicates a single GeoCarb observation time, and individual red boxes represent GeoCarb footprints.*

7.2.2 Satellite Calibration Intercomparison Study (SCIS)

The quantitative determination of global trends in the Earth's atmosphere, ocean, cryosphere, biosphere, and land surface depends significantly on the ability of the scientific community to construct multi-instrument/multi-platform data sets based on satellite observations covering periods of a decade or longer. As part of the 2015 NASA Research Opportunities in Space and Earth Sciences (ROSES-15) solicitation, the Satellite Calibration Interconsistency Studies (SCIS) program selected 12 projects in August 2016 to participate in the quantitative comparison of multiple satellite data products primarily focused on research and operations to facilitate the development of multi-instrument/multi-platform data sets involving satellites from multiple providers. The selected projects will address interconsistency issues of two or more satellite sensors, at least one of which is currently supported through NASA's Earth Science Program, and at least one of which is supported by some other organization (U.S. or foreign).

The "knitting together" of such data sets requires that the relative calibrations of the different sensors, their degradation over time, and the nature of the algorithms used to convert raw measurements into environmental parameters all be quantitatively understood. Given the diversity of sources of the instruments and algorithms, as well as the unique characteristics of each, focused effort is needed in creating such combined data sets. This challenge has been widely recognized by satellite operators and the existing organizations through which they coordinate their activities, such as the Committee on Earth Observing Satellites (CEOS), the World Meteorological Organization (WMO) and the Coordination Group for Meteorological Satellites (CGMS). Resulting data of value to operating missions and the sponsoring programs will be freely distributed and utilized as appropriate.

The SCIS program will support the 12 selected projects with a total funding of approximately $5.5M for a period of 3-years, although some projects have shorter periods of performance. NASA will evaluate the need of future SCIS solicitations as these projects near completion.

Table 6: ROSES-15 SCIS Selected Projects

Principal Investigator	Organization	Project Title
Brian Barnes	University of South Florida	Tampa Synergistic Multi-Sensor Calibration for Global and Coastal Observations of Aquatic Environments
Andreas Colliander	NASA Jet Propulsion Laboratory	Intercalibration of Low Frequency Brightness Temperature Measurements for Long-Term Soil Moisture Record
Jeffrey Czapla-Myers	University of Arizona	Intercalibration of GEO and LEO Sensors Using the Radiometric Calibration Test Site (RadCaTS) at Railroad Valley, Nevada
David Doelling	NASA Langley Research Center	Open Access Spectral Band Adjustment Factors for Consistent Inter-Satellite Calibration and Retrievals
Eric Fetzer	NASA/Jet Propulsion Laboratory	A Merged Temperature and Water Vapor Record from Modern Sounders
Mathew Gunshor	University of Wisconsin, Madison	Re-Calibrate Water Vapor Bands from International Geostationary Satellites for Consistency with AIRS
Christian Kummerow	Colorado State University	A Long-Term Satellite Climate Data Record of Global Precipitation
Can Li	University of Maryland, College Park	Producing Consistent Trace Gas Retrievals Through Inter-Calibration of Hyperspectral UV Measurements from OMI and GOME-2A
Hamidreza Norouzi	New York City College of Technology	A Multi-Sensor Calibration Algorithm for Improving Emissivity Retrieval by Integrating Microwave Brightness Temperature Diurnal Cycle
Lawrence Strow	University of Maryland Baltimore County	A Homogenous Infrared Hyperspectral Radiance and Level 3 Climate Record Combining NASA AIRS, JPSS CrIS, and EUMETSAT IASI
Eric Vermote	NASA Goddard Space Flight Center	Toward a Consistent Land Long Term Climate Data Record from Large Field of View Polar Orbiting Earth Observation Satellites
Juying Warner	University of Maryland, College Park	Tropospheric Ammonia Derived from AIRS and CrIS for a More Continuous Data Record Using a Uniform Retrieval Algorithm

7.2.3 Earth Science U.S. Participating Investigators (USPI)

The Earth Science U.S. Participating Investigator (USPI) program conducts investigations on foreign space missions that address the Earth Science Research

Program objectives listed in the NASA Science Plan (https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_Science_Plan_PDF_Update_508_TAGGED.pdf). This research contributes and facilitates access to foreign space agencies' assets with particular interest given to having close connections with the satellite observations of international partners, especially as coordinated through the Committee on Earth Observation Satellites (http://www.ceos.org/), as well as other international bodies, such as the Coordination Group for Meteorological Satellites (http://www.cgms-info.org/) and the World Meteorological Organization (http://www.wmo.int/pages/prog/sat/)..

In February 2017, NASA selected 7 proposals as part of the 2016 NASA Research Opportunities in Space and Earth Sciences (ROSES-16) solicitation for the USPI program (see Table 7). Selected investigations will expand scientific links with future European and Asian space missions. The total funding for these investigations, over a period of five years, is approximately $5.1 million.

