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National Aeronautics and Space Administration

Office of Inspector General

Office of Audits

NASA's Earth Science Mission Portfolio

November 2, 2016

Report No. IG-17-003

Office of Inspector General

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RESULTS IN BRIEF

NASA's Earth Science Mission Portfolio

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November 2, 2016 IG-17-003 (A-15-014-00)

WHY WE PERFORMED THIS AUDIT

For more than 50 years, NASA has launched satellites and other scientific instruments into space to observe Earth and collect information on climate, weather, and natural phenomena such as earthquakes, droughts, floods, and wildfires. This Earth observation data provides individual citizens, commercial entities, and government and military organizations information to prepare for and react to weather phenomena and natural disasters, manage agricultural and other natural resources, and operate transportation systems.

NASA's Earth science missions are heavily influenced by external stakeholders including the President, Congress, other Federal agencies, and the National Research Council (NRC), which in 2007 issued a Decadal Survey identifying Earth science priorities and recommending NASA pursue 15 specific missions. In response, NASA's Earth Science Division (ESD) published *NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (Architecture Plan), which attempted to incorporate both the recommendations of the Decadal Survey and Presidential and congressional priorities, and described 20 Earth science missions the Agency planned to undertake.

In this audit, we assessed NASA's management of its Earth science portfolio to determine whether the Agency is effectively meeting stakeholder needs, how it is addressing challenges to implementing its Earth science priorities, and the ways in which stakeholders use the Earth observation data NASA collects. In addition, we reviewed the status of the 69 satellite and instrument missions in NASA's Earth science portfolio as of September 2016. To complete this work, among other things, we reviewed relevant NASA policies and procedures; assessed publicly available data regarding missions currently in planning, development, implementation, or operations; and interviewed relevant NASA officials and other stakeholders.

WHAT WE FOUND

NASA's Earth science portfolio adequately reflects stakeholder input, ESD's approach to developing the Architecture Plan was reasonable, and the Plan includes missions that address all six of the Agency's Earth science focus areas. However, due primarily to budget issues and the availability and affordability of launch vehicles, NASA has not carried out the Architecture Plan as intended and is increasingly reliant on an aging Earth observation infrastructure to monitor the planet. Specifically, although the Architecture Plan envisioned launching 17 missions by 2020, including 11 by the end of 2016, as of September 2016 the Agency had launched only 7 missions, and it is unlikely the others will launch on the schedule outlined in the Plan. Consequently, as missions are delayed the Architecture Plan has become increasingly outdated and includes missions that may become a lower priority for the science community. While the delays have not prevented NASA from substantially meeting stakeholder needs for Earth observation data, more than half the Agency's 16 operating missions have surpassed their designed lifespan and are increasingly prone to failures that could result in critical data loss and gaps in long-term observation records.

Over the past several decades, NASA has faced constraints affecting the management and balance of its Earth science portfolio, including (1) unrealistic cost estimates, (2) cost growth, (3) budgetary constraints, (4) changing priorities and direction from the President and Congress, (5) launch vehicle issues, and (6) mission and instrument failures. While ESD has taken steps to address these constraints by forming partnerships with other Government entities and foreign space agencies, improving the methodology for NRC Decadal Surveys (including the second Earth Science Decadal Survey expected in 2017), and extending current missions, these issues are likely to continue to affect the Agency's Earth science portfolio.

Over the past 15 years the number of products delivered to users by NASA has risen dramatically from about 8.14 million in 2000 to 1.42 billion in 2015. Government agencies, scientists, private entities, and other stakeholders rely on NASA to process raw information received from Earth observation systems into useable data. Moreover, NASA's Earth observation data is routinely used by government agencies, policymakers, and researchers to expand understanding of the Earth system and to enhance economic competitiveness, protect life and property, and develop policies to help protect the planet. Finally, NASA is working to address suggestions that it use commercially provided data to augment its Earth observation data. However, NASA must reconcile its policy that promotes open sharing of data at minimal cost to users with a commercial business model under which fees may create a barrier to use.

WHAT WE RECOMMENDED

To improve NASA's management of its Earth science portfolio, we recommended the Agency update the Architecture Plan every 5 years to align with the release of Earth Science Decadal Surveys and mid-term Surveys to account for portfolio changes, and develop strategies to engage with commercial companies to investigate cost-beneficial acquisition, disposition, and use of Earth observing data.

The Agency concurred with our recommendations and described planned actions. We find the actions responsive and will close the recommendations upon verification the Agency has taken the planned action.

For more information on the NASA Office of Inspector General and to view this and other reports visit http://oig.nasa.gov/.

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Acronyms

DAAC	Distributed Active Archive Centers
EOSDIS	Earth Observing System Data and Information System
ESD	Earth Science Division
FY	Fiscal Year
ISS	International Space Station
JASD	Joint Agency Satellite Division
JAXA	Japan Aerospace Exploration Agency
NOAA	National Oceanic and Atmospheric Administration
NPD	NASA Policy Directive
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPR	NASA Procedural Requirements
NRC	National Research Council
OIG	Office of Inspector General
USGS	U.S. Geological Survey

NOTE: For mission acronyms not listed on this page, see Appendix B.

INTRODUCTION

Weather- and climate-sensitive industries such as agriculture, insurance, real estate, and manufacturing account for up to 40 percent of the U.S. economy annually, or $4 trillion in 2010.[1] Moreover, climate, weather, and natural phenomena including earthquakes, droughts, floods, and wildfires affect the health and wellbeing of everyone on Earth.[2] Accordingly, space-based observations of these events and their associated causes and effects are essential to plan for and mitigate deleterious impacts.

For more than 50 years, NASA has developed and launched satellites and other scientific instruments into space to observe Earth (Earth observation systems) and has shared the data collected with academia, researchers, private industry, and the general public. Indeed, missions that are part of NASA's Earth science portfolio compose most of the United States' Earth observation infrastructure. In addition to its own projects, NASA assists other Federal agencies with developing, launching, and operating Earth observation systems. For example, between 1960 and 2011 NASA built more than 50 weather satellites used by the National Oceanic and Atmospheric Administration (NOAA) and other Government agencies. However, significant budget cuts in the early 2000s and debate regarding the appropriate level of NASA resources to dedicate to Earth observations has limited NASA's ability to advance its Earth observing technologies and launch new missions.

