Coordination Group for Meteorological Satellites

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Prepared by: NASA
Agenda Item 2
Discussed at Plenary

NASA REPORT ON THE STATUS OF CURRENT AND FUTURE SATELLITE MISSIONS

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Executive Summary

The National Aeronautics and Space Administration (NASA) continues operating more than two dozen Earth-observing satellites and instruments. 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 its partners launched four missions: the Earth Surface Mineral Dust Source Investigation (EMIT) instrument to the International Space Station, the Surface Water and Ocean Topography (SWOT) satellite, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument hosted on a communication satellite, and four small satellites as part of Time-Resolved Observations of Precipitation structure and storm Intensity with Constellation of Smallsats (TROPICS) mission.

As of early 2023, the Earth System Observatory (ESO) comprising of the Atmospheric Observing System (AOS), Space Biology and Geology (SBG), and Mass Change (MC) missions have transitioned into the formulation phase (Phase A) with architectures at an appropriate level of maturity. These architecture concepts represent balanced acquisition strategies, leveraging unique NASA expertise, contributions from international partnerships, as well as industry capabilities by competing at least 50% of the ESO instruments and the spacecraft.

On May 2, 2023, NASA released the final Earth System Explorers (ESE) Announcement of Opportunity (AO). Consistent with the U.S. Administration's priorities and urgent national need for understanding and addressing climate change and reducing greenhouse gas emissions, at least one of the estimated four selected proposals will prioritize Greenhouse Gases as one of its Targeted Observables.

NASA REPORT ON THE STATUS OF CURRENT AND FUTURE SATELLITE MISSIONS

1 Introduction

The National Aeronautics and Space Administration (NASA) continues operating for more than two dozen Earth-observing satellites and instruments. 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 and instruments operating in Low Earth Orbit (LEO), highlighting recently launched missions.

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, the Earth Information Center, Commercial Smallsat Data Acquisition (CSDA) program, the Open-source science initiative, and the Greenhouse Gas Monitoring and Information Center.

2 Currently operating satellite systems

Table 1 provides a list of all currently operating NASA Earth-observing satellites. The recently launched Earth Surface Mineral Dust Source Investigation (EMIT), Surface Water and Ocean Topography (SWOT), Tropospheric Emissions: Monitoring of Pollution (TEMPO), and Time-Resolved Observations of Precipitation structure and storm Intensity with Constellation of Smallsats (TROPICS) are highlighted below.

2.1 Earth Surface Mineral Dust Source Investigation (EMIT)

The Earth Surface Mineral Dust Source Investigation (EMIT) instrument was launched from Kennedy Space Center in Florida aboard SpaceX's 25th commercial resupply to the International Space Station (ISS) on July 14, 2022. EMIT is the fourth Earth Venture Instrument (EVI-4) selection. It employs an advanced imaging spectrometer to map the surface mineralogy of arid dust source regions. The observations are helping improve models and acquire an

improved understanding of the role of mineral dust in the warming or cooling of the Earth's atmosphere. The EMIT instrument is based on NASA developed technology dating back to the early 1980s. It has been used on research aircraft to apply imaging spectroscopy to identify minerals on Earth's surface, as well as to the study of a broad set of Earth system science questions spanning geology and natural hazards, the climate system, aquatic settings, and the water cycle, the atmosphere, the carbon cycle, ecosystems, and more.

EMIT is now addressing its prime mission objectives while creating new opportunities to advance those broader science goals. After beginning prime operations, EMIT demonstrated an additional crucial capability to detect the presence of methane, a powerful greenhouse gas, with high accuracy and precision (Figure 1). EMIT data products are publicly available through VISIONS: The EMIT Open Data Portal, as well as the NASA Land Processes Distributed Active Archive Center (LP DAAC) (Table 2).

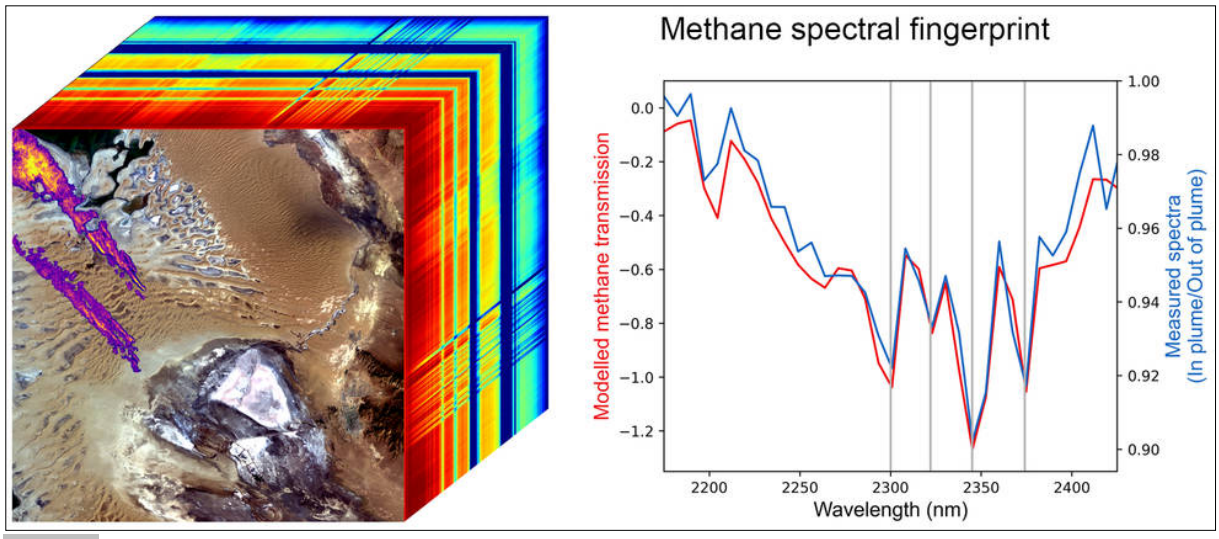

Figure 1: The cube (left) shows methane plumes (purple, orange, yellow) over Turkmenistan. The rainbow colors are the spectral fingerprints from corresponding spots in the front image. The blue line in the graph (right) shows the methane fingerprint EMIT detected; the red line is the expected fingerprint based on an atmospheric simulation and the blue line is the measured fingerprint. Credits: NASA/JPL-Caltech

2.2 Surface Water and Ocean Topography (SWOT)

On December 16, 2022, NASA launched the Surface Water and Ocean Topography (SWOT) satellite from Vandenberg Space Force Base in central California. SWOT was developed in partnership with the French space agency Centre National d'Études Spatiales (CNES), with contributions from the Canadian Space Agency (CSA) and the UK Space Agency (UKSA). The SWOT mission includes several advanced instruments listed in Table 1, including the first in-flight usage of wide-swath SAR interferometry, and will measure the elevation of

nearly all the water on Earth's surface for the first time, including freshwater bodies and the ocean, and how they change over time. These measurements provide insights into how a warming climate affects water storage in lakes, rivers, and reservoirs, sea level rise along the coasts, and will help communities better manage their water resources and prepare for floods and other disasters.

