CGMS-50 NASA-WP-04
Final, 10 June 2022

Prepared by NASA

NASA REPORT ON THE STATUS OF CURRENT AND FUTURE SATELLITE MISSIONS

Charles E. Webb, Jamie W. Wicks, Lacey McCarthy, Richard S. Eckman, Pamela Millar[1], Philip M. Larkin, Robert Bauer[1], Jack Kaye, and Maudood Khan

NASA Headquarters
[1]NASA Goddard Space Flight Center

Executive Summary

The National Aeronautics and Space Administration (NASA) continues to provide operational support for twenty-two Earth-observing satellites. Guided in its efforts by the recommendations of the decadal survey, *Thriving on our Changing Planet*, NASA's Earth Science Division (ESD) continues to execute a balanced and robust program of technology development, research, and applications.

During the past year, NASA and the U.S. Geological Survey (USGS) successfully launched the Landsat 9 mission. Though similar to its predecessors, Landsat 9 can transmit data with higher radiometric resolution, which enables it to detect subtle differences on Earth's surface. With two Landsat series satellites currently on orbit, NASA and USGS are able to image the globe every eight days.

In June 2021, NASA successfully launched the TROPICS Pathfinder satellite. It is a test satellite similar to the ones expected to be flown as part of the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission. TROPICS Pathfinder enables real-world testing of the planned technology, communications, and data processing system, allowing adjustments to increase TROPICS mission success. The full TROPICS mission to study tropical cyclones will consist of six CubeSats equipped with small microwave radiometers stationed in three orbital plans. Three launches of two CubeSats each are expected to take place by the end of July 2022.

Earth System Observatory (ESO) missions in pre-Phase A are undergoing Mission Concept Reviews in preparation to enter Phase A, where they will develop a baseline mission concept, validate requirements, and establish mission architecture.

NASA REPORT ON THE STATUS OF CURRENT AND FUTURE SATELLITE MISSIONS

1 INTRODUCTION

The National Aeronautics and Space Administration (NASA) continues to provide operational support for *twenty-two* Earth-observing instruments and satellites. *Five* of the satellites are in the prime mission phase, and *seventeen* are in an extended mission phase. Since 2019, research enabled by this data has contributed to approximately 10,000 research publications. Although all NASA missions are conceived of as research systems (rather than as operational systems), their efficient communication and ground data handling systems continue to support operational activities, although few satisfy near-real-time application needs.

Section 2 provides a listing of NASA Earth-observing satellites operating in Low Earth Orbit (LEO). In addition, it provides highlights from the recently launched Sentinel-6 Michael Freilich mission.

Section 3 provides status updates on several small satellite technology missions that were launched within the last few years.

Section 4 provides a status update on a NASA satellite operating at Lagrange Point 1.

Section 5 provides status updates on issues related to formation flying, collision avoidance, continued advancements in small satellite technology, and instruments on the International Space Station.

Section 6 discusses future satellite systems development.

Section 7 provides a brief summary of the Senior Review process as well as NASA missions and assets that are contributing to global greenhouse gas monitoring.

2 CURRENTLY OPERATING SATELLITE SYSTEMS

Table 1 provides a list of all currently operating NASA Earth-observing satellites. The recently launched Landsat 9 and TROPICS Pathfinder satellite are highlighted below.

The Landsat 9 mission successfully launched from Vandenberg Space Force Base in California on 27 September 2021, and it continues a 50-year Landsat legacy of monitoring the Earth's land and coastal areas. A joint mission with the U.S. Geological Survey (USGS), Landsat 9 joins Landsat 8 in space, which was launched in 2013 and replaces Landsat 7, which was launched in 1999. Though similar to its predecessors, Landsat 9 can transmit data with higher radiometric resolution, which enables it to detect subtle differences on the Earth's surface. It carries two instruments, the Operational Land Imager 2 (OLI-2) and Thermal Infrared Sensor 2 (TIRS-2). These satellites are operated by USGS and together cover the globe every eight days, collecting ~1,500 images daily. Figure 1 shows the satellite's first images released during its in orbit check out period in late 2021. Landsat 9 is fully operational, and its data are freely available to the public from the USGS website.

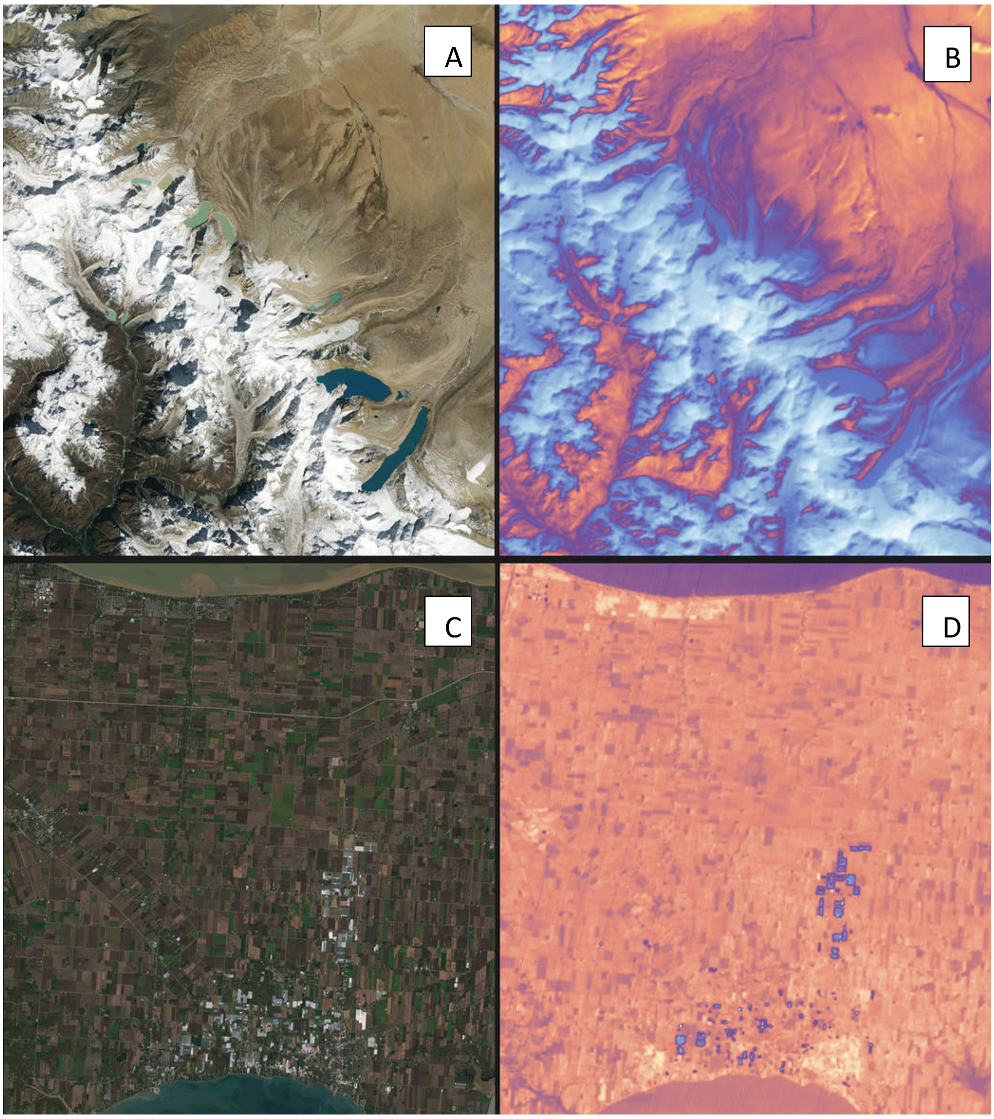

Figure 1: A) OLI-2 imagery of the snow and glaciers in the Himalayan mountains leading to the flat Tibetan Plateau to the north. B) TIRS-2 thermal data of the same area. Cool colors indicate relatively cooler surface temperatures, warm colors indicate relatively warmer surface temperatures. C) OLI-2 imagery of farm fields (brown and green rectangles) in southern Ontario, Canada, sandwiched between Lake Erie and Lake St. Clair. D) In this TIRS-2 image of the same Canadian farmlands, produce greenhouses (white and grey rectangles at the bottom in image (C)) show up as relatively cooler (blueish). Credits: NASA/USGS