In this audit, we assessed NASA's management of its Earth science portfolio – with a particular focus on the low Earth orbit satellite and instrument missions that provide global coverage – to determine whether the Agency is effectively meeting the needs of its stakeholders. Specifically, we evaluated (1) how NASA has addressed stakeholders' priorities, (2) the challenges the Agency has faced implementing its priorities, and (3) the ways in which researchers and society access and use the data NASA collects. See Appendix A for details on the audit's scope and methodology.

Background

Earth science is the study of the Earth system, changes to that system, and the causes that underlie such changes. The Earth system involves the interaction of the planet's atmosphere (the layer of surrounding gases and aerosols), biosphere (the global ecological system integrating all living beings), cryosphere (the portions of the surface where water is in solid form, including sea ice, glaciers, and frozen ground), geosphere (solid parts), hydrosphere (the combined mass of water on, under, and over the planet), and pedosphere (the outermost layer composed of soil that lies below the vegetative cover of the biosphere and above the hydrosphere).

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[1] Dutton, J.A., Bulletin of the American Meteorological Society, "Opportunities and Priorities in a New Era for Weather and Climate Services, September 2002; National Research Council, "Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations," The National Academies Press, Washington, D.C., 2003; and National Oceanic and Atmospheric Administration, Budget Estimates Fiscal Year 2010, Congressional Submission.

[2] While weather is the measurement or assessment of atmospheric conditions over a geographical location at a particular moment in time, climate is the measurement of these conditions over an extended period of time, typically years.

NASA's Earth science missions collect regional and global Earth observation data on these systems. Ground sensors, airplanes, and unmanned aerial vehicles collect regional data while satellites collect data on a global scale. For example, NASA's S-Band Dual-Polarimetric Radar at Wallops Flight Facility makes site specific measurements of precipitation, including rainfall rate, particle size distribution, water content, and precipitation type. This data is then used to inform and validate the algorithms used on the Agency's Global Precipitation Measurement (GPM) satellite mission, which collects data regarding rain and snow precipitation throughout the world.[3]

Earth observation data provides decision makers at all levels, from individual citizens to commercial entities to government and military organizations, information to prepare for and react to weather phenomena and natural disasters, manage agricultural and other natural resources, and operate transportation systems. Individuals routinely use Earth observation data to inform decisions about where to travel, what to wear, and how to react to inclement weather. More broadly, such information is vital to operating modern transportation systems and helping prepare society for the potential changes scientists predict could occur as a result of global warming. To that end, NASA's policy is to share the Earth observation data the Agency collects so it can be used to address basic Earth science questions and develop practical applications to benefit the public.

History of Earth Science at NASA

The National Aeronautics and Space Act of 1958 gives NASA responsibility for conducting activities that contribute to "the expansion of human knowledge of phenomena in the atmosphere and space."[4] In the 1960s, Congress began funding activities to study the Earth and its resources, and NASA efforts initially focused on improving weather prediction through the use of satellites. In 1976, the Act was amended to give the Agency authority to undertake stratospheric ozone research. The Act was again revised in 1984 to give the Agency responsibility for "the expansion of human knowledge of the Earth." In 1987, NASA introduced its "Mission to Planet Earth" with two objectives: (1) establish a space-based global observational system and (2) use the data collected to document, understand, and eventually predict global change. NASA followed this effort in the 1990s when the Agency established the Earth Observing System Program with the primary purpose of making Earth observations from space to model climate change. In November 1997, the Program launched NASA's first Earth Observing System instrument aboard the Tropical Rainfall Measuring Mission satellite to gather rainfall data to inform weather and climate models. Although designed to operate for 3 years, the Mission was extended multiple times and collected data for more than 17 years before NASA ended it in April 2015.

Over the past 4 decades NASA has launched more than 110 low Earth orbit satellite and instrument missions related to Earth science. However, despite numerous successes NASA's Earth science activities have not been without controversy. For example, in the mid-1990s Congress debated the merits and affordability of NASA's Mission to Planet Earth and on occasion crafted appropriations language that reduced funding for the Agency's Earth science programs to pay for planetary science and other priorities. This debate has continued and from time to time intensified as governments around the world focus more attention on global climate change and the role of human activity in that change.

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3 GPM, launched in February 2014, is an international satellite mission to provide observations of rain and snow worldwide every 3 hours.

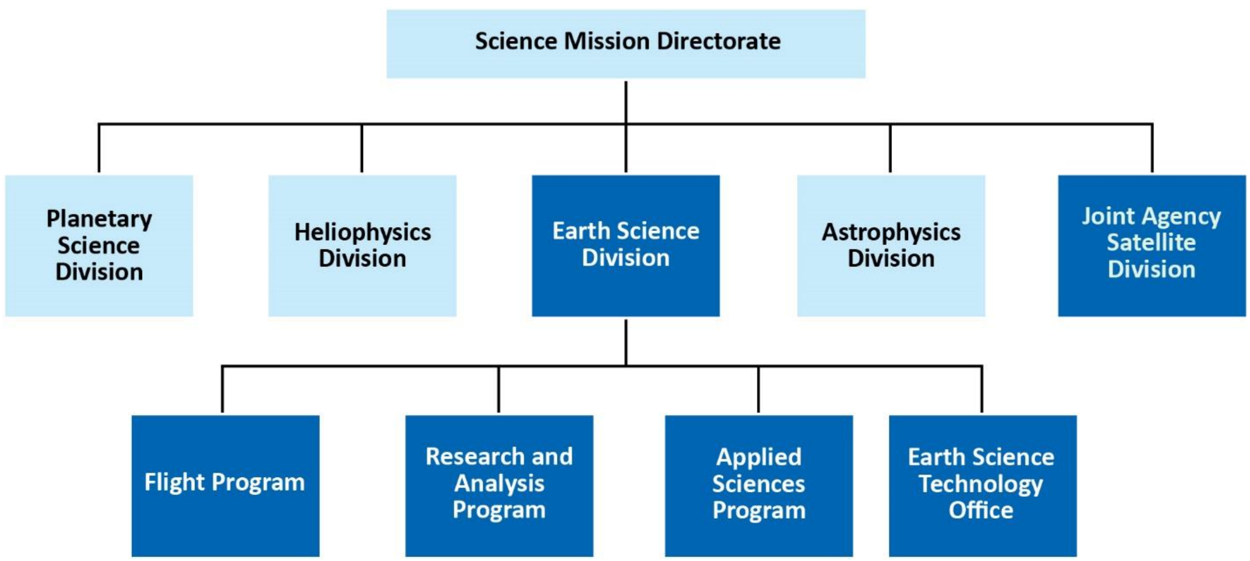
4 National Aeronautics and Space Act of 1958, Pub. L. No. 85-568, July 29, 1958.