SWOT successfully completed its commissioning phase and is currently undergoing calibration and validation activities and will begin science operations in the summer of 2023. First light images, shown in Figure 2 were released in March 2023, and confirmed that SWOT's KaRIn instrument improves the spatial resolution by a factor of ten when compared to other satellite altimeters. Data will become fully and freely available to the public after SWOT enters prime operations later in 2023 through NASA's Physical Oceanography Distributed Active Archive Center (PO DAAC) (Table 1).

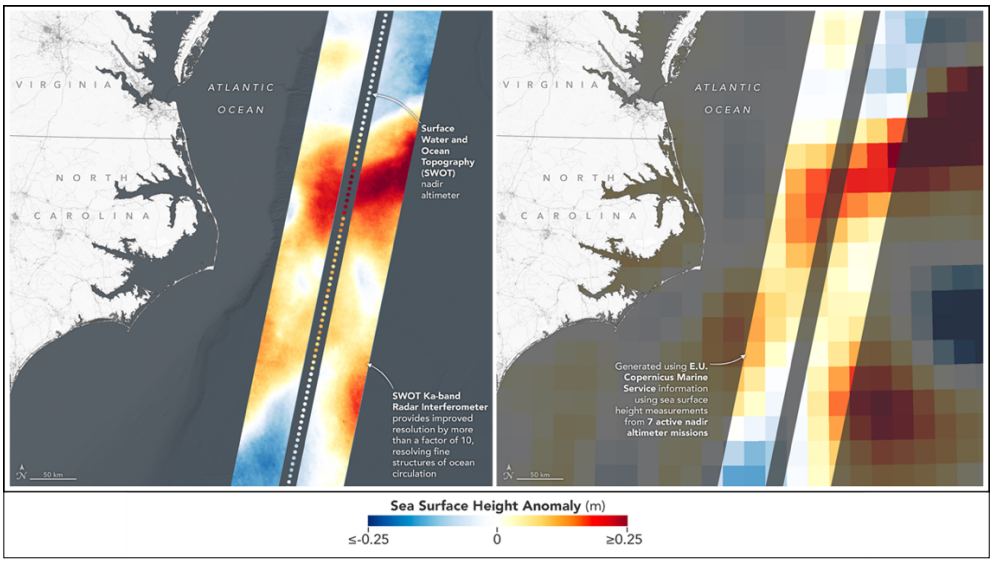

Figure 2: The data in the left graphic are the first sea level measurements by SWOT's KaRIn instrument, gathered on January 21, 2023, compared to data over the same area by altimeters on seven other instruments in the right graphic. Red represents sea levels higher than the global average, while blue is lower. Credits: left: NASA/JPL-Caltech; right: NASA/JPL-Caltech/Copernicus Marine Service of ESA

2.3 The Tropospheric Emissions: Monitoring of Pollution (TEMPO)

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument launched on April 7, 2023, from Cape Canaveral Space Force Station in Florida as a hosted payload on a commercial Intelsat 40e satellite. TEMPO is a grating spectrometer and is the first Earth Venture Instrument (EVI-1) selection. From a fixed geostationary orbit above the equator, TEMPO will be the first space-based instrument that monitors at an hourly timescale day-time concentrations of major air pollutants over North America. It will play a central role in the scientific analysis of pollution, including studies of rush hour pollution, the potential for

improved air quality alerts, the effects of lightning on ozone concentrations, the transport of pollution resulting from forest fires and volcanoes, and even the effects of fertilizer application.

TEMPO will begin commissioning activities in summer 2023. Instrument was powered on June 7, 2023, and is in extended degassing period. Operations are anticipated to begin in fall 2023 after which data will be publicly available through NASA's Atmospheric Science Center (ASDC) (Table 1). TEMPO mission overview was provided during the recently held CGMS-51 Working Group III meeting (Agenda Item 4.2).

2.4 Time-Resolved Observations of Precipitation structure and storm Intensity with Constellation of Smallsats (TROPICS)

The Time-Resolved Observations of Precipitation structure and storm Intensity with Constellation of Smallsats (TROPICS) launched on May 7 and May 26, 2023. TROPICS is one of the two missions selected as part of the third Earth Venture Instrument (EVI-3) competition. The TROPICS constellation consists of four CubeSats with multi-channel passive compact microwave radiometers in low Earth orbit (30-degree inclination; 550 km altitude), which will ensure shorter revisit times. The TROPICS constellation also includes the TROPICS Pathfinder satellite launched in June 2021.

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. TROPICS will begin commissioning activities in summer 2023, followed by calibration and validation activities. Data is anticipated to be openly available to the public later in 2023 through NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC) (Table 1). TROPICS mission overview was provided during the recently held CGMS-51 Working Group III meeting (Agenda Item 4.2).

