CGMS-44 NASA-WP-01
9 June 2016

Prepared by NASA
Agenda Item: D.2
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 17 Earth Science missions. Since the last CGMS-43 (May 2015), NASA's Earth Science program has not launched any new missions but several missions continue in development, with three missions due to launch in the coming year. During this time period, the Aquarius mission ended due to a failure of the SAC-D satellite platform, and the Soil Moisture Active-Passive (SMAP) mission was commissioned for routine operations but suffered a failure of its active instrument. All missions are currently producing data, but several also show signs of aging resulting in reduced data collection or reduced science utility. 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 13 missions and 7 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 17 Earth Science missions (see Tables 1 to 3). Since the last CGMS-43 (May 2015), NASA's Earth Science program has not launched any new missions but several missions continue in development, with three missions (CYGNSS, ISS-SAGE III and ISS-LIS) due to launch in the coming year. During this time period, the Aquarius mission ended due to a failure of the SAC-D satellite platform, and SMAP was commissioned for routine operations but suffered a failure of its active instrument. All missions are currently producing data, but several also show signs of aging resulting in reduced data collection for two (GRACE and SORCE), and one (EO-1) is currently scheduled for decommissioning in the next 12 months. 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 13 missions and 7 instruments (on host missions) in the future.

2 CURRENT SATELLITE SYSTEMS

The following tables summarize NASA's satellite systems:

Table 1: Current NASA LEO Satellites
Table 2: Current NASA HEO (or other) Satellites
Table 3: Current NASA 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
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

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.*

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
NMP EO-1	NASA	9:45 (D) 680 km	21-Nov-2000	Archive Earth Explorer New Data	ALI, Hyperion, LEISA AC	Land surface and earth resources
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, O3, GHG, aerosols
CALIPSO	NASA (support from CNES)	13:30 (A) 705 km	28-Apr-2006	ASDC	CALIOP, IIR, WFC	Aerosols and clouds
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
RapidScat-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km	20-Sep-2014	PO.DAAC	Scatterometer	Ocean surface wind speed and direction

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

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 (SWIR module not functioning)*
* *AMSU on Aqua (channel-4 failed)*
* *SORCE - Battery degradation, Instruments turned off during orbit night, data retrieved for up to 4 orbits/day only*
* *Cloudsat - Battery degradation, Instruments turned off during orbit night*
* *GRACE – Battery degradation, instruments turned off 40-60days twice/year (during each maximum eclipse period)*

3 STATUS OF CURRENT LEO SATELLITE SYSTEMS

Jason-2 and Suomi-NPP are operating nominally. There is no other significant information to report.

4 STATUS OF CURRENT HEO (OR OTHER) SATELLITE SYSTEMS

Not mentioned in the last CGMS-43 report was the Deep Space Climate Observatory (DSCOVR) mission. Under a reimbursable arrangement with NOAA, NASA refurbished the Deep Space Climate Observatory (DSCOVR) to continue solar wind measurements at the Sun-Earth Lagrange-1 (L1) point. DSCOVR was successfully launched by the US Air Force in February 2015, reached the L1 point in June, and transitioned successfully from NASA to NOAA operations in October 2015. DSCOVR, the nation's first operational satellite in deep space, is set to replace NASA's 17-year old Advance Composition Explorer (ACE) research satellite as America's primary warning system for solar magnetic storms and solar wind data (ACE will continue its role in space weather research).

Both NOAA's Space Weather Prediction Center and the US Air Force's Weather Agency use DSCOVR to support operational space weather forecasting and prediction during this solar cycle and beyond. For its space weather mission, DSCOVR uses two primary instruments, the DSCOVR Faraday Cup and the Goddard Fluxgate Magnetometer, together known as the PlasMag. The DSCOVR Faraday Cup is a retarding potential particle detector, located on the spacecraft upper deck facing towards the Sun, which provides high time resolution solar wind proton bulk properties (wind speed, density and temperature). It is designed to operate through high-energy particle storms that commonly accompany critical space weather events. The Fluxgate Magnetometer measures the interplanetary 3-D vector magnetic field and is located at the tip of a 4.0 m boom to minimize the effect of spacecraft fields. Together, these two instruments measure the components of solar wind plasma and a 3-D magnetic field vector, which allow DSCOVR to provide advanced warning of space weather events.