Table 7: ROSES-15 USPI Selected Projects

Principal Investigator	Organization	Project Title
Ralf Bennartz	Vanderbilt University	Information Content Analysis and Algorithm Development Passive Microwave Systems for Atmospheric Monitoring
Douglas Mach	Universities Space Research Association, Columbia	U.S. and European Geostationary Lightning Sensor Cross-Validation Study
Peter Minnett	University of Miami, Key Biscayne	Sea-Surface Temperatures from Copernicus Sentinel-3s and EUMETSAT Polar System Second Generation (EPS-SG)
Vijay Natraj	NASA Jet Propulsion Laboratory	Retrieval of Aerosol Composition and Vertical Distribution Using Oxygen A-Band and Multi-angle Polarimetric Measurements from the EUMETSAT Polar System–Second Generation Satellite
Sassan Saatchi	NASA Jet Propulsion Laboratory	Development and Validation of Tropical Forest Aboveground Biomass Estimation from BIOMASS Mission Observations
Omar Torres	NASA Goddard Space Flight Center	Implementation of NASA-GSFC Tropospheric Ozone, Sulphur Dioxide and Aerosol Retrieval Algorithms at GEMS Viewing Geometry
Eric Vermote	NASA Goddard Space Flight Center	Sentinel 3 Data for Land Science: Calibration, Algorithm Development, Product Evaluation, Generation, and Validation

7.3 CubeSat Technology Satellite Demonstrations

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

Several technology demonstration satellites that may be of interest to CGMS members are currently in Earth orbit or are planned to launch in the near future. Most were selected in response to the 2012 and 2015 solicitations from the In-Space Validation of Earth Science Technologies (InVEST) program under NASA's Earth Science Technology Office (ESTO), while another was selected for technology demonstration in response to the Earth Venture Instrument (EVI-2) call in 2014. A brief description and current status of several of these are presented below.

The Radiometer Assessment using Vertically Aligned Nanotubes **(RAVAN)** consists of a fully functional 3U CubeSat platform with radiometer instruments that is compact, low cost, and absolutely accurate to NIST traceable standards that 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/m^2 absolute) for the first time. RAVAN launched on November 11th, 2016 on an Atlas V rocket from Vandenberg Air Force Base into an orbit that is nearly circular, sun-synchronous, and close to 600km. RAVAN is currently operational. 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 **ICECube** 3U CubeSat will perform 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. Submillimeter wave remote sensing has the capability to penetrate clouds and measure ice mass and microphysical properties. ICECube was launched on April 18th, 2017 from Cape Canaveral on a ULA Atlas V 401 rocket carrying Orbital ATK's seventh contracted commercial resupply services mission (OA-7) to the ISS. ISS deployment of ICECube is scheduled for mid-May 2017. Once deployed from the ISS, ICECube is configured to spin continuously around the axis to the Sun at ~1.2 degrees per second, allowing for maximum solar power reception and periodic Earth and space views for instrument calibration. The goal is to operate in LEO for at least 3 months in order to meet the measurement objectives with an on-orbit demonstration of an NEDT of ~0.1K for 1-second long observations and a calibration error of 2.0 K or less as measured from deep-space observations.

The HyperAngular Rainbow Polarimeter **HARP**-CubeSat 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-Ecoysystem (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 from Cape Canaveral on the Space-X-12 ISS resupply mission no earlier than August 1st, 2017, with deployment from the ISS shortly thereafter.

The Microwave Radiometer Technology Acceleration **(MiRaTA)** is a 3U CubeSat that will validate new ultra-compact and low-power technology for CubeSat-sized microwave radiometers operating near 52-58, 175-191, and 206-208 GHz and validate new GPS receiver and antenna array technology necessary for CubeSat tropospheric radio occultation sounding. MiRaTA will also test a new approach to radiometer calibration using concurrent GPS radio occultation (GPSRO) measurements. A slow pitch up/down maneuver will be executed once per orbit to permit the radiometer and GPSRO observations to sound overlapping volumes of atmosphere through the Earth's limb, where sensitivity, calibration, and dynamic range are optimal. These observations will be compared to radiosondes, global high-resolution analysis fields, other satellite observations, and with each other using radiative transfer models. MiRaTA will demonstrate high-fidelity, well-calibrated radiometric sensing from a CubeSat platform. MiRaTA will not only validate multiple subsystem technologies, but will also demonstrate new sensing modalities that would dramatically enhance the capabilities of future weather and climate sensing architectures. Lessons learned by MiRaTA on-orbit will be leveraged by the **T**ime **R**esolved **O**bservations of **P**recipitation structure and storm **I**ntensity with a **C**onstellation of **S**mallsats (TROPICS) project as appropriate. MiRaTA is scheduled to be delivered for integration on June 26th, 2017 to launch with JPSS-1 September 21st, 2017 from Vandenberg Air Force Base, California.