Table 1: Current NASA ESD satellites and instruments in Low Earth and Geostationary Orbits

Mission	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
CALIPSO[1,4,5] (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

Table 1: Current NASA ESD satellites and instruments in Low Earth and Geostationary Orbits (continued)

Mission	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
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
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)

Table 1: Current NASA ESD satellites and instruments in Low Earth and Geostationary Orbits (continued)

Mission	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
CYGNSS[6] (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	Eight SmallSats with GPS	PO.DAAC
GRACE-FO[8] (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, Accelerometer, GPS RO	PO.DAAC
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

Table 1: Current NASA ESD satellites and instruments in Low Earth and Geostationary Orbits (continued)

Mission	Science and Application	ECT/Inclination & Mean Altitude	Launch Date	Instruments	Data Access
SWOT[7] (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	16 Dec 2022	KaRIn, Jason-class Altimeter, DORIS Antenna, Microwave Radiometer, X-band Antenna, LRA, GPS Receiver	PO.DAAC
TEMPO[7] (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	Geosynchronous 37,000 km	7 Apr 2023	Scanning UV/visible spectrometer	ASDC
TROPICS[7] (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats)	Collect 3D temperature and humidity observations to improve understanding of cyclone lifecycles and cyclone intensification	30-deg Non Sun-synchronous 550 km	7 May 2023 & 25 May 2023	Four CubeSats with Multi-channel passive compact microwave radiometers	GES DISC

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.
5. On April 19, CALIPSO NASA/CNES Joint Steering Group (JSG) approved the end of science operations to occur on August 1, 2023. Once the science instruments have been powered off, the remaining power margins will allow the CNES team to conduct the spacecraft decommissioning activities through December 2023. An additional JSG is planned for September 27, 2023, to approve the final mission termination and decommissioning activities. In FY2024, the project will transition to Phase F, mission closeout, performing a final reprocessing of the 2006-2023 science data record and archiving the full dataset at the NASA Atmospheric Science Data Center (ASDC) by the end of FY2025.
6. CYGNSS lost contact with one of eight spacecraft in November 2022 with no impacts to science requirements.
7. SWOT, TEMPO, and TROPICS launched and are undergoing commissioning, calibration, and validation before officially entering into Primary Operations later in the summer and fall of 2023.
8. GRACE-FO mission is comprised of two identical satellites.

*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 Nanosat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

The 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.

Developed by scientists at the Los Alamos National Laboratory, the instrument has significant onboard data preprocessing capability. The instrument will help assess whether a constellation of CubeSat-like satellites can gather and process high-resolution data to detect, map, and quantify Earth's dilute gases as efficiently as larger, single-platform satellites.

First of the two NACHOS satellites, NACHOS-1, was launched in February 2022 onboard the NG-17 Cygnus resupply mission to ISS. It was subsequently deployed from the departing Cygnus spacecraft on June 30, 2022. On July 2, 2022, NACHOS-2 was launched directly to designated orbit onboard a Virgin Orbit vehicle. While NACHOS-1 imager operated as expected, the spacecraft deorbited in February 2023 before obtaining targeted science data. The mission team is working to correct related satellite pointing issues on NACHOS-2. Once the fix is complete, it is anticipated that NACHOS-2 will provide science data within its expected multi-year lifetime.

3.2 Hyper-angular Rainbow Polarimeter (HARP)

The Hyper-angular Rainbow Polarimeter (HARP) deorbited in May 2022 following more than 775 days in space.

A 3U CubeSat developed at the University of Maryland, Baltimore County, HARP was launched from the Wallops Flight Facility to the Space Station on November 2, 2019, and was deployed from ISS in mid-February 2020. It includes a wide field of view polarimeter – the first on a CubeSat platform – that observes Earth from up to sixty viewing angles, (four) wavelengths, and (three) polarizations channels. HARP demonstrated its ability to monitor aerosols and cloud properties and made comparative observations with the MODIS and ABI instruments. The HARP team also successfully demonstrated calibrated measurements of aerosols at multiple AERONET locations. A near identical instrument, HARP-2, is scheduled to fly on the NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. HARP data was utilized for the development of HARP-2, which is ready to be integrated onto the PACE spacecraft.

3.3 Compact Infrared Radiometer in Space

The Compact Infrared Radiometer in Space (CIRiS) was launched from Cape Canaveral Air Force Station to the ISS on December 5, 2019, and deployed in February 2020. A 6U CubeSat developed at Ball Aerospace, CIRiS 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 for satellite systems operating at the Lagrange Point

The Deep Space Climate Observatory (DSCOVR) was launched on February 11, 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 have been operating almost continuously with only minor interruptions relying 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.

Recent EPIC and NISTAR calibrations 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.

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 for research and development satellite systems

5.1 Formation flying

Several 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 was built up over a decade, starting with the launch of Aqua in 2002, and continuing with Polarization and Anisotropy of Reflectance for Atmospheric Sciences coupled with Centre

National d'Études Spatiales (CNES) Observations from a Lidar (PARASOL), which was launched in 2004 and decommissioned in 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 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.

In 2018, following a reaction-wheel anomaly on CloudSat, both the CALIPSO and CloudSat spacecraft were lowered out of the A-Train orbit to maintain the coincident measurements. Aqua and Aura no longer have enough fuel to maintain their positions in the A-Train and are drifting with respect to their original mean local crossing times. After two decades of operations and producing excellent complementary science, many of the A-Train missions are reaching the end of their mission life and will be decommissioned over the next few years. OCO-2 and GCOM-W1 continue to maintain their locations in the A-Train.

Aqua, Aura, and OCO-2 are participating in the 2023 Earth Science Senior Review for mission extensions (Section 7.1.1). Since the 2020 Senior Review, CloudSat and CALIPSO are evaluated annually, contingent on spacecraft and instrument health. After 17 years, the CALIPSO satellite will be decommissioned later in 2023 due to insufficient fuel to maintain its orbit resulting in reduced power availability.

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.