Advanced warnings are crucial because solar storms have the potential to produce major disruptions to our infrastructure here on Earth. The most severe solar storms can send enormous clouds of magnetic plasma that can cause strong electrical currents in the ionosphere and inside the Earth, disrupting electrical power grids, corroding gas and oil pipelines, and impeding the use of the Global Positioning System (GPS) by search-and-rescue crews.

In addition to the Space Weather mission, DSCOVR also provides unique and relevant Earth science because of its Lagrange point 1 (L1) orbit, approximately one million miles from Earth. Its two Earth science instruments, EPIC and NISTAR are observing the full sunlit side of the Earth for a variety of scientific applications.

The Earth Polychromatic Imaging Camera (EPIC) provides calibrated images measuring the radiance from the sunlit face of the Earth on a 2048 x 2048 pixel CCD in 10 narrowband channels (UV and visible). It forms true-color RGB pictures of the planet with a spatial resolution of ~15 km at the meridian with an approximate 4 hour cadence. These images are available within a day at the EPIC website (epic.gsfc.nasa.gov).

In addition, the ten spectral band images can be used to derive ozone, aerosol, cloud cover and height, sulfur dioxide, and vegetation indices at the same cadence. The absolute calibration of these 10 EPIC channels is currently underway, with preliminary calibrations being used for the initial science products. Total ozone retrievals have been made and compare well with Suomi NPP total ozone maps. Cloud masks, cloud top heights and pressures, and cloud optical thickness products are presently in development. Algorithms are being refined for sulfur dioxide and ash, aerosols, and vegetation indices. Initial results from all of these algorithms are promising. Validation for all of these products is ongoing.

5 STATUS OF CURRENT R&D SATELLITE SYSTEMS

All current satellite missions are producing data, but several also show signs of aging, and one is scheduled for decommissioning in 2016. Signs of battery aging have been observed in 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; in addition, SORCE data are retrieved for only a portion of the orbits, not the entire day. GRACE data include outages of 40-60 days during the periods (approximately twice/year) when the twin satellites experience their longest eclipses. The EO-1 mission is out of orbit maintenance fuel, and the mean local time of the ascending node is expected to reach 8:00am in 2016, reducing the utility of the data. 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 Aqua's AMSU (Channels 4,5, and 7 are non-operational). 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. ISS-RapidScat is functioning nominally, but has experienced infrequent changes in receiver power levels that require re-calibration after a transition. All other sensors are fully functional and are producing standard products that meet or exceed specifications.

5.1 Formation Flying

It is 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 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 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 is planned for California in 2017 that will bring together a wide variety of scientific users 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.