Furthermore, while extending missions such as the Tropical Rainfall Measuring Mission beyond their original design lives has increased NASA's return on investment, it has also resulted in a constellation of aging Earth observation instruments.

Management of NASA's Earth Science Portfolio

NASA's Earth Science Division (ESD) is responsible for developing and operating the Agency's Earth science missions. Additionally, NASA's Joint Agency Satellite Division (JASD) assists other Federal agencies in developing Earth observation systems and serves as the Agency's liaison for projects requested by external customers. As shown in Figure 1, both ESD and JASD are part of NASA's Science Mission Directorate.

Figure 1: Science Mission Directorate Organizational Structure



Source: NASA Office of Inspector General (OIG) presentation of NASA information.

Earth Science Division

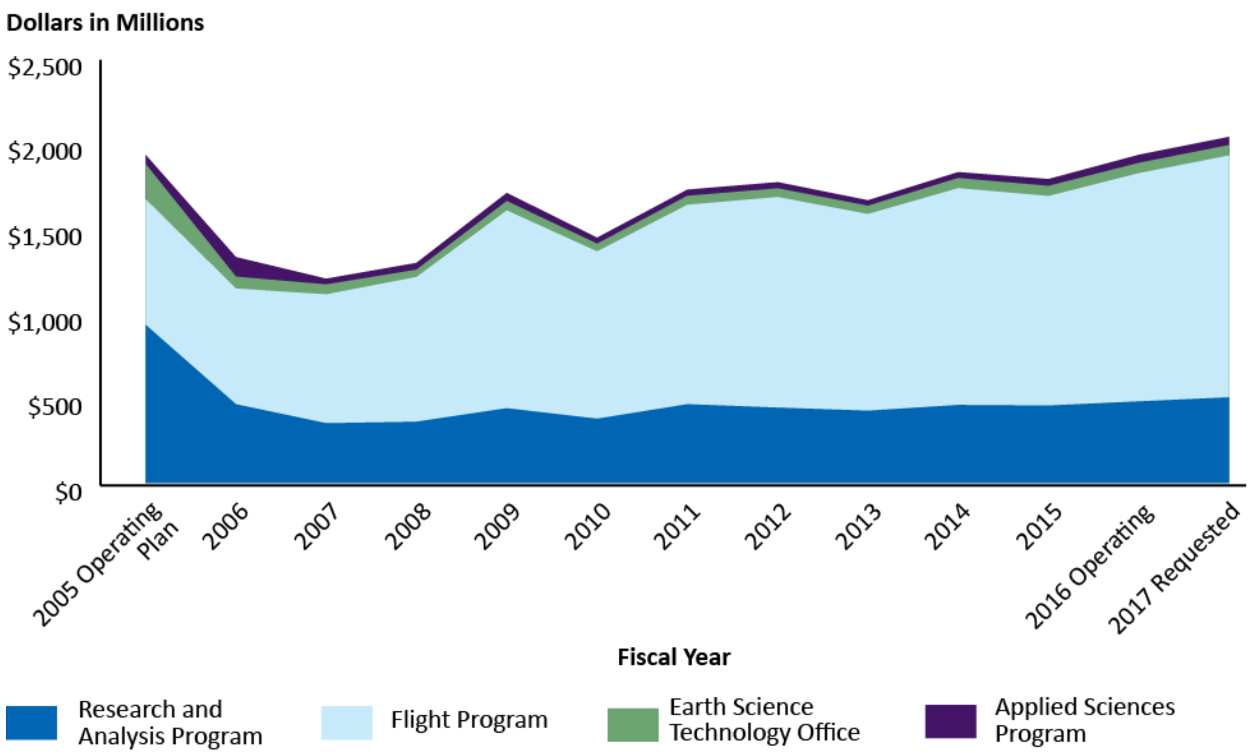
ESD is divided into four components – the Flight Program, the Research and Analysis Program, the Applied Sciences Program, and the Earth Science Technology Office. The four components are responsible for (1) developing technologies; (2) formulating, developing, and operating missions; and (3) producing, collecting and disseminating resulting data to characterize the present state and predict the future evolution of the Earth system.

- The Flight Program manages 49 low Earth orbit satellites or standalone instruments in various stages of development and operation. (See Appendix B for a complete listing of and detailed information about these projects.) Responsibility for these satellites and instruments is divided between the Earth Systematic Mission Program and the Earth System Science Pathfinder Program. The former includes a broad range of investigations aimed at developing a scientific understanding of the Earth system and how it responds to natural and human-induced forces, while the latter focuses on new and innovative techniques to address scientific priorities and includes Earth Venture missions with budgets of less than $150 million. The Flight Program also manages the Agency's Earth Observing System Data and Information System (EOSDIS). Established in 1994, EOSDIS utilizes 12 Distributed Active Archive Centers (DAAC) to process, distribute, and archive the majority of ESD mission data.[5]

- The Research and Analysis Program and the Applied Sciences Program oversee and fund ESD's effort to make Earth observation data understandable to and useful for researchers and members of the public. For example, the Research and Analysis Program's Carbon Monitoring System team identifies how data can be used to characterize, quantify, and predict the evolution of global carbon sources and areas that remove carbon dioxide from the atmosphere known as sinks. Changes to these sources and sinks can impact food security, human health, and water quality.
- The Earth Science Technology Office portfolio includes more than 100 investments for advanced technologies to enable new Earth science measurements, missions, operational requirements, and practical applications.