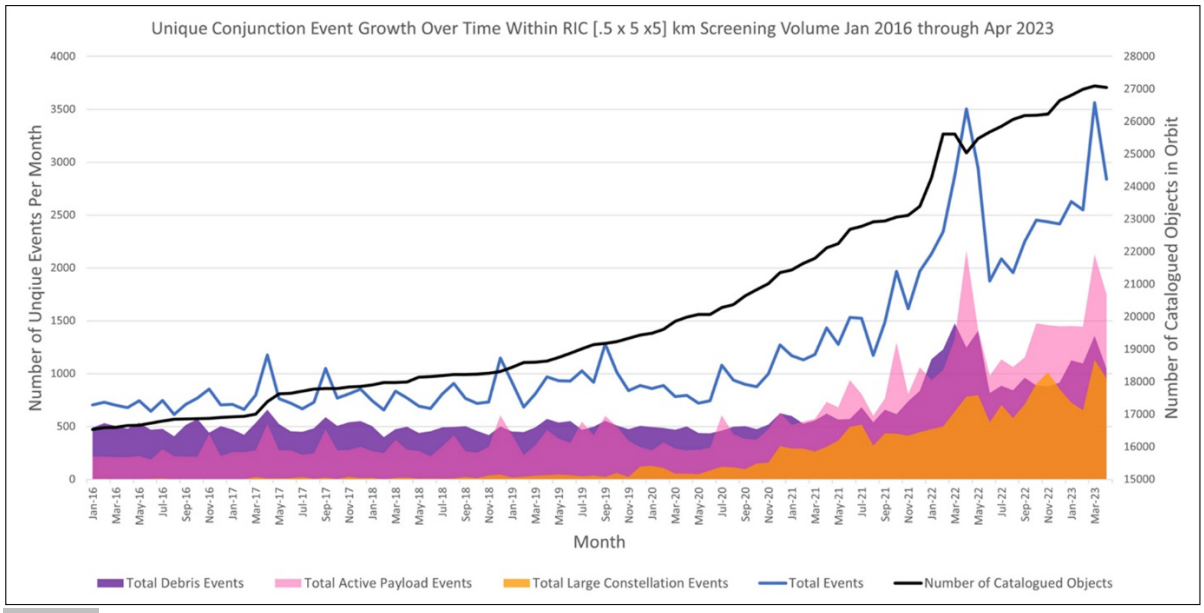

Figure 3: Number of conjunction events since 2016. The blue line shows the total number of unique conjunction events with debris, active satellites, and large constellations. The black line shows the total number of objects (debris & active satellites, including large constellations) on orbit. The RIC (Radial, In-Track, Cross-Track) defines the screening volume around CARA supported NASA missions. 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

A recent history of collision avoidance maneuvers is shown in Figure 3. The number of maneuvers of CARA supported missions per year have increased significantly with the addition of many large satellite constellations operating in LEO. Furthermore, the intensity of the solar cycle is greater than anticipated, resulting in an operational environment that is very dynamic and requires additional maneuvers to counteract drag effects. As the number of potential conjunctions between satellites that have maneuver capabilities and are still actively being managed increases, so does the necessity for improved communications between satellite operators to coordinate avoidance maneuver planning. Figure 3 shows the total number of unique conjunction events has more than tripled from March 2020 to March 2023 and the number of catalogued objects is steadily increasing.

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

A thermal imaging instrument, the Hyperspectral Thermal Imager (HyTI) will demonstrate the acquisition of high-spectral and spatial long-wave infrared image from a 6U CubeSat platform. Built by University of Hawaii at Monoa, HyTI is expected to launch no earlier than February 2024. The mission will use a spatially modulated interferometric imaging technique to produce spectro-radiometrically calibrated image cubes, with 25 channels between 8-10.7 □m, at a ground sample distance of approximately 60 meters. The HyTI performance model indicates narrow band NE∆Ts of less than 0.3 Kelvin. The small form factor of HyTI is made possible via the use of a no-moving-parts Fabry-Perot interferometer and cryogenically-cooled High Operating Temperature – Barrier Infrared detector (HOT-BIRD) focal plane array (FPA) technology developed at JPL. The value of HyTI for Earth science research and applications will be demonstrated via on-board processing of the raw instrument data for producing L1 and L2 products, with a focus on rapid delivery of data for 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 is targeted for launch no earlier than February 2024, and 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.

5.4 Instruments aboard the International Space Station (ISS)

The ISS is an extremely important platform for ESD's mission portfolio and supports operations of seven 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. At the same time, the dynamic operating environment of ISS requires external payloads to continually adapt to interruptions in science observations due to visiting vehicles, platform maneuvers, power outages, and maintenance activities, as well as structural blockages and sources of glint. In 2019, the ISS began increasing

its altitude eventually settling at an altitude with a 4-day orbit repeat cycle. While this repeat cycle is useful when planning for visiting vehicles, it created a significant challenge for several Earth observing instruments that were anticipating global coverage but were unable to do so due to the repeating orbit tracks and limitations in their pointing capabilities. In January 2022, the ISS lowered its orbit to allow for the Earth observing instruments to increase their coverage. Temporary altitude raises continue to impact science observations.

The Earth Surface Mineral Dust Source Investigation (EMIT) instrument began operations in late September 2022, after being installed on the ISS in July. It will continue its prime operations through November 2023. Total Spectral Irradiance Sensor 1 (TSIS-1) will conduct its End of Prime Mission Review in June 2023, and along with Stratospheric Aerosol and Gas Experiment III (SAGE III), were invited to propose mission extensions to the 2023 Senior Review (Section 7.1.1). ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Orbiting Carbon Observatory 3 (OCO-3), and Global Ecosystem Dynamics Investigation (GEDI) proposed to an accelerated Senior Review for mission extension in December 2022. All three missions were approved for extension through September 2026, in alignment with the next Senior Review cycle. To accommodate these extensions, OCO-3 instrument will be placed in storage on the ISS for about six months, estimated to begin in December 2023, depending on launch and installation of other ISS instruments. In March 2023, the GEDI instrument was placed in storage on the ISS for 13-18 months. After storage, OCO-3 and GEDI will each be returned to their operational locations to resume operations.

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 an additional instrument to be installed on the ISS, the Climate Absolute Radiance and Refractivity Observatory Pathfinder (CLARREO-PF) instrument (Section 6.1; Table 3).

Table 2: NASA instruments currently on the International Space Station

Mission	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
EMIT (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	14 Jul 2022	VSWIR spectrometer	VISIONS LP DAAC

6 Future Satellite Systems

6.1 Earth Systematic Mission Program

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. Many of the missions in the ESM portfolio are being developed with key partners, both domestic and international.

The ESM program continues to oversee the development and launch of missions recommended by the 2007 Decadal Survey. These missions include 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).

NASA is 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. NASA is also continuing its partnership with the European Space Agency (ESA) on Sentinel-6B as well as Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL).

The ESM program is also responsible for overseeing formulation and implementation of Earth System Observatory missions designed to address the Designated Observables identified in the 2017 Decadal Survey, including Mass Change; Surface Biology and Geology (SBG); and Atmosphere Observing System (AOS). (Section 6.3.1). Table 3 lists Earth Systematic Missions program content.