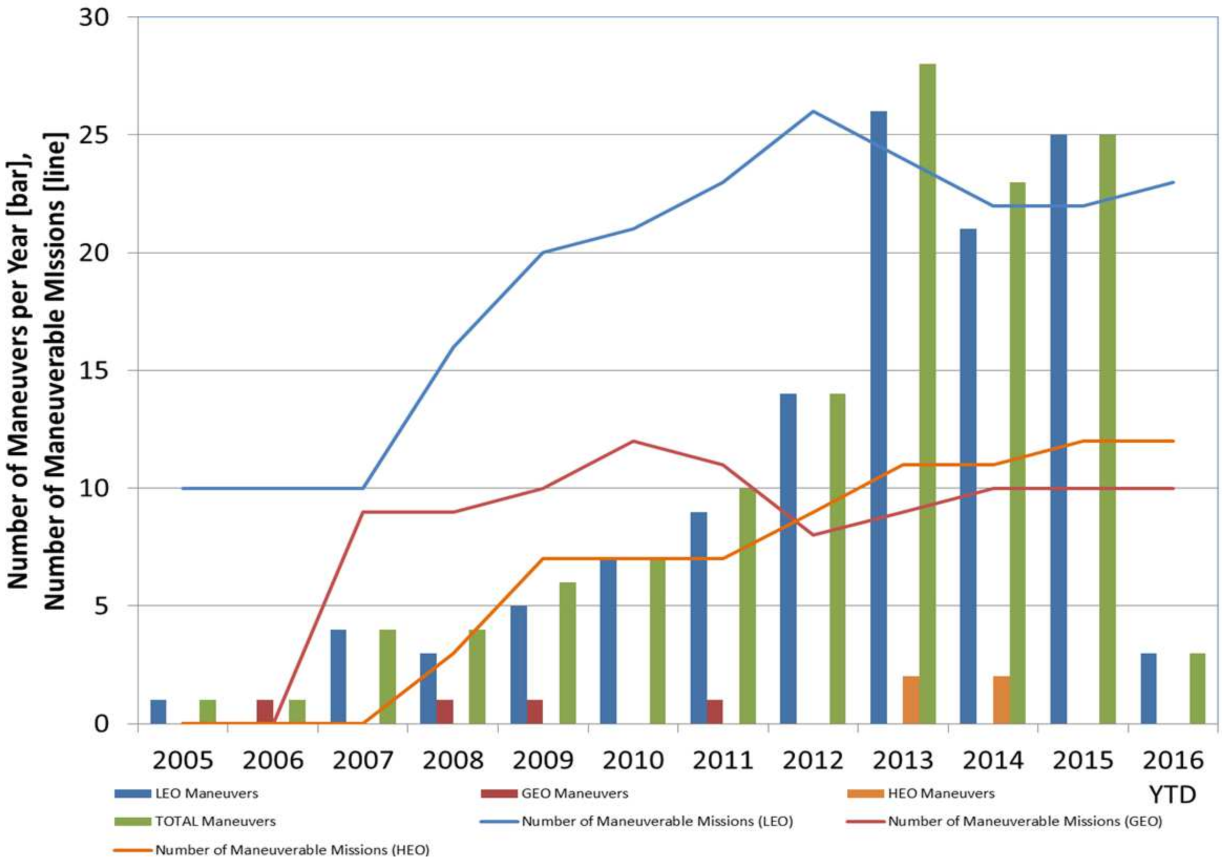

Figure 1: *History of collision avoidance maneuvers.*

5.3 Measurement Continuity and Transition to Follow-on Missions

As satellites and sensors age and new missions measuring key climate parameters with new sensors come on-line, the continuity of the datasets must be addressed if climate data records are to be maintained. Even when successor missions are already on-orbit or planned, the older dataset must be adequately documented and preserved for future research. All operating NASA missions are requested to plan adequately for post-mission reprocessing and expected to satisfy a data preservation specification developed by the Earth Science Data and Information System (ESDIS) project (https://earthdata.nasa.gov/standards/preservation-content-spec). Final datasets for the ACRIMSAT and Jason-1 missions were delivered to the data centers in the past year. A summary of the data plans for the two missions which ended in 2015 is below.

5.3.1 Tropical Rainfall Measuring Mission (TRMM)

TRMM ended data collection on April 15, 2015 and re-entered the Earth's atmosphere on June 15, 2015. At that point it began its close-out period. TRMM will conduct a final reprocessing of the 17+ years of radiometer, radar, and visible/infrared instruments. Upon completion of this reprocessing, the data will become part of the Global Precipitation Measurement (GPM) mission dataset. Indeed, the reprocessing will be done using GPM V05 algorithms for the radar and radiometer products. With this reprocessing TRMM will become a constellation satellite. This will ensure that anytime that GPM algorithms are improved they will always be applied to TRMM data. Any subsequent GPM reprocessing will always reprocess all the data from TRMM. This approach guarantees a consistent precipitation dataset that extends back to the beginning of the TRMM mission in late 1997.