On June 30, 2021, NASA successfully launched the TROPICS Pathfinder satellite. This is a test satellite similar to the ones expected to be flown as part of the Time-Resolved

Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission. The full TROPICS mission will consist of six CubeSats with small microwave radiometers designed to study tropical cyclones. TROPICS satellites will be positioned in three orbital planes and have rapid revisit times. The TROPICS Pathfinder satellite allows real world testing of the mission's technology, communications, and data processing systems, enabling adjustments to increase mission success. Figure 2 shows TROPICS Pathfinder "first light" images of Hurricane Ida just before and after it made landfall in Louisiana. More information about the TROPICS mission is provided in Section 6 and at: https://tropics.ll.mit.edu/CMS/tropics/Mission-Overview

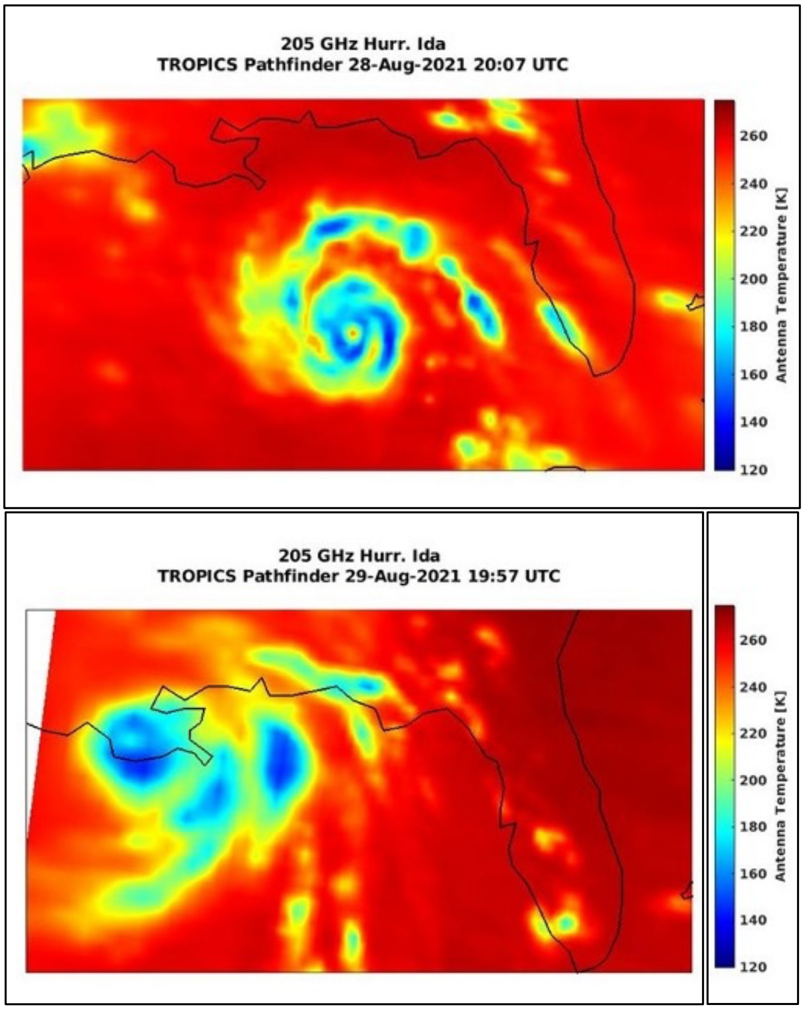

Figure 2: TROPICS Pathfinder images of Hurricane Ida at 205 GHz on 28 August 2021 and 29 August 2021. Images of Hurricane Ida before landfall (left) show a well-defined eye of the storm, as well as inner and outer rainbands that persisted as the storm made landfall in Louisiana (right). The instrument's high frequency channel is sensitive to precipitation, so rainbands are clearly visible. In VIS/IR images, precipitation would be obscured due to clouds. Credits: NASA/TROPICS Pathfinder

Table 1: Current NASA ESD Low Earth Orbit (LEO) Satellites

Satellite	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
Landsat-7[1]	Provide continuity land surface observations to study, predict, and understand the consequences of land surface dynamics	10:00 (D) 705 km	15 Apr 1999	ETM+	USGS
Terra[2] (EOS AM-1)	Collect measurements of Earth's atmosphere, land, snow and ice, ocean, and energy balance to understand Earth's climate and climate change and to map the impact of human activity and natural disasters on communities and ecosystems	10:30 (D) Drifting 705 km	18 Dec 1999	ASTER, MODIS, MOPITT, MISR, CERES	Terra Data Direct Broadcast
Aqua (EOS PM-1)	Measure the water cycle, radiative energy fluxes, aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and air, land, and water temperatures to enhance understanding of the climate system and improve weather forecasting	13:30 (A) Drifting 705 km	04 May 2002	MODIS, AIRS, CERES, AMSU-A, AMSR-E, HSB	EOSDIS Direct Broadcast
Aura[3]	Measure atmospheric chemistry to better understand ozone trends, air quality changes, and linkage to climate change	13:40 (A) 705 km	15 Jul 2004	MLS, TES, HIRDLS, OMI	GES DISC

Table 1: Current NASA LEO Satellites (continued)

Satellite	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
CALIPSO[1,4] (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation)	Observe aerosols and vertical cloud profiles to provide insight into the role that aerosols and clouds play in regulating Earth's weather, climate, and air quality	13:45 (A) Drifting 705/689 km	28 Apr 2006	CALIOP, IIR, WFC	ASDC
CloudSat[4]	Survey the vertical structure and overlap of cloud systems and their liquid and ice-water contents to improve the accuracy of weather forecasts and climate predictions	13:45 (A) Drifting 705/689 km	28 Apr 2006	CPR	CloudSat DPC
Landsat-8[1]	Provide continuity land surface observations to study, predict, and understand the consequences of land surface dynamics	10:11 (D) 705 km	11 Feb 2013	OLI, TIRS	USGS
GPM Core[2] (Global Precipitation Measurement)	Observe rain and snowfall worldwide every three hours, to facilitate monitoring and forecasting weather events such as droughts, floods, and hurricanes, and enable research on precipitation and climate change	65-deg Non Sun synchronous 407 km	27 Feb 2014	GMI, DPR	PMM Data

Table 1: Current NASA LEO Satellites (continued)

Satellite	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
OCO-2 (Orbiting Carbon Observatory)	Collect measurements of atmospheric carbon dioxide to characterize sources and sinks on regional scales and over seasons	13:30 (A) 705 km	02 Jul 2014	Grating Spectrometer	GES DISC
SMAP (Soil Moisture Active Passive)	Measure water in surface soil everywhere on Earth and determine if the ground is frozen or thawed to help monitor drought, predict floods, improve weather forecasting, and assist agriculture planning	18:00 (A) 685 km	31 Jan 2015	L-band Radar, L-band Radiometer	ASF (radar) NSIDC (Cryosphere and land microwave)
CYGNSS (Cyclone Global Navigation Satellite System)	Measure wind speeds over Earth's oceans, increasing the ability to understand and predict hurricanes	35-deg Non Sun-synchronous 500 km	15 Dec 2016	GPS	PO.DAAC
GRACE-FO (Gravity Recovery and Climate Experiment Follow-On)	Measure changes in Earth's gravity field to monitor variations in terrestrial water storage, ice mass, ocean bottom pressure, and sea level to improve weather and drought forecasting	89-deg Non Sun-synchronous 490 km	22 May 2018	MWA, LRI, Accelerometers, GPS RO	PO.DAAC

Table 1: Current NASA LEO Satellites (concluded)