From fiscal year (FY) 2013 through FY 2016, ESD's average annual budget was approximately $1.8 billion. Figure 2 shows the funding for each ESD component from FYs 2005 to 2017.

Figure 2: ESD Budget by Component

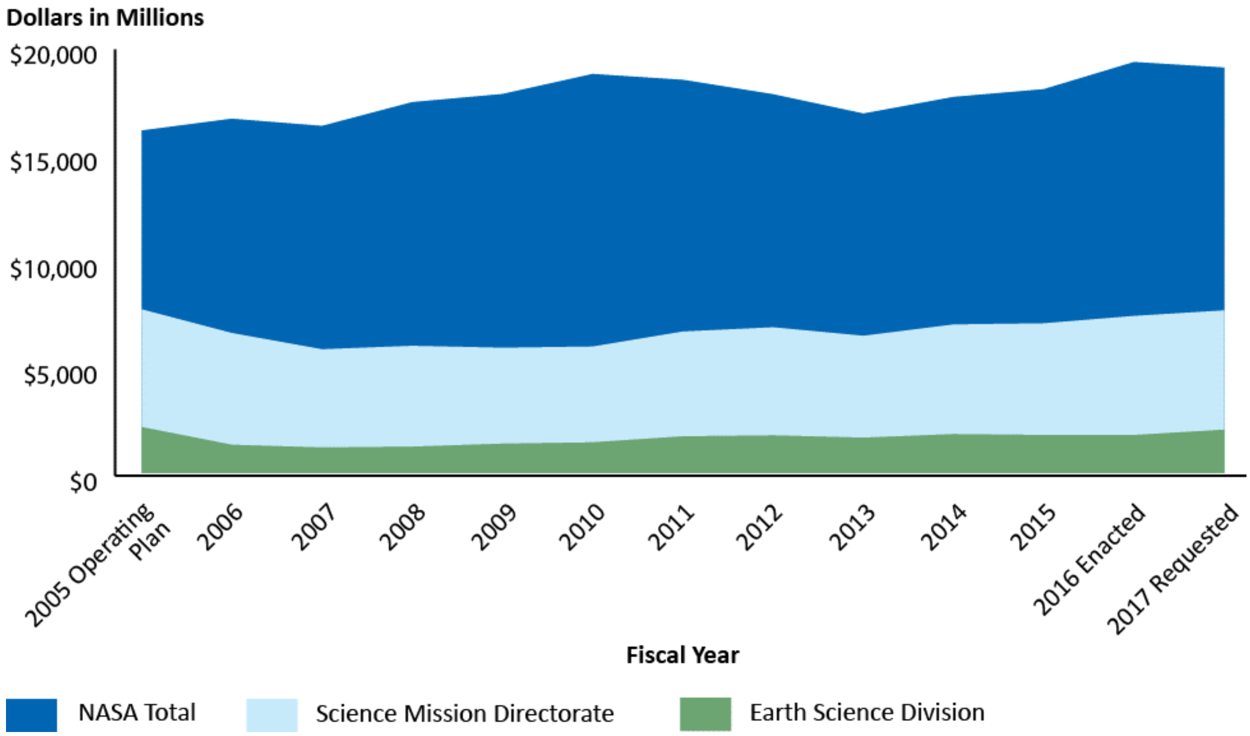


Source: NASA OIG analysis of ESD budget data.

[5] DAACs are located at sites across the country, primarily at NASA Centers, National laboratories, and NOAA facilities. More information on NASA's DAACs can be found at https://earthdata.nasa.gov/about/daacs (last accessed October 13, 2016).

Although ESD's budget increased from about $1.2 billion in FY 2007 to $1.93 billion in FY 2016, it remained slightly below its peak of $2 billion (adjusted for inflation) in FY 2000.[6] Moreover, as shown in Figure 3, as a percentage of the overall NASA and Science Mission Directorate budgets, ESD's budget has remained relatively consistent, accounting for an average of about 11 percent and 33 percent, respectively.

Figure 3: ESD Budget Compared to Agency and Science Mission Directorate Budget



Source: NASA OIG analysis of NASA budget data.

In 2005, a National Research Council (NRC) report questioned reductions to ESD's budget that began around 2000. The report linked budget cuts to mission cancellations, de-scoping, and delays and stated that as a result the Agency's Earth observation program was at risk and opportunities to discover new knowledge diminished.[7] In 2007, NRC recommended NASA's Earth science funding levels be restored to pre-2000 levels.[8]

[6] For FY 2017, NASA requested $2.03 billion for ESD.

[7] NRC, "Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation," 2005.

[8] NRC, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," 2007. In a NASA OIG report, "Investigative Summary Regarding Allegations that NASA Suppressed Climate Change Science and Denied Media Access to Dr. James E. Hansen, a NASA Scientist," June 2, 2008, we reported that Earth science funding decreased by about 37 percent between FYs 2001 and 2006.

Joint Agency Satellite Division

NASA established JASD in April 2010 in an effort to ease strained relationships between the Agency, NOAA, and the U.S. Air Force relating to management of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), a joint satellite program that suffered significant cost overruns and schedule delays.[9] JASD is charged with assisting other Federal agencies with their Earth observation systems by coordinating NASA expertise provided on a reimbursable basis. These projects are planned in coordination with NASA, but funded and operated by the other agencies. As of September 2016, JASD was assisting NOAA with eight Earth observation missions. See Appendix B for more information about these missions.