Table 3: Earth Systematic Mission projects in formulation or implementation

Mission	Science & Application	ECT/Inclination & Mean Altitude Orbit	Expected Launch Date	Instruments
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	2024	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	TBD	Hyper-Spectral Imager for Climate Science (HySICS)
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)

Table 3: Earth Systematic Mission projects in formulation or implementation (continued)

Mission	Science & Application	ECT/Inclination & Mean Altitude Orbit	Expected Launch Date	Instruments
Sentinel-6B[1]	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
CRISTAL[1] (Copernicus Polar Ice and Snow Topography Altimeter)	Measure and monitor surface elevation of glaciers and ice caps and contribute to global ocean topography and coastal/inland water applications	92-deg Non Sun synchronous 760 km	2027	Ka/Ku-Band IRIS, GNSS Receiver, LRA, AMR-CR
SBG (Surface Biology and Geology)	Observe Earth surface features including terrestrial and aquatic ecosystems and species habitats, agriculture, the surface water cycle, the distribution of surface minerals and other natural resources, fires, and fluxes of carbon, water, nutrients, and energy within and among ecosystems, the atmosphere, the ocean, and the Earth to revolutionize scientific understanding of climate change	**TIR** 98.04-deg Sun synchronous 665 km **VSWIR** 97.83-deg Sun synchronous 620 km	**TIR** No Earlier Than (NET) 2027 **VSWIR** NET 2028	**TIR** TIR, VNIR **VSWIR** VSWIR spectrometer

Table 3: Earth Systematic Mission projects in formulation or implementation (continued)

Mission	Science & Application	ECT/Inclination & Mean Altitude Orbit	Expected Launch Date	Instruments
AOS[2] (Atmosphere Observing System)	Measure cloud, precipitation, and aerosol processes across a range of spatiotemporal scale to improve predictions of weather, air quality, and climate	**AOS-Storm** 55-deg Non Sun synchronous 407 km **AOS-Sky** 97.2-deg Sun synchronous 450 km	**AOS Storm** NET 2028 **AOS Sky** NET 2030	**AOS Storm** Backscatter lidar[3], microwave radiometer **AOS Sky** Cloud profiling Doppler Radar[3], Microwave radiometer, Polarimeter, FIR Imaging Radiometer, Backscatter lidar[3]
Mass Change[4]	Provide continuity to 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 500 km	NET 2028	LRI, Accelerometers, GNSS Receiver
Landsat Next	Provide continuity land surface observations to study, predict, and understand the consequences of land surface dynamics	98-deg Sun synchronous 653 km	NET 2030	Three identical satellites with VSWIR and TIR

1 Partner led missions.
2 AOS-Storm will formation fly with the Japan Aerospace Exploration Agency's (JAXA) Precipitation Measuring Mission (PMM); AOS-Sky will formation fly with the Canadian Space Agency's (CSA) High altitude Aerosol Water vapor Clouds satellite (HAWCsat).
3 AOS instruments undergoing trade studies.
4 Mass Change mission is expected to be comprised of 2 satellites.

6.2 Earth System Science Pathfinder

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 (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 Missions

In 2022, NASA announced plans to cancel the development of Geostationary Carbon Cycle Observatory (GeoCarb) mission that was selected in 2016 under the second EV Mission (EVM-2) opportunity due to technical concerns, cost performance, and availability of new alternative data sources, as well as to keep the NASA Earth Science portfolio aligned with overall science priorities. The primary goal of the GeoCarb mission was to probe, in unprecedented detail, the natural sources, sinks, and exchange processes that control carbon dioxide, carbon monoxide, and methane in the atmosphere. Due to the importance of greenhouse gas observations, NASA is prioritizing the selection of at least one of the four estimated awards to address this important observable under the recently released Earth System Explorers Announcement of Opportunity (Section 6.3.3).

On March 14, 2023, the Investigation of Convective Updrafts (INCUS) mission entered Phase B. INCUS was the third EV Mission (EVM-3) selected in November 2021. It consists of three Smallsats each with a five beam, Ka-band radar based on RainCube heritage; a cross-track scanning microwave radiometer (middle Smallsat only) 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.

The Cyclone Global Navigation Satellite System (CYGNSS) mission selected under the first EV Mission (EVM-1) opportunity in 2012 and launched in December 2016 continues to provide science quality data despite lost contact with one of the eight spacecraft. CYGNSS is demonstrating the capability to measure the ocean surface wind field with unprecedented temporal resolution and spatial coverage, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a tropical cyclone. This mission intends to accomplish this through an innovative combination of all-weather performance Global Positioning System (GPS) ocean surface reflectometry with the sampling properties of a dense constellation of eight observatories. The science goal of the mission is to study the relationship

between ocean surface properties (i.e., surface wind speed), moist atmospheric thermodynamics, heat transfer, and convective dynamics in the inner core of a tropical cyclone. This will allow scientists to determine how a tropical cyclone forms, whether or not it will strengthen, and if so by how much. The successful completion of these goals will allow the mission to contribute to the advancement of tropical cyclone forecasting and tracking methods.

6.2.2 Earth Venture Instruments

On May 23, 2023, the Polarized Submillimeter Ice-cloud Radiometer (PolSIR) instrument was selected under the sixth EV Instrument (EVI-6) opportunity. PolSIR will consist of two identical CubeSats flying in orbits separated by three to nine hours to study ice clouds that form at high altitudes throughout tropical and subtropical regions to determine how and why they change throughout the day. These measurements will provide crucial information about how to accurately simulate these high-altitude clouds in global climate models.

In late 2019, the under the fifth EV Instrument (EVI-5) opportunity, funding was awarded to the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) instrument, 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 GLIMR instrument recently entered the implementation phase and launch will be determined at a later date once an access-to-space solution is determined.

In early 2018, two selections were made under the fourth EV Instrument (EVI-4) opportunity: the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) and the Earth Surface Mineral Dust Source Investigation (EMIT). EMIT was launched and installed on the ISS in 2022 (Section 2.1; Table 2). 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 reveal fluctuations in Earth's thermostat by capturing the full spectrum of Arctic radiant energy. PREFIRE is anticipated to launch in 2024.

In 2016, two selections were made under the third EV Instrument (EVI-3) opportunity: the Time Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) and the Multi-Angle Imager for Aerosols (MAIA). Two sets of two TROPICS Cubesats were launched on May 8 and May 26, 2023 (Section 2.4; Table 1). MAIA seeks to determine the relative toxicity of various airborne particulate matter types by size distribution, chemical composition, 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 the Italian space agency Agenzia Spaziale Italiana (ASI) PLATiNO-2 satellite and will be launched in 2025.