The Radar-in-a-CubeSat (**RainCube)** will consist 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, and is manifested for an ISS resupply launch in the second quarter of 2018, to be deployed from the ISS thereafter.

The CubeSat Infrared Atmospheric Sounder (**CIRAS**) will consist of a fully operational 6U CubeSat platform with a miniaturized hyperspectral infrared spectrometer instrument (sounder) as its payload. The CIRAS payload has similar performance to legacy atmospheric infrared sounders such as the Atmospheric Infrared Sounder (AIRS) on Aqua and the Cross-track Infrared Sounder (CrIS) on NPP but uses only the MWIR (from 1950 cm^{-1} to 2090 cm^{-1}) at higher spectral resolution (0.5 cm^{-1}) to resolve water vapor and CO2 (for temperature) absorption features. CIRAS is capable of scanning ±55° to provide global daily coverage, but will be limited due to data rate constraints on the first unit. CIRAS is not yet manifested but is planned for launch in the 2018/2019 timeframe.

The Temporal Experiment for Storms and Tropical Systems Technology Demonstration (**TEMPEST-D**) will demonstrate 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. TEMPEST-D is expected be ready for delivery to the launch provider in August 2017 for a potential ISS resupply launch in the second quarter of 2018, and with deployment from the ISS soon thereafter.

7.4 Satellite Needs Working Group

The President's Budget for Fiscal Year 2016 issued guidance that made NASA responsible for acquiring the space segment of all U.S. Government-owned civilian Earth-observing satellites, except for National Oceanic and Atmospheric Administration (NOAA) weather and space weather satellites. NASA worked with the U.S. Group on Earth Observations (USGEO) to develop a process whereby USGEO collects needs for satellite Earth observations from U.S. government agencies, and NASA evaluates those needs. In early 2016, USGEO's Satellite Needs Working Group (SNWG) ran a prototype process, using lessons learned from it to develop a new process. In June of 2016, SNWG and NASA kicked off the new satellite needs process, following the timeline in Table 8.

Table 8. Satellite Needs Timeline

Date	Action
June 17, 2016	USGEO SNWG and NASA conduct kickoff meeting
September 1, 2016	Agencies submit needs to USGEO
November 2, 2016	NASA receives needs from USGEO
June 1, 2017	NASA responds to user agencies and OMB

On November 2, NASA received 77 needs from 17 federal agencies and departments (Table 9). To assess these needs, NASA Headquarters formed a team consisting of over 35 members from Headquarters, Goddard Space Flight Center, Langley Research Center, the Jet Propulsion Laboratory (JPL), and others. NASA divided the needs among teams according to areas of expertise common to the team.

In conducting its initial review of the needs, NASA found that many submissions consisted of multiple related needs that the agency bundled into one submission. Furthermore, after discussing some of the needs with the submitting agencies, some agencies elected to combine or in one case split their submissions. In total, NASA counted 122 needs for individual data sets or data products. The needs varied across a broad variety of disciplines, though land use and land cover needs were by far the most common, comprising 55 of the original 77. Submissions varied from straightforward needs for continuation of existing measurements to highly complex needs that would require new satellites or even entirely new measurement techniques. Several agencies needed data related to fire management, especially the fuel loads, positions of fires, and the condition of the land after the fires. Other agencies needed observations of plant health, animal movement, and trace gases in the atmosphere. Some needed visible light images on very fine scales of less than a meter, while others wanted detailed spectral images on a much coarser scale. Some agencies needed data every hour, while others were satisfied with only one good image, and wanted updates only if a disaster drastically changed the landscape.

NASA has completed its internal assessments of the needs and is writing up the responses to the agencies. Most will at least be partially met by NASA data, whether from current or planned missions. Some needs will be most economically met by commercially available data. Others will be considered as challenges for potential future missions. Some may inspire new commercial ventures to meet those needs.

Table 9. Satellite Needs Submissions by Organization

U.S. Federal Agency	# Needs
Agricultural Research Service (USDA)	2
Bureau of Land Management (DOI)	3
Bureau of Reclamation (DOI)	1
Department of Energy	13
Environmental Protection Agency	5
Farm Service Agency (USDA)	1
Federal Emergency Management Agency (DHS)	1
Foreign Agricultural Service (USDA)	3
Forest Service (USDA)	3
National Agricultural Statistics Service (USDA)	1
National Oceanic and Atmospheric Administration	8
National Science Foundation	1
Natural Resources Conservation Service (USDA)	2
Risk Management Agency (USDA)	2
U.S. Agency for International Development	9
U.S. Fish and Wildlife Service (DOI)	5
U.S. Geological Survey (DOI)	17
Grand Total	**77**

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