As of September 2016, there were 69 Earth observing satellite and instrument missions in various stages of development and operation that NASA had direct involvement (see Figure 4). Specifically, ESD had 33 missions in development and 16 in operation – 10 of which had been extended beyond their initial operations period. JASD had 8 NOAA missions in development, NOAA was operating 10 missions, and the U.S. Geological Survey (USGS) was operating 2 Landsat missions.[10]

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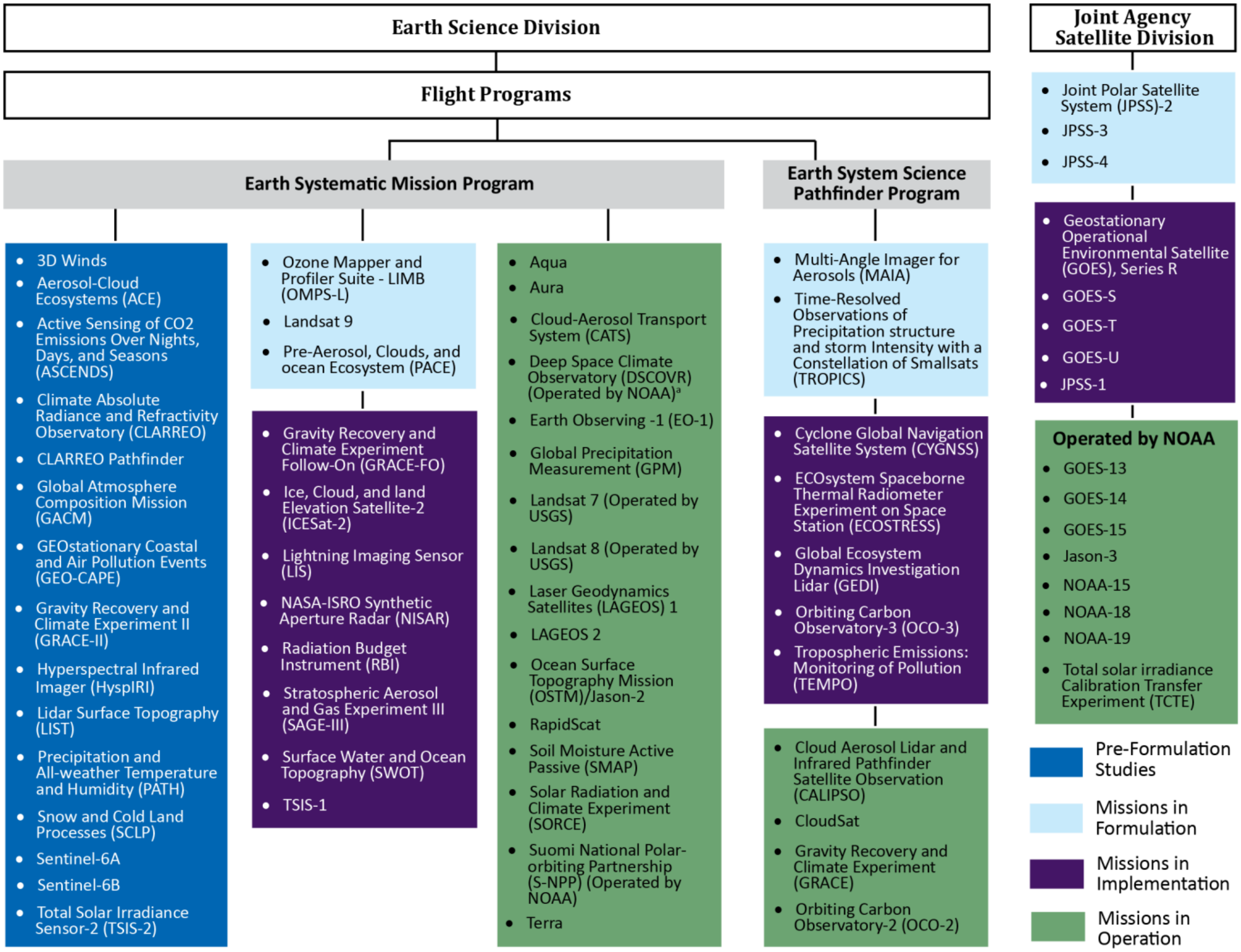
[9] NPOESS was intended to bring together existing polar satellite observation systems operated by the Departments of Commerce and Defense to create an integrated system to monitor global environmental conditions and collect and disseminate data related to weather, atmosphere, oceans, land, and near-space environment. The White House dissolved the partnership in February 2010 due to cost, schedule, and performance issues and established NASA's role in the procurement and development of NOAA satellite missions, such as the Joint Polar Satellite System, which resulted in creation of JASD.

[10] In contrast to the NOAA missions, NASA funds development of the Landsat satellites, which are then turned over to USGS who has primary responsibility for funding their on-orbit operations.

Figure 4: NASA Earth Science Missions



Source: OIG presentation of Science Mission Directorate information.

[a] DSCOVR, formerly known as Triana, was built by NASA before the mission was cancelled and the satellite put into storage in 2001. In 2012, the satellite was brought out of storage as a NOAA-led mission in partnership with NASA and the Air Force. NASA operates two instruments on the mission.

Earth Science Focus Areas

NASA divides the study of Earth science into six focus areas: Atmospheric Composition, Carbon Cycle and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather. We provide more detail about each area below.

Atmospheric Composition

This focus area involves understanding the Earth's radiation balance, air quality, and ozone layer. NASA's Aqua and Terra satellites, which corroborate pollution sources reported in the Environmental Protection Agency's Air Quality Index, are examples of resources that collect data related to this focus area.[11] Part of many weather reports, the Air Quality Index provides information on the level of air pollution in particular places at particular times and allows individuals sensitive to elevated pollution levels to take appropriate steps to protect themselves from adverse health effects.