Satellite	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
ICESat-2 (Ice, Cloud, and Land Elevation Satellite)	Measure surface elevation to track height changes of glaciers, sea ice, and forests to estimate future changes and impacts	92-deg Non Sun-synchronous 500 km	15 Sep 2018	ATLAS	NSIDC
Sentinel-6 Michael Freilich	Measure ocean surface height to monitor global sea level; provide tropospheric temperature and humidity data to improve weather forecasts, climate models, and hurricane tracking	66-deg Non Sun-synchronous 1336 km	21 Nov 2020	Poseidon-4 SAR Radar Altimeter, AMR-C, GNSS-RO, GNSS-POD, DORIS, LRA	PO.DAAC
Landsat 9[1]	Provide continuity in land surface observations to study, predict, and understand the consequences of land surface dynamics	98.2-deg Near-polar, Sun-synchronous 705 km	27 Sep 2021	TIRS-2, OLI-2	USGS

1 NASA supports operations through the science instrumentation. Partners include U.S. Geological Survey (USGS) for Landsat; CNES for CALIPSO
2 Support for operation of the GPM Dual-frequency Precipitation Radar (DPR) and Terra ASTER is provided by JAXA.
3 Support for operation of the Aura OMI instrument is provided by the Royal Netherlands Meteorological Institute (KNMI).
4 CloudSat lowered its altitude in February 2018 from 705 km to ~689 km. CALIPSO joined CloudSat in formation flying at this lower altitude in September 2018. Although both orbits were initially Sun-synchronous, the equator crossing times are allowed to drift, and the mean altitudes are decreasing

*Instruments in red are failed/decommissioned or have reduced functionality, as follows:

Failed/Decommissioned Instruments:	Reduced Functionality Instruments:
HSB and AMSR-E on Aqua	ASTER on Terra (SWIR module not functioning)
HIRDLS and TES on Aura	AMSU on Aqua (channels 1, 2, 4, 5 and 7 failed)
L-band Radar on SMAP WFC on CALIPSO	CloudSat (daylight operations only)

3 OPERATING STATUS UPDATES OF SMALL SATELLITE SYSTEMS

3.1 COMPACT SPECTRAL IRRADIANCE MONITOR – FLIGHT DEMONSTRATION

Compact Spectral Irradiance Monitor – Flight Demonstrator (CSIM-FD) is a six-unit (6U), ultra-compact, solar spectral irradiance (SI) monitor covering 200-2400 nm, with the required SI-traceable accuracy and on-orbit stability to meet solar input measurement requirements for establishing benchmark climate records. The CSIM instrument completed its primary solar irradiance measurement demonstration in 2020. In March 2020, CSIM publicly released one year of data. Extended operations continued through 2021, allowing the CSIM team to evaluate long-term environmental and performance degradation. Due to on-orbit radiation impacts to the spacecraft's electronics, communications with the spacecraft were lost in February 2022, and CSIM operations have ceased.

CSIM was developed at the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado in Boulder with funding from NASA's Instrument Incubator Program (IIP). In 2013, it transitioned to a flight demonstration activity and was launched into a Sun-synchronous orbit in December 2018 aboard a SpaceX Falcon 9 rocket under a ride-share agreement. The CSIM instrument design and layout is a significant departure from the previous SIM instruments, achieving large reductions in mass, volume, and power requirements, and enabling a flight-qualified instrument in a 6U CubeSat package. CSIM's data are available through CSIM's website (https://lasp.colorado.edu/home/csim/) and the LASP Interactive Solar Irradiance Data Center (https://lasp.colorado.edu/lisird/).

3.2 THE TEMPORAL EXPERIMENT FOR STORMS AND TROPICAL SYSTEMS TECHNOLOGY DEMONSTRATION

After nearly three years on orbit, the Temporal Experiment for Storms, and Tropical Systems Technology Demonstration (TEMPEST-D) satellite re-entered Earth's atmosphere (de-orbited) on 22 June 2021.

TEMPEST-D was launched to the International Space Station (ISS) in May 2018 and was subsequently deployed from the ISS in July. Shortly after achieving first light in September 2018, TEMPEST-D captured its first full swath image of Hurricane Florence over the Atlantic Ocean. The mission validated a new millimeter-wave radiometer capable of observing the time evolution of clouds and precipitation processes from a 6U CubeSat platform. The radiometer provided observations at five frequencies from 89 to 183 GHz, demonstrating performance indistinguishable from operational-class imaging radiometers. Data acquired from TEMPEST-D satellite has enabled detailed studies of precipitation microphysics while allowing evaluation of the potential for multi-incidence angle data (along track data) to provide improved vertical resolution of retrievals. A promising application is improving information content with respect to planetary boundary layer through multi-angle sounding.

The TEMPEST-D mission flight spare instrument was launched to the ISS on 21 December 2021, as part of the U.S. Space Force Space Test Program – Houston 8 (STP-H8) mission. The instrument, TEMPEST-H8, is installed on the ISS alongside the Compact Ocean Wind Vector Radiometer (COWVR). TEMPEST-H8 will demonstrate low-cost sensor technologies for the Air Force and acquire simultaneous surface wind and atmospheric sounding data over the ocean.

3.3 COMPACT INFRARED RADIOMETER IN SPACE

The Compact Infrared Radiometer in Space (CIRiS) is a 6U CubeSat developed at Ball Aerospace. It was launched from Cape Canaveral Air Force Station to the ISS on 5 December 2019 and deployed in February 2020. It features an uncooled long-wave infrared radiometer with three bands designed for high radiometric performance from LEO, including absolute in-orbit calibration. CIRiS measurements support studies of the hydrological cycle, urban climate, and extreme storms. CIRiS data will contribute to advancements in climate modeling and support land use management via vegetation monitoring and water absorption mapping. Following several months of communication issues, CIRiS entered primary operations in 2021 and has successfully demonstrated detection of fire from space using calibrated bolometers.

4 STATUS UPDATES OF SATELLITE SYSTEMS OPERATING AT THE LAGRANGE POINT

The Deep Space Climate Observatory (DSCOVR) was launched on 11 February 2015, to the Sun-Earth first Lagrange (L1) point, 1.5 million kilometers from Earth toward the Sun, to provide continuous solar wind measurements for accurate space weather forecasting and to observe the full sunlit disk of Earth from a new and unique vantage point. While NOAA operates the DSCOVR spacecraft and its space weather instruments, NASA operates and calibrates the two Earth science instruments onboard, the Earth Polychromatic Imaging Camera (EPIC) and National Institute of Standards and Technology Advanced Radiometer (NISTAR).

EPIC and NISTAR operate almost continuously with only minor interruptions other than a hiatus between 27 June 2019 and 02 March 2020 due to degradation of the inertial navigation unit (gyros). NASA developed and uploaded a software patch that relies only on the star tracker for spacecraft attitude determination, which allows DSCOVR to maintain an approximately 0.02 degree pointing accuracy, like its pre-gyro-failure operations, keeping Earth fully in the EPIC field-of-view.

EPIC and NISTAR calibrations performed after March 2020 show no change in the performance or calibration constants of the instruments. Unlike data acquired from LEO, the DSCOVR Earth science data products cover the whole sunlit face of Earth every 1 or 2 hours, providing a unique, sunrise-to-sunset synoptic view at a single GMT. This unique vantage point allows the generation of new science data products: total column ozone, cloud reflectivity, SO_2 plume from a volcanic eruption, and sunlit leaf area index (SLAI). Ozone and cloud reflectivity are directly used to estimate the amount of UV radiation reaching the ground with the addition of another EPIC products: aerosol optical depth and absorption. Ozone and aerosol retrievals are uniquely enhanced using the retrieval of cloud and aerosol plume height from EPIC's O_2 A- and B-bands. A new ocean surface product (photosynthetically available radiation, PAR) became publicly available since April 2021.

A special issue of *Frontiers Remote Sensing* journal "DSCOVR EPIC/NISTAR: 5 years of Observing Earth from the first Lagrangian Point" has been issued with 23 papers accepted or published. The EPIC RGB color images continue to enjoy significant popularity with the public and media. The DSCOVR vantage point at L1 affords opportunities for some very unique images. All EPIC color images are publicly available at: http://epic.gsfc.nasa.gov.