As part of this last TRMM reprocessing, and the ensuring integration into GPM, data will be stored in the HDF5 format. The names of the TRMM data products will follow the GPM convention rather than the old TRMM style. This reprocessing is actually V8 for TRMM. However, it will be part of the GPM V05 reprocessing. As a result the data product version number for this reprocessed data will be V05.

The reprocessing will make substantial improvements in the TRMM Microwave Imager (TMI) both in the areas of calibration and geolocation. As part of the TMI improvement the level 1 format will also be changed. Part of the calibration improvements come from the additional deep space calibrations that were carried out at the end of the mission. TRMM is unique in having deep space calibrations both at the beginning and the end of the mission. The TRMM Ku Precipitation Radar (PR) will also have calibration changes applied. The format for PR will be the same as the GPM Ku rather than the existing format. TRMM Radar 1C and all current TRMM level 2 products will be merged into a single Ku level 2 product as is done for GPM.

The entire 17+ years of TRMM data should be reprocessed by early 2018. It will be a greatly improved dataset that is consistent with the ongoing precipitation data being produced by GPM. Access to TRMM data can be obtained by registering at registration.pps.eosdis.nasa.gov. After registration users will have access to TRMM and GPM data.

5.3.2 Aquarius

The NASA Aquarius ocean salinity mission ended data collection June 7, 2015, when the spacecraft power supply to the navigation system failed. Data collection began August 25, 2011. The Aquarius Phase F closeout period began in October 2015, and will complete December 2017. The Aquarius Project is conducting a final reprocessing of the approximately 3 years and 9 months of data, with particular attention to providing the best quality data record possible with current understanding of the calibration and geophysical models. As understanding improves with time, the archived dataset and associated documentation will allow for future upgrades in independent research projects, and support a sea surface salinity measurement continuity project. The Aquarius data are intended to stand as a baseline for satellite salinity climate data records with other missions.

The final Aquarius Sea Surface Salinity dataset will be Version 5, and delivered to the PODAAC by the end of December 2017. The Version 4 algorithm left a number of open issues that will be resolved in a systematic manner in Version 5. The algorithm updates will include the final instrument calibrations, improved geophysics (density, spice, rain impact model, sea surface temperature, atmospheric and air-sea interaction physics, etc.), improved galaxy correction, and other improvements based on SMAP results. An uncertainty analysis will be completed, and an updated user guide will be prepared. Although Version 5 will be the final project-generated dataset, the L0 and L1a data will be archived to enable future improvements and reprocessing under independent research projects.

The archive of record for Aquarius archived data products is NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC): http://podaac.jpl.nasa.gov/SeaSurfaceSalinity/Aquarius

5.4 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, 2015 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 will be conducted in 2017.

5.5 Real-time Direct Broadcast Data

Several of NASA’s missions provide for the real-time transmission of satellite data to the ground in support of operational activities and disaster monitoring. As the Earth is being observed by satellite instruments on these platforms the data is transmitted using omni-directional antennas. Users who have compatible ground receiving equipment and are in direct line of sight to the satellite may receive these transmissions. This Direct Broadcast capability is currently available for selected instruments on the Aqua, Terra, and Suomi-NPP missions. More information on the required hardware and ground station processing software can be found at NASA's Direct Readout Laboratory (DRL) website: http://directreadout.sci.gsfc.nasa.gov. NASA also provides access to Near Real-Time (NRT) global data and products from the MODIS (on Terra and Aqua), OMI and MLS (on Aura), and AIRS (on Aqua) instruments in less than 2.5 hours from observation from the Land and Atmosphere Near real-time Capability for EOS (LANCE) data system at http://earthdata.nasa.gov/lance

6 FUTURE SATELLITE SYSTEMS

With the U.S. President's FY2017 budget request, 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 4 summarize NASA's future plans for the launch of 13 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 in formulation or development contained in the ESM program are the Ice, Cloud, and Land Elevation Satellite (ICESat)-2, Stratospheric Aerosol and Gas Experiment (SAGE)-III, Lightning Imaging Sensor (LIS), Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) and Surface Water Ocean Topography (SWOT) missions.

