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NASA REPORT ON THE STATUS OF CURRENT AND FUTURE SATELLITE SYSTEMS

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Executive summary

NASA currently supports the operations of 19 Earth Science missions. Over a 15-month period from February 2014 through April 2015, NASA's Earth Science program successfully launched 5 new missions, and decommissioned 2. Although all missions were conceived as research missions, it has turned out that the efficiency of the communications and ground data handling systems has supported operational and near-real-time applications. All missions are currently producing data, but several also show signs of aging, and 2 are currently scheduled for decommissioning in the next 12 months.

NASA's Earth Science Program is implementing a balanced and robust plan to accomplish a broad set of critical Earth observation measurements from space. The program advances knowledge of the integrated Earth system, the global atmosphere, oceans (including sea ice), land surfaces, ecosystems, and interactions between all elements, including the impacts of humans. A balance of satellite measurements, science research, technology development and applications are needed to address a complex global Earth system. NASA's plans include the launch of 11 missions and 4 instruments (on host missions) in the future.

NASA Report on the status of current and future satellite systems

1 CURRENT SATELLITE SYSTEMS

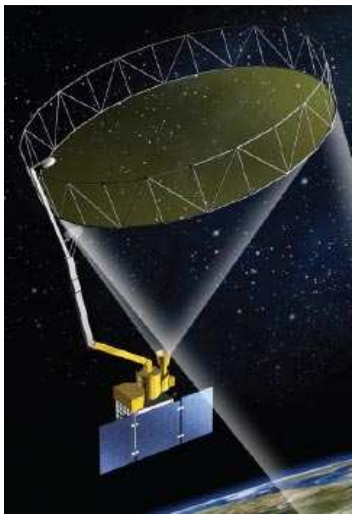
NASA currently supports the operations of 19 Earth Science missions (see Tables 1 and 2). Over a 15-month period from February 2014 through April 2015, NASA's Earth Science program successfully launched 5 new missions, and decommissioned 2. A short summary of the new missions launched, and the circumstances of the 2 mission terminations, is found below.

The **Orbiting Carbon Observatory-2 (OCO-2)** mission launched on July 2, 2014. OCO-2 is NASA's first dedicated Earth remote sensing satellite to study global atmospheric carbon dioxide from space with the precision, resolution, and coverage needed to characterize sources and sinks (fluxes) on regional scales (≥1000km). OCO-2 will also be able to quantify CO_2 variability over the seasonal cycles year after year.

The **RapidScat** instrument was launched on September 20, 2014 and successfully integrated onto the International Space Station (ISS). RapidScat is a scatterometer that replaces the inoperable SeaWinds payload aboard the QuickSCAT satellite for measuring wind speed and direction over the ocean. RapidScat will be useful for weather forecasting, hurricane monitoring, and observations of large-scale climate phenomena such as El Niño.

The **Cloud-Aerosol Transport System (CATS)** instrument was launched on January 10, 2015 and successfully integrated onto the International Space Station (ISS) on January 22, 2015. CATS is a lidar remote-sensing instrument that will extend profile measurements of atmospheric aerosols and clouds from the ISS and will improve our understanding of aerosol and cloud properties and interactions, as well as improve climate change models. CATS is specifically intended to demonstrate a low-cost, streamlined approach to developing ISS science payloads.

The **Soil Moisture Active Passive (SMAP)** mission, launched on January 31, 2015. The SMAP mission is designed to globally measure soil moisture and determine the freeze or thaw state over a three-year period, every 2-3 days. The figure on the right shows the large 6-meter antenna that is shared by both the L-Band Radar and the L-Band microwave radiometer instruments. SMAP will provide critical information for drought early warning, flood prediction, crop productivity, weather forecasting and the Carbon cycle.