5 STATUS UPDATES OF RESEARCH AND DEVELOPMENT SATELLITE SYSTEMS

5.1 FORMATION FLYING

A number of NASA and U.S. satellites operate in close proximity at approximately 705 km altitude and ascending equator crossing times of 13:30. Known as the A-train, this constellation has been built up over more than a decade, starting with the launch of Aqua in 2002, and continuing with Polarization and Anisotropy of Reflectance for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL), which was launched in 2004 and decommissioned 2013; Aura (launched in 2004); CloudSat (launched in 2006, exited the A-train in 2018); Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (launched in 2006, exited the A-train in 2018); the Japanese GCOM-W1 "SHIZUKU" satellite (launched in 2012); and the Orbiting Carbon Observatory-2 (OCO-2) (launched in 2014).

The A-train constellation is actively managed to ensure appropriate separation. The proximity of these spacecraft enables nearly simultaneous measurements although the data are contributed by multiple platforms from multiple providers. The broad range of complementary techniques (e.g., different wavelengths and viewing geometries) used across these platforms are particularly valuable for studying atmospheric chemistry and physics because they enable comprehensive measurement of trace gasses and particle composition. The value of such coincident measurements was further demonstrated by the CALIPSO team's decision to follow CloudSat out of the A-train after CloudSat's reaction-wheel failure. Despite the exit of these two missions, there remains a strong emphasis in the NASA research program to make synergistic use of instruments, as demonstrated by the A-train.

Based on the results of the 2020 Earth Science Senior Review, NASA granted Aqua, Aura, CALIPSO, CloudSat, and OCO-2 mission extensions through fiscal year 2023. After one to two decades of operations and producing excellent complimentary science, many of the A-Train missions will be decommissioned over the next few years.

5.2 COLLISION AVOIDANCE MONITORING

All NASA missions are required to protect the orbital environment they operate in by utilizing Conjunction Assessment Risk Analysis (CARA) services and to perform risk assessment for potential close approaches with orbital debris and other operational satellites.

In December 2020, NASA released the *Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook* to improve global awareness of space activity and share NASA's lessons learned regarding close approach coordination and mitigation. This handbook is freely available at: https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf. A recent history of collision avoidance maneuvers is shown in Figure 3. The number of CARA-supported maneuverable missions in LEO since 2007 is generally trending upward and there are thousands of maneuverable non-NASA missions sharing these orbits. The number of maneuvers per year is increasing significantly with the current solar cycle and the addition of many large new constellations operating in LEO. As the number of potential conjunctions between operational maneuverable satellites increases, so does the necessity for improved communications between satellite operators to coordinate avoidance maneuver planning. Shown in Figure 3 are the total number of unique conjunction events since 2016, which have tripled since 2018.

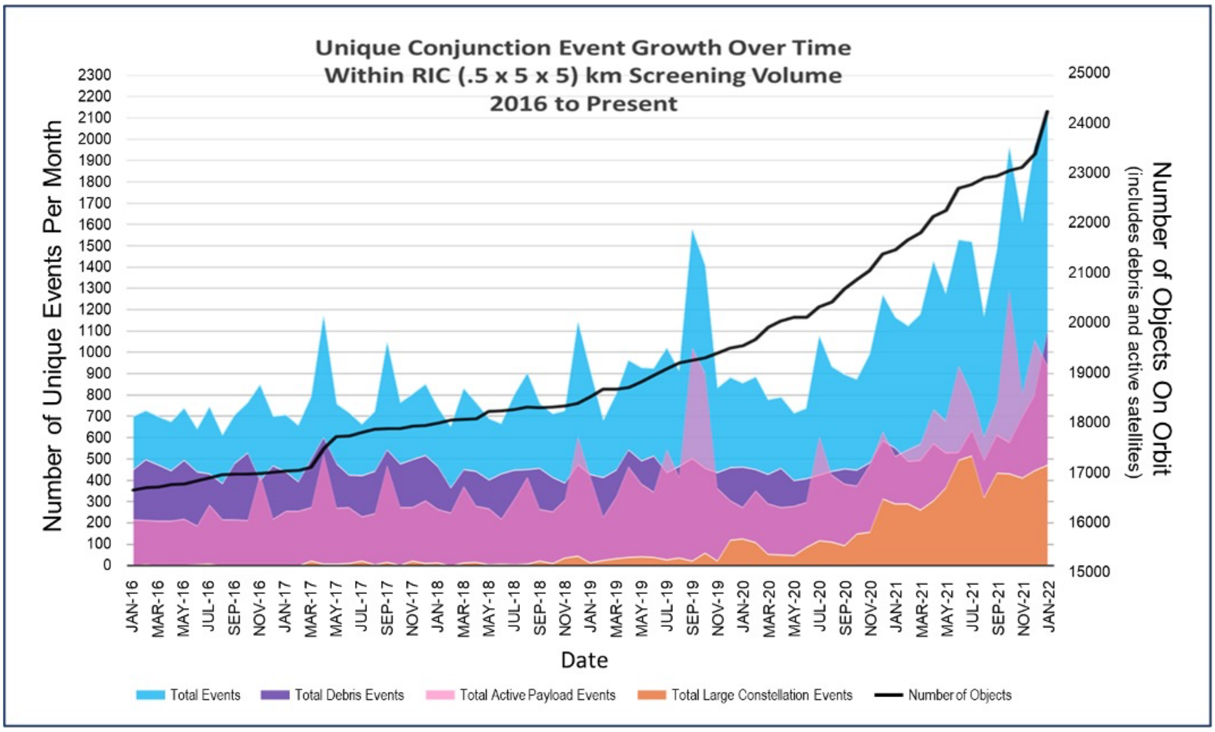

Figure 3: Number of conjunction events since 2016 The blue shaded area shows the total number of unique conjunction events with debris, active satellites, and large constellations has tripled since 2018. The black line shows the total number of objects (debris & active satellites, including large constellations) on orbit has increased 30% since November of 2021. The RIC (Radial, In-Track, Cross-Track) defines the volume around CARA supported NASA missions screened. It's a 0.5km x 5km x 5km ellipsoid centered at the spacecraft with radial being 0.25km above and below, In-track being 2.5km in front and behind, and Cross-Track being 2.5km on either side. Credits: CARA

NASA has agreements with a variety of mega-constellation organizations, including SpaceX and OneWeb, that formalize coordination and sharing of information necessary to maintain and improve space safety. In addition to increasing the resources dedicated to conjunction assessment, NASA continually improves the agency's orbital debris requirements and procedures and regularly invests in analysis tool improvements.
The orbital debris environment is rapidly changing, and with the addition of large constellations, the need for close coordination between all satellite operators has significantly increased the workload for missions and the CARA team. In February 2022,

NASA submitted a letter to the Federal Communications Commission (FCC) regarding concerns about a significant increase in the frequency in conjunction events and potential impacts to NASA science and human spaceflight missions. Other than conjunction events, sun-glint and field of view blockages from the thousands of satellites orbiting the Earth could negatively impact various NASA science measurements. The full letter is available at https://www.scribd.com/document/557924666/NTIA-NASA-NSF-letter-to-FCC-regarding-Starlink-Gen-2.

5.3 SMALL SATELLITE TECHNOLOGY DEMONSTRATION

5.3.1 HYPERSPECTRAL THERMAL IMAGER

Hyperspectral Thermal Imager (HyTI) is a thermal imaging instrument built by University of Hawaii at Manoa. This mission will demonstrate how high spectral and spatial long-wave infrared image data can be acquired from a 6U CubeSat platform. HyTI will use a spatially modulated interferometric imaging technique to produce spectro-radiometrically calibrated image cubes, with 25 channels between 8-10.7 ųm, at a ground sample distance of approximately 60 meters. The HyTI performance model indicates narrow band NE∆Ts of < 0.3 K. The small form factor is made possible via the use of a no-moving-parts Fabry-Perot interferometer and the Jet Propulsion Laboratory's (JPL) cryogenically cooled High Operating Temperature (HOT) Barrier Infrared Detectors (BIRDS) Focal Plane Array (FPA) technology. Launch is scheduled for no earlier than Fall 2022. The value of HyTI to Earth scientists will be demonstrated via on-board processing of the raw instrument data to generate L1 and L2 products, with a focus on rapid delivery of data regarding volcanic degassing, land surface temperature, and precision agriculture applications.