The Agency continues with the pre-formulation studies, formulation, and development of other Decadal and climate missions such as NASA ISRO-Synthetic Aperture Radar (NI-SAR), Pre-Aerosols, Carbon and Ecosystems (PACE), Climate Absolute

Radiance and Refractivity Observatory Pathfinder (CLARREO PF) instrument, CLARREO mission, Active Sensing of Carbon dioxide Emissions over Nights, Days and Seasons (ASCENDS), Aerosols, Clouds and Ecosystems (ACE), Geostationary Coastal and Air Pollution Events (GEO-CAPE), and Hyperspectral Infrared Imager (HyspIRI).

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. 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, including the Orbiting Ocean Observatory 3 (**OCO-3**) instrument for the measurement of atmospheric carbon dioxide (CO_2). 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.

NASA selected the Cyclone Global Navigation Satellite System (**CYGNSS**) mission as part of the Earth Venture Mission (EVM-1) solicitation in 2012. The CYGNSS mission is scheduled for launch in October 2016. CYGNSS will provide measurements of ocean surface winds with high temporal sampling in all precipitating conditions. Its goals and objectives focus on understanding and improving the forecasting of tropical cyclones. CYGNSS consists of a constellation of eight small observatories, each of which carries a 4-channel bistatic radar receiver tuned to receive GPS navigation signals scattered from the ocean surface. The receivers measure the distortion to the navigation signals caused by the ocean roughness, from which the near-surface wind speed is retrieved in a manner analogous to traditional ocean wind scatterometers. The eight satellites are spaced approximately twelve minutes apart in a common circular orbit at 510 km altitude and 35 deg inclination to provide frequent temporal sampling in the tropics. The CYGNSS mission is currently in Phase D assembly, integration and test of the 8 observatories at the Southwest Research Institute. In parallel with the hardware development, the mission's science algorithm team is working with the Science Operations Center at the University of Michigan to prepare for production of its Level 1, 2 and 3 science data products: ocean surface scattering cross section (1), instantaneous ocean surface wind speed (2) and gridded ocean surface wind speeds (3). The mission's science applications team is developing and testing data assimilation schemes for introducing CYGNSS data into modified versions of the NOAA Hurricane Weather Research and Forecasting (HWRF) model. Preliminary simulations indicate that there will be a significant positive impact on HWRF track and intensity forecast skill.

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 most recent 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.

Table 4 - Future NASA Research and Development (R&D) Satellites

Satellite	Space Agency	Orbit Information	Launch Date	Instruments	Details: Applications
SAGE-III-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	2016	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)	2016	Optical Imager	Lightning
CYGNSS	NASA	8 small satellites, 35 Deg Inclination, Non Sun-Sync 500 km	Oct 2016	GPS	Ocean surface winds for tropical storms and hurricanes.
GRACE-FO (Follow-On)	NASA/GFZ	89 Deg Inclination Non Sun-Sync 490 km	Aug 2017	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	Oct 2017	ATLAS	Ice sheet thickness, sea ice thickness, vegetation height, carbon and biomass
OCO-3-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	2018	Spectrometer	Carbon Dioxide distributions
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

GEDI-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	<Mar 2019	LIDAR	Forest vertical structure
SWOT	NASA/CNES	78 Deg Inclination Non Sun-Sync 891 km	2020	Ka-Band Radar Interferometer, AMR, GPSP, LRA, Poseidon Altimeter	Oceanography (wide swath ocean surface topography) and Hydrology (lake levels, river discharge)
CLARREO Pathfinder Hosted Payload Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km (ISS)	2020	RS	Reflected Solar (RS) Earth radiance
TEMPO Hosted Payload Instrument only	NASA	Geosynchronous	TBD	UV and VIS Spectrometer	Atmospheric pollution over the Americas. Tropospheric ozone, ozone precursors, aerosols, and clouds.
PACE (Pre-ACE)	NASA	Sun-Synchronous 650 km	TBD	Spectrometer, Polarimeter	Aerosols, ocean color
ASCENDS	NASA	10:30 (A) 450 km	TBD	Laser	Carbon Dioxide (day and night)
CLARREO	NASA	90 Deg Inclined	TBD	IR, RS, GNSS	Spectrally resolved and calibrated Infrared (IR) and Reflected Solar (RS) Earth radiance, GNSS (T,P,humidity)
NI-SAR	NASA/ISRO	98 Deg Inclination, Sun-Sync (6AM-6PM), 747 km	TBD	L-band, S-band SAR (repeat-pass interferometry, polarimetry)	Earth surface deformation, ecosystems and biomass change, ice motion
HyspIRI	NASA	TBD	TBD	Hyperspectral and TIR Imagers	Terrestrial and aquatic ecosystems, fires, mineral resources, volcanoes