Two selections were made in 2014 under the second EV Instrument (EV-2) opportunity: the Global Ecosystem Dynamics Investigation (GEDI) and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS). While ECOSTRESS is currently installed and collecting data, GEDI is temporarily in storage for 13-18 months beginning in March 2023 (Table 2).

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) was selected in 2012 under the first EV Instrument (EV-1) opportunity. TEMPO launched on April 7, 2023, as a hosted payload on a commercial communications satellite to geostationary orbit and is currently going through check out and commissioning before beginning primary operations later this year (Section 2.3; Table 1).

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 EV Continuity 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-4 (JPSS-4) satellite, which is scheduled to launch by December 2027.

Table 4: Upcoming Earth Venture projects in formulation or implementation

EV	Mission	Science and Application	Expected Launch Date	Instrument	Mission Website
EV-I	**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	2025	Two push broom 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	2024	Two CubeSats with Thermal Infrared Spectrometers (TIRS)	https://prefire.ssec.wisc.edu/
	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	TBD	Hyperspectral ocean color radiometer	https://eos.unh.edu/glimr
	PolSIR (Polarized Submillimeter Ice-cloud Radiometer)	Measure the radiant energy emitted by clouds to significantly improve our understanding of how ice clouds change and respond throughout the day in response to a changing climate	TBD	Two CubeSats with Polarized Submillimeter Ice-cloud Radiometers	TBD

Table 4: Upcoming Earth Venture projects in formulation or implementation (continued)

EV	Mission	Science and Application	Expected Launch Date	Instrument	Mission Website
EV-C	**Libera** on JPSS-4	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/
EV-M	**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 Earth System Observatory

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.

After an extensive multi-year study phase to assess a broad trade space of potential architectures, NASA initiated pre-formulation studies in spring of 2021 for all except the SDC Designated Observable mission. Decision was made that SDC will remain in an extended study phase to take advantage of lessons learned from the NASA-ISRO Synthetic Aperture Radar (NISAR) mission, which will serve as a trailblazer for the rest of ESO. In pre-formulation, the ESO mission project offices established at NASA field centers further defined mission concepts, executed trade studies, and continued to develop opportunities for collaboration with international partners.

In spring 2022, AOS, SBG, and MC underwent Mission Concept Reviews that examined each mission's objectives and their ability to fulfill those objectives. In July 2022, following the Mission Concept Reviews, NASA established an Independent Review Board (IRB) to proactively

assist with assessing mission-specific and cross-cutting elements of ESO, provide early-stage feedback, and ensure NASA adopts lessons learned from previous large, strategic science missions. The IRB examined the mission pre-formulation technical concepts for robustness and the ability to satisfy each mission's essential requirements. The IRB identified critical cross-cutting factors across ESO's organization and management, science priorities and integrated operations, technical approach, and schedule and cost. The review found the current designs are capable of achieving the basic science requirements set out by the 2017 Earth science Decadal Survey. The IRB report also suggested specific technical and organizational recommendations to ensure success. NASA is assessing and incorporating the IRB recommendations through the formulation phase to ensure the success of each mission and overall ESO. As recommended by the IRB, NASA will ask the National Academies of Sciences0, Engineering and Medicine Committee on Earth Sciences and Applications from Space (ESAS) to review the current status of mission plans compared to Decadal Survey recommendations as part of the upcoming decadal midterm review process.

As of early 2023, the AOS, SBG, and MC ESO missions have transitioned into the formulation phase with architectures at an appropriate level of maturity for NASA's project life cycle Phase A. These architecture concepts represent balanced acquisition strategies, leveraging unique NASA expertise, contributions from international partnerships, as well as industry capabilities by competing at least 50% of the ESO instruments and the spacecraft. During formulation, in Phases A and B, NASA will work to finalize the mission architectures, as well as better identify and mitigate safety, technical, acquisition, cost, and schedule risk to improve the fidelity and realism of the cost and schedule estimates prior to moving into implementation and establishing baseline requirements.

Over the past six decades, NASA's Earth science fleet has provided critical observations underpinning most of what we know about our planet's changing climate. With several key satellites nearing end of life, NASA's Earth System Observatory (ESO) is planned as the next generation of Earth-observing satellites, building on the successes of the current fleet. Each ESO satellite will be uniquely designed to target observables identified as key to answering the most urgent questions of our time. Collectively, ESO will provide a multi-dimensional, holistic view of Earth, from bedrock to atmosphere. The information gained from each ESO mission will guide efforts related to understanding climate change, mitigating disasters, fighting forest fires, improving weather and air quality forecasts, and improving real time agricultural processes, among many other uses and applications.

6.3.2 Earth System Explorers Program

NASA is in the process of initiating Earth System Explorers program is designed to enable high quality Earth system science investigations through Principal Investigator-led missions that acquire and deliver measurements of one or more observables identified in the 2017 Decadal Survey as Earth System Explorer Targeted Observables (TO): Atmospheric Winds, Greenhouse Gases, Ice Elevation, Ocean Surface Winds and Currents, Ozone and Trace Gases, Snow Depth and Snow Water Equivalent, and Terrestrial Ecosystem Structure. These Explorer missions will conduct scientific investigations that can be developed relatively quickly 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.

NASA released the final Announcement of Opportunity (AO) first Earth System Explorers (ESE) missions was released on May 2, 2023. Consistent with the U.S. Administration's priorities and urgent national need for understanding and addressing climate change and reducing greenhouse gas emissions, at least one of the estimated four selected proposals from Step 1 will prioritize Greenhouse Gases as one of its Targeted Observables. The final Announcement of Opportunity can be accessed at https://go.nasa.gov/ese2023ao.

6.3.3 Decadal Survey Incubation Activities

The Planetary Boundary Layer (PBL, https://science.nasa.gov/earth-science/decadal-pbl) and Surface Topography and Vegetation (STV, https://science.nasa.gov/earth-science/decadal-stv) Incubation Teams met for the first time in June 2023, and are expected to meet again in Fall 2023. The teams were established last year to inform program strategy and decisions in pursuit of Decadal Survey Incubation (DSI) program goals, which 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. While overall management of the program was assigned to ESTO, program activities are closely coordinated with NASA Earth Science Division's Research and Analysis (R&A) Program.