5.3.2 SIGNALS OF OPPORTUNITY P-BAND INVESTIGATION

The Signals of Opportunity P-band Investigation (SNOOPI) is a reflectometry microwave instrument built by Purdue University in partnership with Goddard Space Flight Center (GSFC) and JPL. The mission will demonstrate how direct, and Earth reflected signals of opportunity in P-band from geostationary telecommunications satellites can be acquired from a 6U CubeSat platform for retrievals of root zone moisture (RZSM) and snow water equivalent (SWE). The mission will use P-band receivers to collect direct and Earth reflected signals and cross-correlate the data to extract RZSM and SWE measurements. These retrievals will measure snow and soil moisture, whose data are vital for applications like food security and water resources management. SNOOPI will be the first in-orbit demonstration of the P-band signals of opportunity technique and will advance the prototype instrument to Technology Readiness Level 7. It is targeted for launch no earlier than August 2022.

5.3.3 COMPACT TOTAL IRRADIANCE MONITOR

The Compact Total Irradiance Monitor-Flight Demonstration (CTIM-FD) is an eight-channel 6U CubeSat instrument for measuring total solar irradiance (TSI). Expected to launch in 2022, CTIM-FD will be on orbit for one year and allow scientists to assess whether small satellites can be as effective at measuring TSI as larger sensors like the Total Irradiance Monitor (TIM) aboard the SORCE and TSIS-1 missions. Lighter and more compact, CTIM-FD features several improvements to the original TIM design. The use of Vertically Aligned Carbon Nanotube (VACNT) bolometers marks a significant milestone in the quest to develop lightweight components for CubeSat-compatible instruments. These silicon-based bolometers will dramatically reduce the weight of the CTIM-FD CubeSat without compromising its ability to measure the total irradiance of the Sun (200 – 2400 nm) with an uncertainty of less than 0.01 percent.

5.3.4 NANOSAT ATMOSPHERIC CHEMISTRY HYPERSPECTRAL OBSERVATION SYSTEM

Launched in February 2022 onboard the NG-17 Cygnus resupply to ISS, Nanosat Atmospheric Chemistry Hyperspectral Observation System (NACHOS) is a 3U CubeSat that will validate an ultra-compact hyperspectral imager that records observations at sufficiently high spectral resolution to confidently separate trace gases (e.g., NO_2, SO_2, O_3, CH_2O) from the atmosphere. The instrument has significant onboard preprocessing data capability. Developed by scientists at the Los Alamos National Laboratory, NACHOS will help assess whether constellations of CubeSat-like small satellites can gather and process high-resolution data to detect, map, and quantify Earth's dilute gases as efficiently as larger, single-platform satellites. NACHOS-1 will remain aboard Cygnus until July, when the spacecraft will unberth from the ISS and place NACHOS-1 in low-Earth orbit before the cargo spacecraft reenters Earth's atmosphere. The NACHOS team will spend three months commissioning NACHOS-1 before it begins its technology validation and science mission, which is expected to last about one year. A second NACHOS CubeSat, NACHOS-2 will be launched no earlier than September 2022.

5.4 INSTRUMENTS ABOARD THE INTERNATIONAL SPACE STATION

The ISS is an extremely important platform for ESD's mission portfolio and supports operations of six Earth-observing instruments (Table 2). Because it operates in a non-Sun-synchronous orbit that permits observations over a range of local times, the ISS provides a unique vantage point for observing Earth from space. However, the dynamic ISS operating environment requires external payloads to continually adapt to interruptions in science observations due to visiting vehicles, platform maneuvers and maintenance activities, as well as structural blockages and sources of glint. In addition to the interruption of science observations, in late 2019 the ISS began increasing its altitude and eventually settled at an altitude with a 4-day orbit repeat cycle. This repeat cycle is useful when planning for visiting vehicles, however, it created a fairly significant issue for several Earth observing instruments that were anticipating global coverage and were unable to achieve that coverage due to the repeating orbit tracks and limitations in their pointing capabilities.

Stratospheric Aerosol and Gas Experiment III (SAGE III) completed its End of Prime Mission Review in October 2020, and along with the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Lighting Imaging Sensor (LIS) missions, received a mission extension following the 2020 Earth Science Senior Review. Orbiting Carbon Observatory 3 (OCO-3) and Total Spectral Irradiance Sensor 1 (TSIS-1) continue to operate in their prime mission phases until September 2022 and March 2023, respectively. In 2021, GEDI completed its End of Prime Mission Review and submitted a proposal for a mission extension that was approved through early 2023 or when a replacement instrument is scheduled for installation.

NASA has committed to use and operate the ISS through 2030, which will allow for new Earth-observing instrument payloads to be added. ESD is developing two additional instruments to be installed on the ISS, the Climate Absolute Radiance and Refractivity Observatory Pathfinder (CLARREO-PF) instrument and Earth Surface Mineral Dust Source Investigation (EMIT). The sixth Earth Venture Instrument (EVI-6) call for proposals is also allowing ISS as a potential platform for proposers. Earth Surface Mineral Dust Source Investigation (EMIT) is currently scheduled to launch to the ISS in June 2022 on board SpaceX's 25th Commercial Re-Supply mission (CRS-25). Additional information about these instruments is provided in Section 6.

Table 2: NASA instruments currently on the International Space Station

Satellite	Science and Application	Launch Date	Instrument	Data Access
SAGE-III (Stratospheric Aerosol and Gas Experiment)	Measure the vertical distribution of aerosols, ozone, water vapor and other trace gases in Earth's stratosphere and troposphere to enhance understanding of ozone recovery and climate change processes in the upper atmosphere	19 Feb 2017	Solar Occultation Instrument	ASDC
LIS (Lighting Imaging Sensor)	Measure global lightning to better understand its cause and connections with severe weather events	19 Feb 2017	Lightning Imaging Sensor (LIS)	GHRC
TSIS-1 (Total Spectral Irradiance Sensor)	Measure total and spectral Solar irradiance (TSI & SSI) to better understand the Sun's natural influence on Earth's ozone layer, atmospheric circulation, clouds, and ecosystems	15 Dec 2017	Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM)	GES DISC
ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station)	Measure evapotranspiration to provide insight to plant-water dynamics and how ecosystems change with climate	29 Jun 2018	Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)	LP.DAAC
GEDI (Global Ecosystem Dynamics Investigation)	Provide high-resolution observations of forest vertical structure to characterize the effects of changing climate and land use on ecosystem structure and dynamics and enable significantly improved quantification and understanding of the Earth's carbon cycle and biodiversity	05 Dec 2018	LIDAR	LP.DAAC (L1,L2) ORNL DAAC (L3,L4)
OCO-3 (Orbiting Carbon Observatory)	Collect measurements of atmospheric carbon dioxide to characterize sources and sinks on regional scales and over seasons	04 May 2019	Grating Spectrometer	GES DISC

6 FUTURE SATELLITE SYSTEMS

6.1 EARTH SYSTEMATIC MISSION PROGRAMS

NASA’s Earth Systematic Missions (ESM) include 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 research missions once on orbit, and produces standard mission products in support of NASA and national research, applications, and policy communities. The ESM program continues to oversee the development and launch of missions recommended by the 2007 Decadal Survey. These missions include Surface Water Ocean Topography (SWOT); NASA-ISRO Synthetic Aperture Radar (NISAR); Plankton, Aerosol, Cloud, ocean Ecosystem (PACE); Climate Absolute Radiance and Refractivity Observatory Pathfinder instrument on ISS (CLARREO-PF); and Total Spectral Solar Irradiance Sensor 2 (TSIS-2). The ESM program is also responsible for overseeing formulation and development of missions designed to address the Designated Observables identified in the 2017 Decadal Survey (Section 6.3.1).