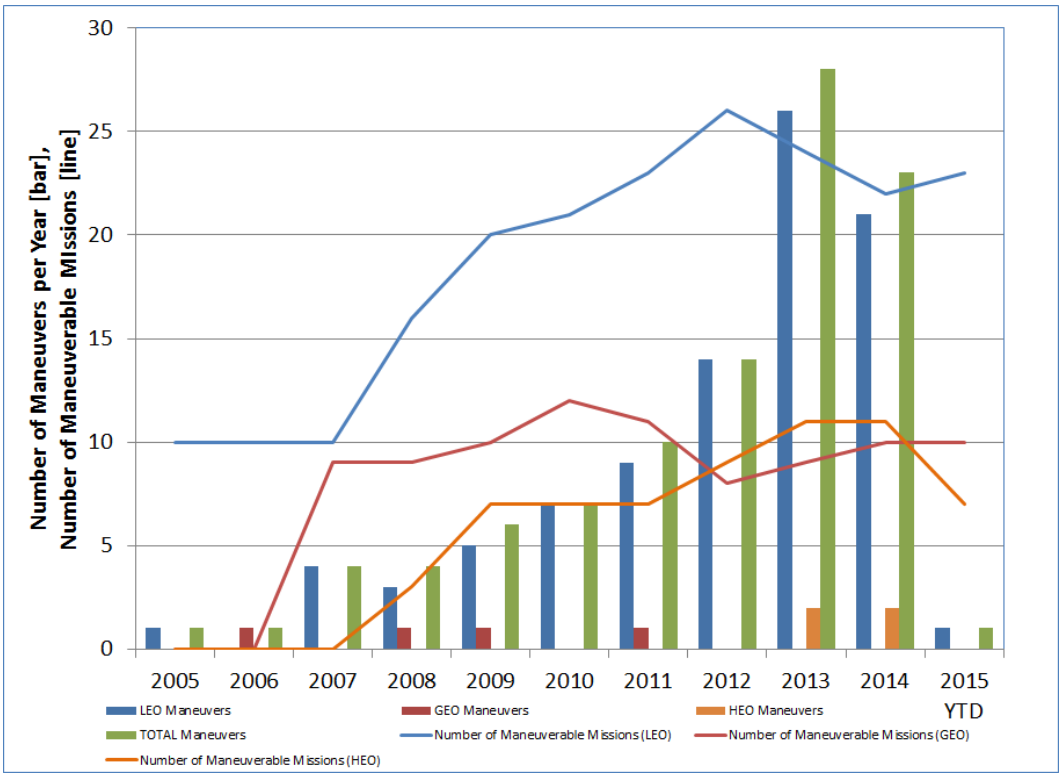
ACRIMSAT was decommissioned July 31, 2014, due to battery failure. The mission team observed severe battery degradation when the mission re-entered eclipse orbits in November 2013, and in December 2013, contact was lost with the satellite. Recovery attempts to re-establish communications were unsuccessful, and in July 2014, NASA decided to cease further attempts and decommission the satellite. The ACRIMSAT Total Solar Irradiance dataset is currently undergoing a final calibration and re-processing, and the documented dataset will be available to the community in late 2015 for further research.

After 17.5 years, the **TRMM** satellite ceased operations due to the depletion of orbit maintenance fuel. The first indication that fuel was exhausted was observed in July 2014; orbit maintenance was halted and a slow descent from the science orbit of 402.5km began. At the same time, several science and engineering end-of-mission tests were scheduled, and the final science data were collected in March and April 2015, before the instruments were powered down April 1 and April 8. The spacecraft was decommissioned April 15, 2015. Covering almost 2 decades, the TRMM 17-year precipitation and lightning datasets are recognized as immensely valuable for climate research and model improvements; both datasets will be reprocessed with updated algorithms to enable a consistent record with their follow-on missions (GPM and ISS-LIS). The documented and reprocessed datasets will be available to the community in 2017 for further research.

All remaining missions are currently producing data, but several also show signs of aging, and 2 are 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 40-50 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 2) are the Landsat-7 ETM+ (failed Scan Line Corrector), 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), Aqua's AMSU (Channels 4,5, and 7 are non-operational) and Aqua's AMSR-E (antenna rotates at 2rpm vs. 40rpm making the data useful for cross-calibration only). Instruments that no longer provide data (noted in RED, Table 2) are Aqua's HSB and Aura's HIRDLS. All other sensors are fully functional and are producing standard products that meet or exceed specifications.

Once new missions are launched, NASA must continually monitor their positions to avoid collisions with other satellites. Increased 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 the figure on the right. 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.



1.1 Measurement Continuity and Transition to Follow-on Missions

With the decommissioning of 2 missions in the past year, and the expectation of another 2 in 2016, 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 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 ESDIS project. For the missions which were recently decommissioned, or expected to decommission in the next year, the following plans are in place:

ACRIMSAT: The total solar irradiance dataset for the ACRIM series of sensors will be processed with updated calibrations based on engineering model tests at the LASP TSI Radiometer Facility, documented and archived in the NASA DAAC system by the end of 2015.

TRMM: The Precipitation and Lightning datasets will be documented, processed with updated algorithms developed to be consistent with the follow-on missions GPM and ISS-LIS, and archived in the NASA DAAC system by the end of 2017.

QuikSCAT: The 10-year QuikSCAT dataset ended when the antenna mechanism failed, and has been reprocessed and is currently available. The QuikSCAT calibration standard was transferred to OSCAT, and is currently being cross-calibrated with the ISS-Rapidscat mission. The cross-calibration is expected to be complete before QuikSCAT re-enters its next eclipse season and is decommissioned.

EO-1: The EO-1 image data is currently incorporated with the Landsat data archive, and will be fully documented in the 12 months following decommissioning.