In April 2022, 35 awards were made under a NASA ROSES solicitation, of which 6 were for Technology tasks; 25 were Science tasks; 3 were for conducting Observing System Simulation Experiments (OSSE's), and 1 for Incubation Team Co-leadership. Information regarding the awarded proposals is available at: https://esto.nasa.gov/project-selections-for-dsi-21/.

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.

7 Additional Topics of interest to CGMS members

7.1 Senior Review

The Earth Science 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 every three years. At the invitation of ESD, each mission submits a formal proposal that documents the goals of the extension, the health and status of the satellite(s) and instrument(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.

In December 2022, three Earth Science ISS missions, GEDI, ECOSTRESS, OCO-3, proposed to an out of cycle Senior Review and were granted mission extensions through September 2026, in alignment with the next Senior Review Cycle.

The 2023 Earth Science Senior Review is currently underway. Twelve missions were invited to propose for mission extensions: Aqua, Aura, CYGNSS, DSCOVR (EPIC and NISTAR instruments), GPM, GRACE-FO, ICESAT-2, OCO-2, SAGE-III, SMAP, Terra, and TSIS-1. After evaluation by the review panels, a final report will be prepared and released by the end of fiscal year 2023. The final report from the 2020 Senior Review can be found at https://science.nasa.gov/earth-science/missions/operating.

7.2 Open-source Science

In early 2023, the White House Office of Science and Technology Policy (OSTP) announced new actions to advance open and equitable research. OSTP declared 2023 as the Year of Open Science, featuring actions across the federal government aiming to advance national open science policy, provide access to the results of the nation's taxpayer-supported research, accelerate discovery and innovation, promote public trust, and drive more equitable outcomes. To help build a culture of open science, NASA launched the Open-Source Science Initiative (OSSI). Open-source science is a commitment to the open sharing of software, data, and knowledge (algorithms, papers, documents, ancillary information) as early as possible in the scientific process. The principles of open-source science are to make publicly funded scientific research transparent, inclusive, accessible, and reproducible. Advances in technology, including collaborative tools and cloud computing, help enable open-source science, but technology alone is insufficient.

Open-source science requires a culture shift to a more inclusive, transparent, and collaborative scientific process, which will increase the pace and quality of scientific progress. OSSI is a comprehensive program of activities to enable and support moving science towards openness, including policy adjustments, supporting open-source software, and enabling cyberinfrastructure. OSSI aims to implement NASA's Strategy for Data Management and Computing for Groundbreaking Science 2019-2024, which was developed through community input.

The Science Mission Directorate (SMD) has released SPD-41a: Scientific Information Policy for the SMD (https://science.nasa.gov/science-red/s3fs-public/atoms/files/SMD-information-policy-SPD-41a.pdf) to provide guidance on the open sharing of publications, data, and software created in pursuit of scientific knowledge. SPD-41a builds upon the core principles of openness, equity, and security for SMD-funded research. The updates in SPD-41a policy reflect new federal guidance on Ensuring Free, Immediate, and Equitable Access to Federally Funded Research, studies from the National Academies, and input from the SMD scientific community.

SMD continues studying best practices and capabilities for future architecture and computational requirements to meet its Open-Source Science policies. Identified best practices and capabilities will inform plans for transitioning to a Data and Compute Infrastructure that

supports Open-Source Science policies. This includes providing new ways to discover scientific information including expanding the ability to search for relevant publications, data, and software.

Finally, Transform to Open Science is a 5-year NASA SMD initiative geared towards accelerating the adoption and understanding of open science with training and outreach. The program kicks off in a Year of Open Science 2023 with the initial opportunities for training and the public release of the curriculum. TOPS provides an opportunity for all researchers to become familiar with open science practices.

7.3 Earth Information Center (EIC)

In 2021, NASA Administrator Bill Nelson announced a concept for NASA's Earth Information Center; an opportunity for the agency to leverage its data and modeling capabilities to work with federal, state, local, and tribal partners in communities most affected by climate change. To demonstrate how actionable data and information can connect to a broad range of users for decision making, the Earth Information Center (EIC) showcases NASA and partner observations as the engine behind understanding our Earth as an integrated system. Through displays and interactive capabilities, the EIC supports decision makers, partners, and people in developing the tools they need to mitigate, adapt, and respond to our changing planet. The Earth Information Center allows visitors to see how our planet is changing in areas that affect lives and livelihoods - sea level rise, air quality, wildfires, greenhouse gases, sustainable energy, and agriculture. The EIC will open to public on June 26, 2023.

7.4 Commercial Smallsat Data Acquisition (CSDA) program

Established in 2020, the Commercial Smallsat Data Acquisition (CSDA) program aims to identify, evaluate, and acquire data from commercial sources that can complement NASA Earth science research and application goals.

In 2018, under a pilot program, NASA selected and augmented the funds of researchers whose ongoing research could potentially benefit from commercial data, and who had the expertise to adequately evaluate the usefulness of data for advancing NASA Earth science research and application goals. NASA provided commercial data to researchers by signing a Blanket Purchase Agreement (BPA) and End User License Agreement (EULA) with Planet Labs, DigitalGlobe (now known as Maxar Intelligence), and Spire Global, Inc. In April 2020, NASA released the results of evaluations, which found the commercial data and imagery useful for advancing NASA's Earth science research and applications goals.

In December 2022, the program completed the evaluation of Synthetic Aperture Radar (SAR) data from Airbus U.S (https://www.airbus.com/en/products-services/space/earth-observation/satellite-imagery). NASA ESD augmented funds of 26 existing research projects that had the expertise to fully utilize the datasets and advance their research and application goals. Optical data from Black Sky (https://www.blacksky.com/) is currently being evaluated by a team with expertise in optical data. The results of both these evaluations will be released in 2023. CSDA will begin evaluating the quality and usefulness of data from four commercial

vendors. These include, 1) Capella Space (https://www.capellaspace.com/); 2) ICEYE U.S. (https://www.iceye.com/en-us/); 3) GHGSat (https://www.ghgsat.com/en/), and 4) GeoOptics (https://geooptics.com/). Principal Investigators for evaluation were selected under solicitation A.43, ROSES 2022. Below is a brief description of the data that the vendors are providing.