GEO-CAPE	NASA	Geosynchronous	TBD	UV-Vis-NIR, IR imagers (CO detection)	Air pollution forecasting and transport, sources of aerosols and O3, coastal ecosystems, CO, NO2, SO2, HCHO
ACE	NASA	TBD	TBD	Spectrometer, Polarimeter, LIDAR, Cloud Radar	Aerosols, ocean color, cloud profiles
MAIA	NASA	LEO	TBD	Multi-angle Imager	Atmospheric aerosols
TROPICS	NASA	LEO Constellation	TBD	Microwave radiometer	Precipitation, temperature, humidity, imagery, cloud ice

6 ADDITIONAL TOPICS OF RELEVANCE TO CGMS

6.1 COSMIC (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 GPS 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 Global Positioning System (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 3), 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.

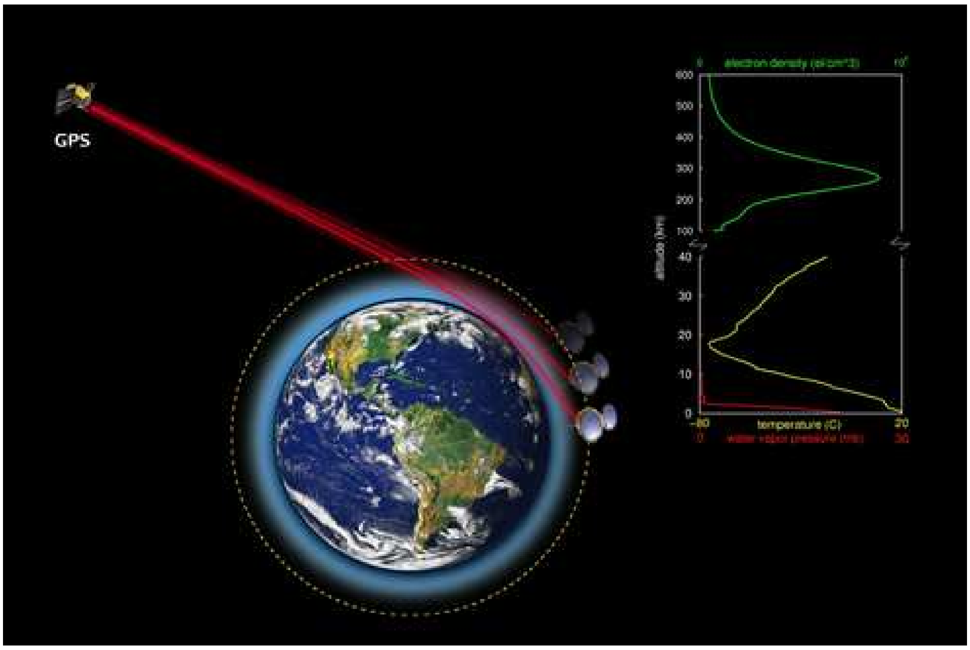

Figure 3: *FORMOSAT-3/COSMIC, Profiling the Atmosphere by Radio Occultation.*

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 6.3 million profiles. Much longer than the original three year design life, three out of six satellites (Flight models #1, #2, #5) are still active and providing approximately 600-1,400 profiles per day ten years after launch. Of the remaining three inactive satellites, flight model #6 may return to service, but flight models #3 and #4 are retired and 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). 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), and is used for monitoring the structure and spatial and temporal variation of the atmospheric boundary layer (Sokolovskiy et al., 2007; Ao et al., 2012). 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) and 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). COSMIC data have been used in over 440 high quality research publications between 2006 and 2015 (source: Web of Science). To date, UCAR/COSMIC has registered over 3,500 data users from 86 countries.