Carbon Cycle and Ecosystems

The Carbon Cycle and Ecosystems focus area involves the detection and prediction of Earth's ecological and biogeochemical cycles, including focus on land cover, biodiversity, and the global carbon cycle. Information in this area is used to inform conservation policies and efforts. For example, researchers at New York's Stony Brook University are using remote sensing technology from Aqua and Landsat, a joint program between USGS and NASA that has operated and provided continuous topographical monitoring for more than 40 years, to identify changes to penguin population size and distribution, data points that serve as key indicators of the health and status of the Southern Ocean ecosystem.[12]

Climate Variability and Change

This focus area involves understanding the roles and interactions of the oceans, land, and ice in the climate system. The U.S. Global Change Research Program anticipates national economic losses of $1.2 trillion through 2050 due to extreme weather events as a result of climate change.[13] Multiple NASA missions focus on understanding climate change and developing strategies to mitigate losses. For example, the Gravity Recovery and Climate Experiment (GRACE) tracks climate-related changes in groundwater and water storage for the National Drought Mitigation Center, which helps develop and implement measures to reduce societal vulnerability to drought.[14]

Earth Surface and Interior

The Earth Surface and Interior focus area involves characterization of the Earth's surface and interior and the assessment of responses to natural hazards and extreme events. Information in this focus area provides data to assess, mitigate, and forecast natural disasters such as earthquakes, fires, landslides, tsunamis, and volcanic eruptions. For example, the U.S. Forest Service relies on NASA satellites to detect wild fires and provide real-time fire maps.

Water and Energy Cycle

This focus area involves understanding the transfer and storage of water and energy in the Earth system. Knowledge about water quality and quantity – derived in part from NASA's GPM and Soil Moisture Active Passive (SMAP) missions – has a direct impact on the communities and businesses along the

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[11] Aqua launched in May 2002 to study Earth's water cycle. Terra launched in December 1999 to study Earth's atmosphere, ocean, land, snow, and ice.

[12] Landsat 8 launched in February 2013 and provides coverage of continental Earth surfaces.

[13] The U.S. Global Change Research Program was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act of 1990 to help understand, assess, predict, and respond to human-induced and natural processes of global change.

[14] GRACE launched in 2002 to study the effect of gravity on Earth's surface, including oceans and land masses.

coastal shoreline, home to 39 percent of the U.S. population and an area that accounts for roughly half of the output of the U.S. economy.[15]

Weather

The Weather focus area entails the capability to predict weather and extreme weather events. Missions such as GPM and NOAA's Geostationary Operational Environmental Satellites (GOES) measure rainfall and other characteristics of weather to improve our understanding of severe storms and support flood and drought monitoring and forecasting.[16] Since 1980, the United States has experienced 196 weather- and climate-related disasters with losses exceeding $1 billion each with the total cost of these events exceeding $1.1 trillion.[17]

Earth Science Stakeholders

NASA's Earth science missions are heavily influenced by external stakeholders, including the President, Congress, other Federal agencies, academia, and researchers. The President and Congress establish national policy through laws and Executive Orders and make decisions about program funding. For example, the National Aeronautics and Space Administration Authorization Act of 2010 charged the Director of the Office of Science and Technology Policy with producing a strategic plan for Earth observations.[18] The resulting National Plan for Civil Earth Observations tasked NASA with conducting sustained satellite observations for research to advance understanding of changes to the Earth system and related climate change.[19]

Federal agencies that rely on NASA's global observations also influence the Agency's Earth observation priorities. For example, in the mid-1960s USGS proposed developing a land imaging satellite program that ultimately led to the joint NASA-USGS Landsat Program. Landsat, which has operated for more than 40 years and provides the longest continuous global record of the Earth's surface, has enabled scientists to assess changes over time.[20]

Beyond Government stakeholders, NRC provides NASA with input from Earth science experts and users of Earth observation data and makes recommendations for programs and projects through reports and surveys. As discussed in more detail in the following section, the NRC's Decadal Surveys are the primary mechanism for the scientific community to provide input into NASA missions.

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[15] SMAP launched in January 2015 to study soil moisture and freeze-thaw conditions.

[16] The GOES series of satellites helps the National Weather Service detect and track severe weather such as hurricanes. The current operating series includes GOES N through P satellites – designated GOES-13, -14, and -15 on orbit – that were launched in 2009 and 2010.

[17] As of September 2016. See http://www.ncdc.noaa.gov/billions/events for a listing of the events (last accessed October 13, 2016).

[18] National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267, § 702.

[19] Office of Science and Technology Policy, "National Plan for Civil Earth Observations," July 18, 2014.

[20] Landsat 1 launched in July 1972 and Landsat 8, the latest satellite in the series, in 2013. Landsat 9 is in formulation and planned for launch in FY 2021.

Earth Science Decadal Survey

In 2004, NASA, NOAA, and USGS requested NRC conduct the first Earth Science Decadal Survey, issued in 2007. The request was part of a trend of increasing reliance on NRC to identify science priorities and provide support and assistance in developing NASA budget requests. For the 2007 Decadal Survey, a committee of experts from 68 Government, academic, and commercial institutions requested proposals from the science community for Earth science programs and missions. The committee reviewed 135 proposals and based on criteria – such as affordability, readiness, risk level, and fit with other missions – recommended NASA pursue 15 specific missions, which the committee divided into three tiers by priority (as shown in Table 1).[21] For these missions the committee assumed an ESD budget of $2 billion per year and calculated rough estimates of the cost of each proposed mission. The NASA Authorization Act of 2010 directed NASA to implement the missions NRC had recommended "as appropriate" and "within the scope" of ESD's authorized budget.[22] NASA has incorporated the missions into its Earth science planning and operational efforts.

Table 1: NRC 2007 Decadal Survey Missions

Mission	Description	Rough Cost Estimate, FY 2006 (Dollars in Millions)
Tier 1 (Launch Dates 2010–2013)		
Climate Absolute Radiance and Refractivity Observatory (CLARREO) (NASA portion)	Solar and Earth radiation; spectrally resolved forcing and response of the climate system	$200
Soil Moisture Active Passive (SMAP)	Soil moisture and freeze-thaw for weather and water cycle processes	$300
Ice, Cloud, and land Elevation Satellite-2 (ICESat-2)	Ice sheet height changes for climate change diagnosis	$300
Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI)	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	$700
Tier 2 (Launch Dates 2013–2016)		
Hyperspectral Infrared Imager (HyspIRI)	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	$300
Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)	Day/night, all-latitude, all-season carbon dioxide column integrals for climate emissions	$400
Surface Water Ocean Topography (SWOT)	Ocean, lake, and river water levels for ocean and inland water dynamics	$450
Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	$550
Aerosol-Cloud-Ecosystems (ACE)	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	$800

[21] NRC, "Earth Science and Applications from Space," 2007.