1.2 Research Missions for Operational Use

Although all missions were conceived as research missions, it has turned out that 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, TRMM 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, currently in progress, will be reviewing 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. Findings of the Senior Review will be available in July 2015.

1.3 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.

Table 1 - Current NASA LEO Satellites

Satellite	Operator	Equatorial Crossing Time	Mean Altitude	Launch Date	Data Access	Instrument Status
Jason-2 (Op) (Ocean Surface Topography Mission)	NASA/NOAA, EUMETSAT/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)	USA NASA/NOAA	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 Research and Development (R&D) Satellites

Satellite	Space Agency	Equatorial Crossing Time and Mean Altitude	Launch Date	Data Access	Instruments	Status, Applications and Other Information
Landsat-7	NASA/USGS	10:05 (D) 705 km	15-Apr-1999	Earth Explorer	ETM+	Earth resources, land surface, environmental and disaster monitoring, agriculture and forestry, ice and snow cover
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/DLR	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/CNES	13:30 (A) 705 km	28-Apr-2006	ASDC	CALIOP, IIR, WFC	Aerosols and clouds
CloudSat	NASA/CSA	13:30 (A) 705 km	28-Apr-2006	Cloudsat DPC	CPR	Cloud vertical profiling
SAC-D / Aquarius	NASA/CONAE	18:00 (A) 651 km	10-Jun-2011	PO.DAAC	L-Band Radiometer, L-Band Scatterometer, CARMEN-1, DCS, HSC, Lagrange, MWR, NIRST, ROSA, SODAD, TDP	Sea Surface Salinity

LDCM (Landsat-8)	NASA/USGS	10:05 (D) 705 km	11-Feb-2013	Landsat-8 Data Products	OLI, TIRS	Earth resources, land surface, environmental and disaster monitoring, agriculture and forestry, ice and snow cover
GPM Core	NASA/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** and HIRDLS on **Aura***

Reduced Function Instruments

** SeaWinds on QuikSCAT (no antenna rotation, only used for cross-calibration)*
** ETM+ on Landsat-7 (failed scan line corrector)*
** ASTER (SWIR module not functioning)*
** AMSU on Aqua (channel-4 failed)*
** AMSR-E on Aqua (reduced rotation rate for cross-calibration with AMSR-2)*
** 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*

2 FUTURE SATELLITE SYSTEMS

With the U.S. President's FY2016 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 3 summarize NASA's future plans for the launch of 11 missions and 4 instruments (on host missions).

2.1 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 four 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, 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 (CLARREO), 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).

2.2 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 missions, and several other missions and instruments in pre-formulation under ESSP, including the OCO-3 instrument.

The Earth Venture-class (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. In FY 2015, NASA will continue the five airborne science investigations selected through the initial Venture Class solicitation (EVS-1) in FY 2009 and started in FY 2010. NASA selected the Cyclone Global Navigation Satellite System (CYGNSS) mission as part of the Earth Venture Mission (EVM-1) solicitation in 2012. CYGNSS is currently in development and will launch in 2016. The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument was selected in November 2012 as part of the Earth Venture Instrument (EVI-1) solicitation. TEMPO will be mounted on a commercial communications satellite in geostationary orbit to monitor air pollutants over North America no earlier than 2018. Future solicitations for the Earth Venture Class projects will be released every 4 years for the EVS and EVM elements and approximately every 18-months for EVI. The next planned release is EVM-2 and EVI-3 in 2015.

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

Satellite	Space Agency	Equatorial Crossing Time and Mean Altitude	Launch Date	Data Access	Instruments	Status, Applications and Other Information
SAGE-III-ISS Intl. Space Station Instrument only	NASA	51.6 Deg Inclination Non Sun-Sync 407 km	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	Feb 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.
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	TBD		Spectrometer	Carbon Dioxode sources and sinks
GRACE-FO (Follow-On)	NASA/GFZ	89 Deg Inclination Non Sun-Sync 490 km	Aug 2017		Gravity, GPS	Ocean currents and mass, ice sheets, GPS (Pressure, Temperature, Humidity)

TEMPO Hosted Payload Instrument only	NASA	Geosynchronous	>Nov 2018		UV and VIS Spectrometer	Atmospheric pollution over North America. Tropospheric ozone, ozone precursors, aerosols, and clouds.
SWOT	NASA/CNES	78 Deg Inclination Non Sun-Sync 891 km	2020	PO.DAAC	Ka-Band Radar Interferometer, AMR, GPSP, LRA, Poseidon Altimeter	Oceanography (wide swath ocean surface topography) and Hydrology (lake levels, river discharge)
PACE (Pre-ACE)	NASA	Sun-Synchronous 650 km	>2020		Spectrometer, Polarimeter	Aerosols, ocean color
ASCENDS	NASA	10:30 (A) 450 km	>2023		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	98 Deg Inclination, Sun-Sync (6AM-6PM), 747 km	2020		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