Capella Space operates a constellation of SAR satellites in three different imaging modes: 1) Spotlight mode where the antenna beam is focused on a point on the Earth for an extended period. Data in the Spot mode is available at 0.5-meter resolution and 5 x 5 km scenes; 2) Sliding Spotlight mode, where instead of illuminating a fixed point on the ground, the acquisition angle is slowly varied to slide the illumination point along the ground. The Sliding spotlight provides excellent image resolution with larger area coverage than spotlight. Data in the Sliding spotlight mode is available at 0.8-meter resolution and 5 x 10 km scenes; 3) Strip map mode where the ground swath is illuminated with continuous sequence of pulses while the antenna beam is fixed in look angle. This results in a SAR image longer than both spotlight and sliding spotlight with a continuous image quality and resolution. Data in the Strip map mode is available at 1.2-meter resolution and 5 x 20 km scenes.

ICEYE U.S. is also operating SAR satellites that provide data in Dwell, Spot, Strip, and Scan imaging modes. Data in Dwell and Spot modes is available at 1 meter resolution at 5 and 15 sq-km scene size. The Strip and Scan mode data is available at 3- and 5-meter resolution and 30 x 50 km, and 100 sq-km scene sizes respectively.

GHGSat is operating a constellation of satellites that provide measurements of methane (CH_4) at 25-meter spatial resolution. Data products include, abundance datasets, concentration maps, and emission rates.

GeoOptics (https://geooptics.com/data/) is providing archived data from a constellation of satellites in low-earth orbit that use signal from Global Navigation Satellite System (GNSS) signals, such as the Global Positioning System (GPS), to examine the Earth's atmosphere. GeoOptics products include lower atmosphere bending angle, refractivity, and temperature and pressure profiles, as well as Total Electron Content (TEC) for the ionosphere.

A second solicitation, A.44 ROSES 2022 was also in released in November 2022 aimed at further promoting the sustained scientific use of purchased data (Planet Labs, Maxar, Spire, and Teledyne Brown Engineering) by the research and applied science communities.

The use of very high-resolution optical imagery from commercial sources for the purpose of assessing the amount of carbon stored outside of the African continent's dense tropical forests has been an outstanding success. An international team lead by scientists at GSFC mapped almost 10 billion individual trees in Africa's drylands and provided the first comprehensive estimate of tree carbon density in the Saharan, Sahel, and Sudanian zones of Africa. In March 2023, the team reported its findings in the journal *Nature* (Tucker et. al., 2023)[1]. The researchers found there are far more trees spread across semi-arid regions of Africa than previously thought, but that they also store less carbon than some models have predicted. Having an accurate tree carbon estimate is essential for climate change projections, which are influenced by how long (referred to as Carbon Residence Time, CRT) trees and other vegetation store carbon. The variable is referred to as the carbon residence time, and is very short for grasses and bushes, which grow seasonally, but much longer for trees that grow for years.

[1]Tucker, C., Brandt, M., Hiernaux, P. *et al.* Sub-continental-scale carbon stocks of individual trees in African drylands. *Nature* **615**, 80–86 (2023). https://doi.org/10.1038/s41586-022-05653-6

NASA fully recognizes the potential contribution data and imagery from commercial SmallSat constellations may have on advancing Earth science research and applications development. Significant partnerships include those with NOAA's Commercial Weather Data Pilot (CWDP) and Commercial Data Purchase (CDP) program, the Working Group for the Interagency Coordination of Commercial Weather Data (ICCWD), and ESA's Earthnet Data Assessment Pilot (EDAP). CSDA's contract vehicle is moving from Blanket Purchase Agreements (BPAs) to Multiple-Award Indefinite-Delivery, Indefinite-Quantity (IDIQ) contracts with Firm-Fixed-Price (FFP) task orders. NASA will continue to require End User License Agreements (EULAs) to enable broad levels of dissemination and shareability of the commercial data with the US government agencies and partners.

Data acquired by CSDA as well as data from the Teledyne Brown Engineering DLR Earth Sensing Imaging Spectrometer (DESIS) have been made available at no cost to researchers and are subject to scientific use licenses. Users may search, discover, and access NASA's commercial SmallSat data holdings, via the web based Smallsat Data Explorer (https://csdap.earthdata.nasa.gov/) tool. Planet and Spire data currently are mirrored in SDX. It also includes EarthDEM data products produced by the Polar Geospatial Center (PGC) at the University of Minnesota.

7.5 Global greenhouse gas monitoring

NASA is one of the many U.S. Government agencies that are actively participating in an Interagency Working Group (IWG) that aims to significantly enhance the national capability to understand, verify, and report sources and sinks of GHG emissions. A Greenhouse Gas Monitoring & Information Center is being established with the following strategic goals:

1. **Accelerate** GHG monitoring, measurement, reporting and verification decision support, connecting technology, tools, and data.
2. **Foster collaboration** with networks of interagency, intergovernmental, and private sector partners to co-develop and increase adoption of impactful applications.
3. **Promote scientific innovation and transparency** by leveraging advanced data systems capabilities and open-source science principles.
4. **Develop products** needed by users, updated on a regular basis, and enabled by advanced science-based capabilities.
5. **Establish bidirectional knowledge transfer** and engagement with federal, state, local and tribal governments, researchers, and the general public.
6. **Integrate diversity, equity and inclusion** in the Center's research, knowledge transfer, community engagement, management, and operations functions.

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 and other hardware, 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 the 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. This imager has significant overlap with the EMIT instrument on the ISS. EMIT, now nearing end of its prime mission that was extended until November 26, 2023, is expected to be used for locating methane sources and emission plumes above a certain threshold around much of the world.

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.

The third generation AVRIS, AVIRIS-3, will begin making measurements in 2023. Compared to AVIRIS-NG, AVIRIS-3 is a more compact instrument with 4x improved throughput and a wider field of view.

It is important to highlight that measurement concepts developed and refined through NASA airborne campaigns and EMIT 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. Western et al., (2023) combined measurements from AGAGE and NOAA surface-based networks with an atmospheric transport model to show how atmospheric abundances and emissions of five CFCs (CFC-13, CFC-112a, CFC-113a, CFC-114a and CFC-115) increased between 2010 and 2020, contrary to the goals of the phase-out set under the Montreal Protocol. While the impact of these emissions on stratospheric ozone recovery is anticipated to be small, the authors suggest that continued increase in emissions may negate some of the benefits gained from emission reductions achieved under the auspices of the Montreal Protocol. Information and insights enabled by ground-based networks is critical to effective monitoring of greenhouse gasses.

In 2012, NASA initiated the Carbon Monitoring System (CMS, 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.