[22] National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267, § 704.

Mission	Description	Rough Cost Estimate, FY 2006 (Dollars in Millions)
Tier 3 (Launch Dates 2016–2020)		
Lidar Surface Topography (LIST)	Land surface topography for landslide hazards and water runoff	$300
Precision and All-Weather Temperature and Humidity (PATH)	High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea-surface temperature	$450
Gravity Recovery and Climate Experiment (GRACE-II)	High-temporal-resolution gravity fields for tracking large-scale water movement	$450
Snow and Cold Land Processes (SCLP)	Snow accumulation for freshwater availability	$500
Global Atmospheric Composition Mission (GACM)	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	$600
Three-Dimensional Tropospheric Winds from Space-based Lidar (3D-Winds)	Tropospheric winds for weather forecasting and pollution transport	$650

Source: NRC 2007 Decadal Survey.

In late 2010, NASA asked NRC to review its efforts to respond to the 2007 Decadal Survey.[23] The resulting report noted that while NASA had "made major investments toward the missions recommended by the survey and . . . realized important technological and scientific progress as a result," the Agency was implementing the "vision" of the Survey at a far slower pace than NRC had envisioned.[24] NRC made several recommendations for improvement, including that NASA consider cost constraints to ensure mission objectives could be achieved and that the Agency secure reliable and affordable launch capabilities for its missions. NASA has made an effort to implement the recommendations. For example, the Agency designed several projects to be flown on the International Space Station (ISS) instead of as "free-flyers" that require their own launch vehicle.[25] In January 2016, the NRC began work on the next Earth Science Decadal Survey. Expected to issue in 2017, the new Survey will identify the science community's priorities through 2027.

[23] The review responded to a mandate in the NASA Authorization Act of 2005 that "the performance of each division in the Science directorate of NASA shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals." National Aeronautics and Space Administration Authorization Act of 2005, Pub. L. No. 109-155, § 301.

[24] NRC, "Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey," 2012.

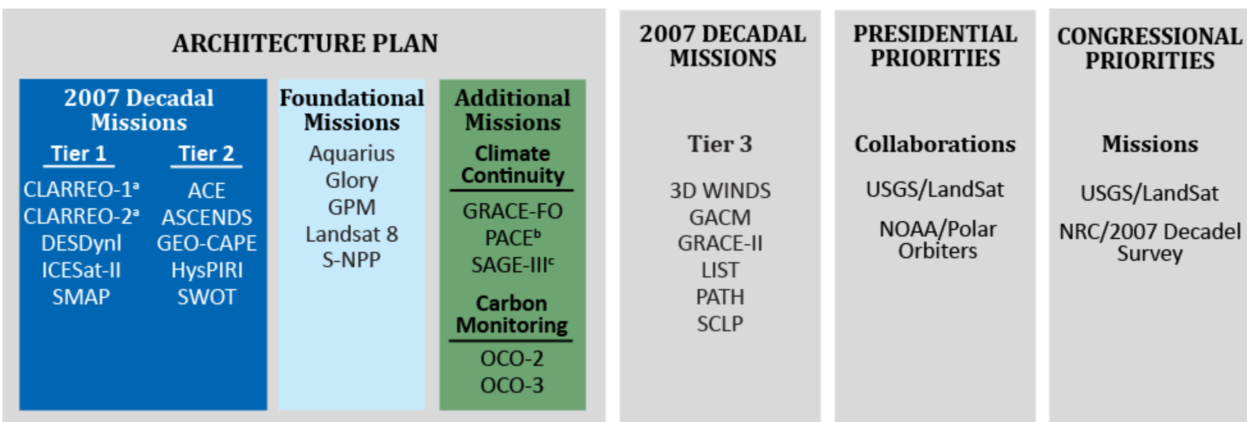
[25] Examples include the Orbiting Carbon Observatory-3 and the Stratospheric Aerosol, Gas Experiment III instruments, both of which are discussed later in this report.

2010 Architecture Plan

After issuance of the 2007 Decadal Survey, ESD published *NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (Architecture Plan), establishing a strategic plan for NASA Earth science observations.[26] The objectives of the Architecture Plan was to present a realistic program for ESD activities informed by the 2007 Decadal Survey, be sensitive to Administration priorities, and be realistically executable within the constraints of the President's proposed FY 2011 budget, which anticipated a budget of about $10.3 billion through FY 2015. As such, the Architecture Plan served to translate Decadal aspirations and Presidential and congressional priorities into a plan that could be advanced given expected budget levels.

The Architecture Plan set out 20 missions, including 5 "foundational missions" already in development at the time the Plan was issued (see Figure 5).[27] According to the Plan, 17 of the missions were scheduled to launch by 2020, while 3 others – ACE, GEO-CAPE, and HyspIRI – were scheduled to launch after 2020.[28] Furthermore, the Architecture Plan included (1) accelerated development of all four Tier 1 missions from the 2007 Decadal Survey, (2) acceleration and expansion of Earth Venture missions, (3) initiation of new space missions to ensure continuity in high-priority climate observations, (4) accelerated launch of two Decadal Tier 2 missions (ASCENDS and SWOT) by 2020, and (5) development of Orbiting Carbon Observatory (OCO)-2 to replace the OCO mission that failed on launch in February 2009.[29]

Figure 5: NASA's Missions by Stakeholder



Source: NASA OIG analysis.

[a] The 2007 Decadal Survey described CLARREO as a single mission with two separate components – one for NASA and one for NOAA. When ESD incorporated the mission into the 2010 Architecture Plan, it became known as the CLARREO-1 and -2 missions. According to ESD officials, the missions have recently been combined back to a single CLARREO mission.

[b] The PACE mission will make global ocean color measurements essential for understanding the carbon cycle and how it both affects and is affected by climate change.

[c] The SAGE-III instrument is used to study ozone, a gas found in the upper atmosphere that acts as Earth's sunscreen.

[26] NASA, "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space," June 2010.

[27] The 2007 Decadal Survey characterized the foundational missions as necessary precursors to several recommended missions.