6.2 Earth Venture Suborbital Missions

The Earth Venture-class (EV) suborbital missions are regularly solicited, quick-turnaround projects that complement the strategic Earth Science satellite missions. The suborbital missions in particular are focused on probing processes through sustained measurements on regional scales that characterize important phenomena or address weaknesses in Earth system models. Of the five airborne science investigations selected in FY2009 and started in FY2010 through the initial Venture Class solicitation (EVS-1), one has ended in September 2015 (DISCOVER-AQ), and the remaining four will complete close-out during FY 2016. All investigations have publicly released their data, and have completed, or nearly completed, the transfer of data from investigation archives to an ESDIS DAAC.

In response to the second Venture Class solicitation (EVS-2), six new airborne investigations were selected and have started in FY2015 (ACT-America, ATom, CORAL, NAAMES, OMG, and ORACLES). Five were selected in November 2014, and one (CORAL) was selected in May 2015. Further information on these investigations can be found on the ESSP Program Office website: http://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder/.

6.3 CubeSat Technology Satellite Demonstrations

Several technology demonstration satellites that may be of interest to CGMS members are planned for the near future. Some were selected in response to a call for in-space technology validation (InVEST) put out by NASA's Earth Science Technology Office (ESTO) while another was selected for technology demonstration in response to the Earth Venture Instrument (EV-I-2) call in 2014. A brief description of several of these follows.

The Radiometer Assessment using Vertically Aligned Nanotubes **(RAVAN)** will consist of a fully functional 3U CubeSat platform with radiometer instrument that is compact, low cost, and absolutely accurate to NIST traceable standards that will pave the way for constellations that are affordable in sufficient numbers to measure Earth's radiative diurnal cycle and absolute energy imbalance to climate accuracies (globally at 0.3 W/m2) for the first time. The key technologies include a gallium fixed-point black body as a built-in 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. RAVAN is on schedule to launch in late 2016

The HyperAngular Rainbow Polarimeter **HARP**-CubeSat will perform a technology validation of a wide field-of-view imaging polarimeter for characterizing aerosol and cloud properties as required by the Aerosol-Cloud-Ecoysystem (ACE) mission. 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 in early 2017.

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 is scheduled to launch in early 2017.

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 CO_2 (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 planned for launch in the 2018/2019 timeframe.

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 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 performances within the mass, volume and power constraints imposed by the 6U class Cubesats. For this technology demonstration, RainCube is a single nadir-looking instrument like CloudSat’s Cloud Profiling Radar and is planned for launch in the 2017/2019 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 6U-class spacecraft altitude to 100 m or better. The TEMPEST-D 6U-Class satellite is expected be ready for delivery to the launch provider in August 2017. TEMPEST-D has been manifested for launch in early 2018 into a 450-km altitude orbit with 51.6 degree inclination.