NASA is also continuing its partnership with the U.S. Geological Survey (USGS) to extend the Landsat series with Landsat Next, which entered the formulation phase in Spring 2022, and with the European Space Agency (ESA) on Sentinel-6, which includes a second satellite (Sentinel-6B) to be launched in five years.

Table 3 lists Earth Systematic Missions currently under development.

Table 3: Earth Systematic Missions under Development

Satellite	Science & Application	ECT/Inclination & Mean Altitude Orbit	Expected Launch Date	Instruments
SWOT (Surface Water and Ocean Topography)	Provide high-resolution ocean and terrestrial surface water topography measurements to observe circulation and storage changes to better understand ocean processes in regulating climate change and the consequence of climate change on the distribution of water on land	78-deg Non-Sun synchronous 873 km	2023	Radar interferometry (KaRIn), Jason-class Altimeter, DORIS Antenna, Microwave Radiometer, X-band Antenna, Laser Reflector Assembly, and GPS Receiver
NISAR (NASA-ISRO Synthetic Aperture Radar)	Measure changes in Earth's surface to improve risk and resource management by understanding the response of ice sheets to climate change; likelihood of solid earth hazards, like earthquakes; and dynamics of carbon storage in various ecosystems	98.4 Sun synchronous 747 km	2023	L- and S-band Synthetic Aperture Radar (SAR)
CLARREO-PF (Climate Absolute Radiance and Refractivity Observatory)	Provide high-accuracy, SI-Traceable calibration measurements of Earth's solar reflectance to enable detection of climate change trends decades sooner	Onboard the International Space Station	2023	Hyper-Spectral Imager for Climate Science (HySICS)

Table 3: Earth Systematic Missions under development (continued)

Satellite	Science & Application	ECT/Inclination & Mean Altitude Orbit	Expected Launch Date	Instruments
TSIS-2 (Total and Spectral Solar Irradiance Sensor-2)	Measure total solar irradiance and spectral solar irradiance to maintain continuity from TSIS-1 to understand solar radiation impacts on Earth's climate	98-deg Sun synchronous 600 km	2025	Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM)
PACE (Plankton, Aerosol, Cloud, and ocean Ecosystem)	Observe aerosols, clouds, and ocean color to enable energy budget and carbon cycle science and support fishery management, air quality forecasting, and disaster response mitigation efforts	98-deg Sun synchronous 676.5 km	2024	Ocean Color Instrument (OCI), Hyper Angular Rainbow Polarimeter (HARP2), and Spectro-Polarimeter for Planetary Exploration (SPEXone)
Sentinel-6B	Measure ocean surface height to monitor global sea level; provide tropospheric temperature and humidity data to improve weather forecasts, climate models, and hurricane tracking	66-deg Non Sun synchronous 1336 km	2026	Poseidon-4 SAR Radar Altimeter, AMR-C, GNSS-RO, GNSS-POD, DORIS, LRA

6.2 EARTH SYSTEM SCIENCE PATHFINDER PROGRAM

The Earth System Science Pathfinder (ESSP) program 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, 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.

Through ESSP, NASA funds the Earth Venture-class (EV) element that includes missions (EVM), instruments (EVI), and suborbital (EVS) airborne science campaigns recommended by the Decadal Survey. The 2017 Decadal Survey recommended adding a measurement continuity component to EV (EVC). These missions are part of a competitive program that complements strategic NASA Earth science missions. In addition, ESSP also oversees the operations of several legacy missions and other missions in development.

EV class missions (excluding EVS) currently in development are listed in Table 4.

6.2.1 EARTH VENTURE MISSION

In June 2012, Cyclone Global Navigation Satellite System (CYGNSS) was selected as the first Earth Venture Mission (EVM-1) and was launched in December 2016 (Section 2, Table 1).

The Geostationary Carbon Cycle Observatory (GeoCarb) was selected as EVM-2 in 2016. The GeoCarb instrument is a four-channel, slit-scan spectrometer and will collect daily measurements of carbon dioxide, carbon monoxide, and methane as well as solar induced fluorescence at a spatial resolution of 3 to 6 miles from a geostationary orbit over the Americas. The primary goal of the GeoCarb mission is to observe plant health and vegetation stress and to probe, in unprecedented detail, the natural sources, sinks, and exchange processes that control carbon dioxide, carbon monoxide, and methane in the atmosphere. The launch date is to be determined.

The EVM-3 Announcement of Opportunity (AO) closed in March 2021 and selection of the Investigation of Convective Updrafts (INCUS) mission was announced on 5 November 2021. INCUS will consist of three Smallsats with a five beam, Ka-band radar based on RainCube heritage; a cross-track scanning microwave radiometer based on TEMPEST-D heritage; and a 1.6-m Ka-band antenna. The mission aims to answer why convective storms, heavy precipitation, and clouds occur exactly when and where they do. NASA ESD will select a launch provider for the estimated 2027 launch.

6.2.2 EARTH VENTURE INSTRUMENTS

The first Earth Venture Instrument selection, EVI-1, announced in 2012, awarded funding to the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission. TEMPO will be the first space-based sensor to monitor daytime concentrations of major chemical air pollutants at an hourly timescale over North America. It will fly as a hosted payload on a commercial communications satellite in geostationary orbit and is currently scheduled for launch in 2023.

EVI-2 selections were announced in 2014. The instruments selected, Global Ecosystem Dynamics Investigation (GEDI) and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), are currently installed on the ISS (Table 2).

In 2016, two selections were made under the third EVI (EVI-3) opportunity: TROPICS and the Multi-Angle Imager for Aerosols (MAIA). TROPICS will characterize the relationship between rapidly evolving storm structures and storm intensity; assess the extent to which environmental moisture controls storm size, structure, and intensity; and demonstrate that storm intensity forecasts can be improved through utilization of rapid-update microwave information. In addition to TROPICS Pathfinder satellite launched in June 2021, the TROPICS constellation will consist of six CubeSats in LEO, which will ensure shorter revisit times. Three launches of two CubeSats each are expected to occur by the end of July 2022. MAIA seeks to determine the relative toxicity of various airborne particulate matter types by size, species, and concentration, and to assess their impacts on adverse birth outcomes, cardiovascular and respiratory disease, and premature deaths. The MAIA instrument will be hosted on a LEO satellite, with a launch date that is to be determined.

In early 2018, two selections were made in the fourth EVI (EVI-4) opportunity: the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) and Earth Surface Mineral Dust Source Investigation (EMIT). PREFIRE is a pair of CubeSats designed to document, for the first time, the variability in spectral fluxes from 5-45 microns on hourly to seasonal timescales and will reveal fluctuations in Earth's thermostat by capturing the full spectrum of Arctic radiant energy. EMIT, to be hosted on the ISS, will map the surface mineralogy of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared (VSWIR). The source region maps will be used to improve forecasts of the role of mineral dust in the radiative forcing (warming or cooling) of the atmosphere. EMIT is manifested to launch in June 2022 to the ISS and PREFIRE is anticipated to launch in 2023.

In late 2019, the fifth EVI (EVI-5) opportunity awarded funding to the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR), a hyperspectral ocean color sensor capable of repeat coverage and operating as a hosted payload in a geosynchronous orbit. The spectrometer achieves a high signal-to-noise ratio across the entire 340-1040 nm spectral range. While the primary mission focuses on ecosystem processes in the Gulf of Mexico, GLIMR will also have a clear view of the continental U.S. coastal waters, and other areas of interest, such as the Caribbean and Amazon River plume.

The EVI-6 opportunity, announced in April 2022, solicits Class D instrument(s) or SmallSat(s). Proposals are due September 1, 2022. Additional information about EVI-6 is available at: https://essp.larc.nasa.gov/EVI-6/.

6.2.3 EARTH VENTURE CONTINUITY

In the 2017 Earth Science Decadal Survey (DS), the U.S. National Academies of Science, Engineering, and Medicine recommended adding a new Earth Venture program element focused on continuity observations.