6.4 Global Wind Measurements

ESA is planning to launch the Atmospheric Dynamics Mission Aeolus satellite (ADM-Aeolus), the first orbiting wind profiler, in 2017. Global wind measurements are likely to greatly improve Numerical Weather Prediction and severe weather warnings. ESA has asked other agencies to contribute to the cal/val of this satellite. Separately, there is a strong need to understand polar warming and ice loss. These two motivations led to the NASA Polar Winds airborne campaigns with the UC-12B based in Greenland during Oct-Nov 2014, and the DC-8 based in Iceland during May 2015. The parallel goals were to demonstrate the ability to assist ADM-Aeolus with cal/val, and to validate numerical model representations of flows over the Greenland ice cap as well as in the offshore ice/water areas around Greenland and Iceland. NASA's Doppler Aerosol WiNd (DAWN) horizontal wind-profiling coherent-detection lidar system flew in both campaigns. For the Iceland campaign, NASA also fielded the Tropospheric Wind Lidar Technology Experiment (TWiLiTE) direct-detection wind lidar and dropsondes; while ESA fielded the DLR Falcon containing both coherent-detection and direct-detection (ADM-Aeolus simulator) wind lidar systems. Joint DC-8 and Falcon flights occurred on six occasions and included about 50 dropsondes. For airborne wind lidar systems, this was the first NASA joint flights of coherent and direct-detection, and the first joint flights of four lidars on two closely spaced aircraft. The analysis of the joint wind data has the potential to help improve the launch configuration of ADM-AEOLUS, and to optimize the processing of the wind measurements. Both airborne campaigns were successful and both of NASA's goals were met; especially the collaboration with ESA, the mapping of barrier winds, flow splitting around Iceland, tip jet dynamics and dimensions, katabatic flow interaction with synoptic circulations and marginal ice zone roll clouds. There were also opportunities to use the DAWN lidar to measure the movement of icebergs relative to the ocean surface currents and near surface winds. Data processing and scientific analyses are ongoing.

MISTiC Winds is an approach to improve short-term weather forecasting based on a miniature high resolution, wide field, thermal emission spectrometry instrument that will provide global tropospheric vertical profiles of atmospheric temperature and humidity at high (3-4 km) horizontal and vertical (1 km) spatial resolution. MISTiC Wind's extraordinarily small size, payload mass of less than 15 kg, and minimal cooling requirements can be accommodated aboard a 27U-class CubeSat or an ESPA-Class micro-satellite. Low fabrication and launch costs enable a LEO sun-synchronous sounding constellation that would collectively provide frequent IR vertical profiles and vertically resolved atmospheric motion vector wind observations in the troposphere. These observations are highly complementary to present and emerging environmental observing systems, and would provide a combination of high vertical and horizontal resolution not provided by any other environmental observing system currently in operation. The spectral measurements that would be provided by MISTiC Winds are similar to those of NASA's Atmospheric Infrared Sounder that was built by BAE Systems and operates aboard the AQUA satellite. These new observations, when assimilated into high resolution numerical weather models, would improve short-term and severe weather forecasting, save lives, and support key economic decisions in the energy, air transport, and agriculture arenas–at much lower cost than providing these observations from geostationary orbit. In addition, this observation capability would be a critical tool for the study of transport processes for water vapor, clouds, pollution, and aerosols. Key technical risks are being reduced through laboratory and airborne testing under NASA's Instrument Incubator Program. Recent proton radiation tests have demonstrated sufficient total-dose tolerance for the core infrared detector array and readout technology. A brass-board version of the core optical assembly of the instrument-an infrared spectrometer, has been fabricated and will be incorporated into an airborne version of the instrument during the spring of 2016, in preparation for testing.

Meanwhile, NASA's Instrument Incubator Program continues to mature new technologies. Continuing its participation in more than several decades of Doppler Wind Lidar potential impact studies, NASA funded a wind OSSE for the Optical Autocovariance Wind Lidar (OAWL). Study results were reported at the American Meteorological Society's annual meeting in January 2016. NASA plans to systematically evaluate evolving wind measurement technologies within ever evolving numerical model resolutions and parameterizations. Multiple wind OSSEs have recently been launched including a MISTiC OSSE and additional OSSEs for atmospheric motion vector (AMV) wind measurements.

7 ACKNOWLEDGMENTS

The authors acknowledge the contributions to sections of this paper from the following: Richard Eckman, Tsengdar Lee, El-Sayed Talaat (NASA Headquarters), James Butler, George Huffman, George Komar, Pamela Millar, Lauri Newman, Erich Stocker, Dong Wu (NASA Goddard Space Flight Center), Michael Kavaya, Jennifer Olson (NASA Langley Research Center), Anthony Mannucci, Thomas Pagano (Jet Propulsion Laboratory, California Institute of Technology), William Schreiner (University Corporation of Atmospheric Research), and Gary Lagerloef (Institute of Environmental Science and Research).

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