In 2018, NASA released the first Earth Venture Continuity (EVC) solicitation, EVC-1, and in February 2020, the Libera mission was selected to demonstrate an innovative and cost-effective approach to maintaining the 40-year data record of the balance between the solar radiation entering Earth's atmosphere and the amount absorbed, reflected, and emitted.

Libera will measure solar radiation in wavelengths reflected by the Earth system (0.3 and 5 microns) and infrared radiation as it exits the top of the atmosphere (5 and 50 microns). The sensor will also measure the total radiation leaving the Earth system (0.3 to 100 microns). An innovative additional “split shortwave” channel (0.7 and 5 microns) was also added to the instrument. These measurements will improve climate certainty by a factor of two and will enable scientists to better understand changes to Earth systems, including whether the planet is getting brighter or darker and heating up or cooling down. Libera will fly on NOAA’s operational Joint Polar Satellite System-3 (JPSS-3) satellite, which is scheduled to launch by December 2027.

Table 4: Upcoming Earth Venture-class missions under development

EV	Satellite	Science and Application	Expected Launch Date	Instrument	Mission Website
EVI	**TROPICS** (Time-Resolved Observations of Precipitation)	Collect 3D temperature and humidity observations to improve understanding of cyclone lifecycles and cyclone intensification	2022	Six CubeSats with rotating microwave radiometer	https://tropics.ll.mit.edu/CMS/tropics
	EMIT-ISS (Earth Surface Mineral Dust Source Investigation)	Measure the different wavelengths of light emitted by minerals on the surface of deserts and other dust sources to determine their composition to better understand how dust warms or cools the atmosphere	2022	VSWIR spectrometer	https://earth.jpl.nasa.gov/emit/
	MAIA (Multi-Angle Imager for Aerosols)	Collect radiometric and polarimetric measurements to characterize sizes, compositions, and quantities of particulate matter in air pollution to combine with health records to better understand connections between air pollution and health problems	To be Decided	Two pushbroom spectropolarimetric camera on a two-axis gimbal	https://maia.jpl.nasa.gov/
	PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment)	Provide full spectral measurements of Far InfraRed (FIR) radiation over the Arctic and Antarctic to allow more accurate predictions of Arctic warming, sea ice and glacier melt, and influence on global sea level and weather systems	2023	Two CubeSats with Thermal Infrared Spectrometers (TIRS)	https://prefire.ssec.wisc.edu/

Table 4: Earth Venture-class missions under development (continued)

EV	Satellite	Science and Application	Expected Launch Date	Instrument	Mission Website
EVI	**TEMPO** (Tropospheric Emissions: Monitoring of Pollution)	Measure tropospheric ozone, ozone precursors, aerosols, and clouds over North America to increase understanding and improve prediction of air quality and climate forcing	2023	Scanning UV/visible spectrometer	http://tempo.si.edu/overview.html
	GLIMR (Geosynchronous Littoral Imaging and Monitoring Radiometer)	Measure electromagnetic spectra from the Gulf of Mexico, southeast US coast, and Amazon River plume to observe and enable rapid response to coastal water disasters like harmful algal blooms and oil spills	2026	Hyperspectral ocean color radiometer	https://eos.unh.edu/glimr
EVC	**Libera** on JPSS-2	Collect shortwave, split shortwave, longwave, and total radiation measurements to continue and enhance the Earth radiation budget data record needed to recognize changes to the climate system and constrain future predictions	2027	Four electrical substitution radiometers (ESRs)	https://lasp.colorado.edu/home/libera/

Table 4: Earth Venture-class missions under development (continued)

EV	Satellite	Science and Application	Expected Launch Date	Instrument	Mission Website
EVM	**GeoCarb** (Geostationary Carbon Cycle Observatory)	Measure carbon dioxide, carbon monoxide, methane concentrations, and solar induced fluorescence to better understand interconnections between carbon and the climate and detect changes in vegetation health	To be Decided	Single slit scanning spectrometer	https://www.ou.edu/geocarb
	INCUS (Investigation of Convective Updrafts)	Measure vertical transport of air and water, known as convective mass flux (CMF), to address why convective storms, heavy precipitation, and clouds occur exactly when and where they do	2027	Cross-track scanning microwave radiometer and Ka-band radar with five beams	https://www.nasa.gov/press-release/nasa-selects-new-mission-to-study-storms-impacts-on-climate-models

6.3 2017 DECADAL SURVEY FOR EARTH SCIENCE RESEARCH AND APPLICATIONS FROM SPACE

NASA relies on the scientific community to identify and prioritize leading-edge scientific questions and the observations required to answer them. In response to a request from NASA, NOAA, and USGS, the National Academies for Science, Engineering and Medicine appointed an *ad hoc* committee, the Committee on Earth Science and Applications from Space (ESAS), to carry out a decadal survey of Earth Science and Applications. In 2018, ESAS released the 2017 Decadal Survey (DS), *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space*. The 700-page document is the second such Earth sciences decadal survey. It provides recommendations from the environmental monitoring, Earth science research, and applications communities for an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs.

The DS contained a strong endorsement of the Program of Record (POR), which comprises satellites or instruments currently on orbit, as well as those already in formulation and implementation, including directed missions and those selected as part of NASA's Earth Venture program. The DS recommended building on this observing system and identified the observations needed to address key science and application objectives and fill gaps in the POR. These observables are allocated to three new program elements: **Designated**, focused on the highest-priority observations; **Explorer**, a competed program to address the remaining targeted observables; and **Incubation**, intended to accelerate the readiness of cost-effective flight implementations not yet mature enough to deploy to capture high-priority observables.

6.3.1 DECADAL SURVEY DESIGNATED OBSERVABLE STUDIES

Following release of the Decadal Survey (DS) report in early 2018, ESD initiated studies to explore implementation options for observing systems to address the DS's five Designated Observables (DO): Aerosols (A); Clouds, Convection, and Precipitation (CCP); Mass Change (MC); Surface Biology and Geology (SBG); and Surface Deformation and Change (SDC). Each study involved multiple NASA centers and, although details vary among the studies, each study team drafted a Science and Applications Traceability Matrix (SATM) as part of an overall value framework against which to assess potential architectures. Information used to develop the SATMs was drawn from the DS and expanded through research and applications community workshops. Each team was challenged to broaden the trade space of potential solutions beyond single-satellite concepts, and to consider options that included multiple satellites in constellation, commercial satellite data, and international partnerships.

In the spring of 2021, under the name Earth System Observatory (ESO), NASA initiated pre-Phase A activities for four of the five Designated Observables: A, CCP, MC, and SBG. This allowed NASA centers to establish project offices to further define the mission concepts, execute trade studies related to architecture(s) identified during the study phase, and continue to develop opportunities for collaboration with international partners. As recommended in the DS, the fifth Designated Observable study team, SDC, will continue its study of potential architectures through launch of the NISAR mission, which is included in the POR, to incorporate lessons learned and provide continuity measurements.

Through 2022, the ESO missions in pre-Phase A are undergoing Mission Concept Reviews in preparation to enter Phase A, where they will develop a baseline mission concept, validate requirements, and establish mission architecture.

6.3.2 DECADAL SURVEY EARTH SYSTEM EXPLORERS PROGRAM

NASA expects to initiate the new Earth System Explorers Program element in 2022 which will be designed to accomplish high-quality Earth system science investigations addressing one or more Explorer targeted observables identified in the Decadal Survey. These missions will conduct scientific investigations that can be developed in approximately 40 months or less and operate up to three years on-orbit.

The competitive selection process will be completed in two steps. For Step 1, NASA anticipates up to four proposals will be selected for nine-month Phase A concept studies. In Step 2, NASA will review the completed concept study reports and expects to select up to two Earth System Explorer missions to continue development.

6.3.3 DECADAL SURVEY INCUBATION ACTIVITIES

Decadal Survey Incubation (DSI) activities were initiated in 2019 to focus on investments for priority observation capabilities that need to be advanced prior to cost-effective implementation in the next decade. The program is focused on the Planetary Boundary Layer (PBL) and Surface Topography and Vegetation (STV) targeted observables only.

While overall management of the program was assigned to ESTO, program activities are closely coordinated with NASA ESD's Research and Analysis (R&A) Program. The goal of the DSI effort is to accelerate the readiness of cost-effective flight implementations of PBL and STV targeted observables. DSI supports maturation of mission, instrument, technology, and/or measurement concepts to address specific high-priority science for the 2027-2037 decade. Two selected study teams – one each for PBL and STV – completed study team reports to inform program strategy and decisions. A solicitation was subsequently released in July 2021 to enable science and technology advancements. NASA received a total of 76 proposals in response to the solicitation, and in April 2022 selected 35 for funding. The total first year of funding to be provided for these investigations is approximately $9.5 million. Information regarding the awarded proposals is available at: https://esto.nasa.gov/project-selections-for-dsi-21/.

7 ADDITIONAL TOPICS OF INTEREST TO CGMS MEMBERS

7.1.1 SENIOR REVIEW

The Senior Review is the process by which Earth Science missions that have completed their prime missions seek to extend their operations. Initially implemented in 2005, the Senior Review was held every two years through 2017, at which point the cadence was changed to three years. At the invitation of ESD, each mission submits a formal proposal that documents the goals of the extension, the health status of the satellite(s), and the budget required for an extension. ESD establishes several review panels to evaluate the scientific value, technical performance, proposed costs, and broader national interests associated with the proposed extensions.

The next Senior Review will occur in 2023. The 2020 Senior Review evaluated 13 Earth Science missions and submitted a final report in August 2020. All 13 missions were found to have very high scientific merit, continue to be widely used by both research and applications communities, and met the requirements for extension in the 2021-2023 timeframe. The final report can be found at https://science.nasa.gov/earth-science/missions/operating.

Since last year, two Earth Science missions, GEDI and ICESat-2, were granted out of cycle mission extensions through 2023 after GEDI completed its Prime Mission in May 2021 and ICESat-2 completed its prime mission in February 2022. The OCO-3 instrument on the ISS will remain operational until early 2023 when the instrument replacing it is expected to arrive.

7.1.2 GLOBAL GREENHOUSE GAS MONITORING

NASA has a long history of monitoring global changes to atmospheric concentrations of trace gases using satellites, airborne platforms, and ground networks. Two instruments capable of observing CO_2 concentrations on a near-global level are currently on orbit. The Orbiting Carbon Observatory-2 (OCO-2) was launched in 2014. It has a three-channel imaging, grating spectrometer that observes an 8-pixel wide swath with spatial footprints of roughly 1.5 x 2 km^2 from polar sun-synchronous orbit. The data are used to improve our understanding of CO_2 fluxes (difference of sources and sinks) at regional scales (~1000 km). Due to the reduced reflectivity of the two near-infrared channels used for CO_2 retrievals over water, OCO-2 observes in nadir viewing (for data over land) and glint viewing (for data over the ocean). A notable science result using OCO-2 data is the independent observational constraint on per capita CO_2 emissions from a subset of cities around the world. Direct CO_2 emissions (per capita) from denser cities are lower, while emissions are higher from cities with higher per capita Gross Domestic Product (GDP).

Using OCO-2 flight spare components, NASA built and launched OCO-3 to the Japanese Equipment Module Exposed Facility on the ISS in 2019. The inclined ISS orbit allows for different sampling of variations in sources and sinks of CO_2 compared to that obtained from OCO-2. Instead of using the spacecraft for pointing with OCO-2, the OCO-3 instrument had an independent, and more agile, pointing capability, Strategic Area Mapping (SAM). SAM allows a unique way of pointing where the narrow swaths can be obtained side-by-side and raster through areas of roughly 100 x 100 km^2. Because OCO-2 is still operating nominally, maintaining the program of record, SAM observations comprise a large percentage of the data for OCO-3. SAM is used to target cities, power plants, and other areas of interest with reasonable revisits to observe changes in emissions over time.

NASA maintains several airborne imaging spectrometers capable of identifying greenhouse gas emission sources and their strength. These include the Airborne Visible InfraRed Imaging Spectrometer – Next Generation (AVIRIS-NG) and Hyperspectral Thermal Emission Spectrometer (HyTES).

AVIRIS-NG measures reflected solar radiance from 380 nm to 2510 nm with 5 nm sampling for monitoring of methane (CH_4). Data from AVIRIS-NG are also being analyzed for potential retrievals from strong carbon dioxide emission sources. Since 2015, several CH_4 campaigns have been completed in the United States. The data have been used to thoroughly map sources of CH_4, including natural gas storage and transmission locations, natural gas wells, coal mines, and livestock facilities.

HyTES is an airborne imaging spectrometer with 256 spectral channels between 7.5 and 12 micrometers in the thermal infrared part of the electromagnetic spectrum. HyTES incorporates several new technologies including a Dyson spectrometer, long, straight slit, curved diffraction grating and Quantum Well Infrared Photodetector (QWIP). The data from the instrument is being used for a variety of applications, including monitoring volcanos and wildfires, assessing water use and availability, and understanding land surface change and urbanization.

It is important to highlight that measurement concepts developed and refined through NASA airborne campaigns are being advanced for deployment in space by several non-government programs, such as the Carbon Mapper program (https://carbonmapper.org/) initiated by Planet in collaboration with JPL and the State of California.

Observations from spaceborne assets are regularly calibrated using measurements recorded at Total Column Carbon Observing Network (TCCON) sites. TCCON comprises ground-based Fourier Transform Spectrometers recording direct solar spectra in the near-infrared spectral region. The measurements allow accurate retrieval of column-averaged abundance of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO. The network was established in preparation for the first OCO mission. The Advanced Global Atmospheric Gases Experiment (AGAGE) network currently measures concentrations of forty atmospheric gases that contribute to global warming and ozone depletion. Some sites in this network have been operating since 1978. These and other ground-based observation networks serve as the validation backbone for other GHG observing satellites, such GOSAT and Sentinel-5, and for closely monitoring seasonal, inter-annual, and decadal changes in greenhouse gas concentrations in the atmosphere. Inferred emissions of atmospheric CFC-11 observations from the AGAGE network suggest global CFC-11 emissions in 2019 decreased by 10 ± 3 Gg yr-1 from their 2014-2017 magnitudes due to emission reductions in China after initial increases from that region earlier in the decade.

In 2012, NASA initiated the Carbon Monitoring System (https://carbon.nasa.gov/index.html) program with explicit goal of prototyping capabilities necessary to support stakeholder needs for Monitoring, Reporting, and Verification (MRV) of carbon stocks and fluxes. The program has funded development of more than 130 freely available data products (https://carbon.nasa.gov/cgi-bin/available_archived_products.pl#arch). Another 20 data products are currently under development. CMS products have been used by the U.S. Environmental Protection Agency (EPA) to improve its methods for reporting CH_4 emissions. Not only did the CEOS contribution to the initial Global Stocktake submission, as mandated by the Paris Climate Accord relied on CO_2 global flux products, but it is expected that continued future improvements in the flux product will help refine Global Stocktake submissions. The U.S.

government has initiated a carbon Measurement, Monitoring, Reporting, Verification (MMRV) program that brings together measurement and analysis activities across the entire U.S. federal government.

Building on success of OCO-2 and -3, NASA will launch the Geostationary Carbon Observatory (GeoCarb) in 2024. Selected as part of NASA's Earth Venture Mission program, GeoCarb is a single-slit, four-channel infrared scanning spectrometer that will fly in a geostationary orbit, allowing retrievals of total atmosphere column of carbon dioxide, CH_4, carbon monoxide, and solar-induced fluorescence (SIF) at a spatial resolution of ~5 to 10 km. GeoCarb will obtain full coverage of land masses over most of the Americas multiple times per day. These data will allow better quantification of emission sources and give a more complete picture of the fluxes of CO_2 and CH_4 from the natural carbon cycle.