[28] Although the Architecture Plan references the Tier 3 missions, they were not included because their launch dates are well beyond 2020.

[29] OCO and OCO-2 were designed to measure carbon dioxide in the atmosphere. OCO-2 successfully launched in July 2014.

Earth Science Portfolio Adequately Reflects Stakeholder Input, But Current Operations and Planned Launches Face Constraints

NASA's Earth science portfolio adequately reflects stakeholder input, ESD's approach to developing the Architecture Plan was reasonable, and the Plan includes missions that address all six Earth science focus areas. However, due primarily to budget issues and the availability and affordability of launch vehicles, NASA has not carried out the Architecture Plan as intended and is increasingly reliant on an aging Earth observation infrastructure to monitor the planet. Specifically, NASA has delivered only 7 of the 20 missions identified in the Plan, and many of the 13 remaining missions will not be delivered on the planned timetable. Moreover, more than half of the Agency's 16 operating missions have surpassed their designed lifespan and are increasingly prone to failures that could result in critical data loss and gaps in long-term observation records.

Earth Science Division Created a Reasonable Plan

ESD used a reasonable approach to identify the 20 missions called for in the Architecture Plan by considering missions already in operation, consulting the 2007 Decadal Survey, and incorporating directives and laws that call for global climate change research and carbon monitoring. The 20 missions include 5 foundational missions already in development by 2010; all Tier 1 and Tier 2 missions called for in the 2007 Decadal Survey; and 5 other missions designed to address laws and Presidential directives. Although JASD missions, such as the GOES and Jason series, were not included in the Plan, NASA considered the needs and desires of partners and stakeholders such as NOAA, the Department of Defense, and foreign space and environmental agencies when devising the Plan.[30]

Ongoing and Planned Earth Observation Missions Respond to Stakeholder Input

We identified 26 directives or requests in laws, an Executive Order, and other Presidential policies related to Earth science observations since 2000, including 6 that directed or requested specific missions. We found NASA has responded to these laws and policies through the Architecture Plan or other ESD or JASD missions.

[30] The Jason satellite series provides ocean topography measurements to gain insight into ocean circulation and climate change.

Presidential and Congressional Requests

Between 2000 and 2016, the President and Congress directed or requested six specific NASA Earth observation missions and provided other guidance on prioritizing Earth observation research. For example, the 2000 NASA Authorization Act directed NASA to collect data related to agriculture and the carbon-cycle, while President Bush's 2006 National Space Policy requested the Agency support disaster response and recovery, work with USGS to provide land remote sensing, and continue polar-orbiting environmental satellite observations.[31, 32] Thereafter, the 2008 NASA Authorization Act directed the Agency to undertake the Deep Space Climate Observatory (DSCOVR) and Glory missions and cooperate with NOAA to study severe storms and tornadoes.[33] The 2010 NASA Authorization Act then directed the Agency to launch the 2007 Decadal Survey missions that fit within its budget, requested priority for activities focused on climate change, and emphasized the importance of continued collaboration with NOAA on NPOESS and other polar orbiters.[34]

NASA addressed all of these requests and directives through the Architecture Plan, missions that existed before the Plan was established, or missions overseen by JASD. Specifically, the Plan includes 10 missions called for in the 2007 Decadal Survey; 3 missions related to climate-focused observations, including follow-ons to the existing GRACE and Stratospheric Aerosol and Gas Experiment (SAGE) missions; 2 missions to replace the failed OCO mission; and 5 missions already under development in 2010 that addressed other requests, including Glory, Landsat 8, and Suomi National Polar-orbiting Partnership (S-NPP). In addition, JASD continues to assist NOAA by building weather satellites – including GOES and Joint Polar Satellite System (JPSS) – and launched DSCOVR in February 2015.

Science Community

The Architecture Plan does not include implementation of the Tier 3 missions identified in the 2007 Decadal Survey because of (1) lack of funding, (2) higher priority science observation needs, (3) planned and current availability of spare instruments, and (4) technology readiness of scientific instruments.

The 2007 Decadal Survey assumed ESD's budget would increase to approximately $2 billion in 2010. Similarly, the Architecture Plan considered the feasibility of missions within the President's FY 2011 budget request of $1.8 billion and out-years increasing to at least $2 billion. Moreover, some missions the Survey identified as requiring new technology development, such as GRACE-II, were deferred and replaced in the near-term with missions that relied on existing technology.

In addition, in devising the Architecture Plan, ESD considered instruments that were already available and ready or nearly ready for launch. For example, when building OCO-2, NASA procured sufficient spare parts to build a replacement if that mission, like its predecessor, was to fail. The availability of these parts meant NASA could build OCO-3 relatively cheaply. Accordingly, after the successful launch of OCO-2 in July 2014, ESD decided to fly OCO-3 on the ISS. Similarly, ESD flew a spare SAGE instrument on the ISS to expand on 25 years of ozone measurements.

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[31] National Aeronautics and Space Administration Authorization Act of 2000, Pub. L. No. 106-391, § 315-316.

[32] U.S. National Space Policy, August 31, 2006.

[33] National Aeronautics and Space Administration Authorization Act of 2008, Pub. L. No. 110-422, § 206-208. The DSCOVR mission, which provides advanced warning of solar weather events, is a partnership between NASA, NOAA, and the Air Force. Glory was launched in March 2011 to measure aerosols such as black carbon soot and solar irradiance but was lost in a launch failure.

[34] National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267, § 702 and 704.

Lastly, although technological development of many Tier 2 and Tier 3 missions began immediately after the 2007 Decadal Survey, some technologies developed more slowly than others and required larger financial investments than expected. To address resource availability, technology readiness, and science needs, ESD developed a modified time frame for launching Tier 2 missions, and included additional missions that did not require significant further development. For example, the SWOT mission was selected as an accelerated Tier 2 mission because it leveraged several prior NASA technology development investments in radar interferometry. Meanwhile, ACE, GEO-CAPE, and HyspIRI mission launches were delayed until after 2020 to allow for additional technological development. We believe this was a reasonable approach to integrating the input of the science community.

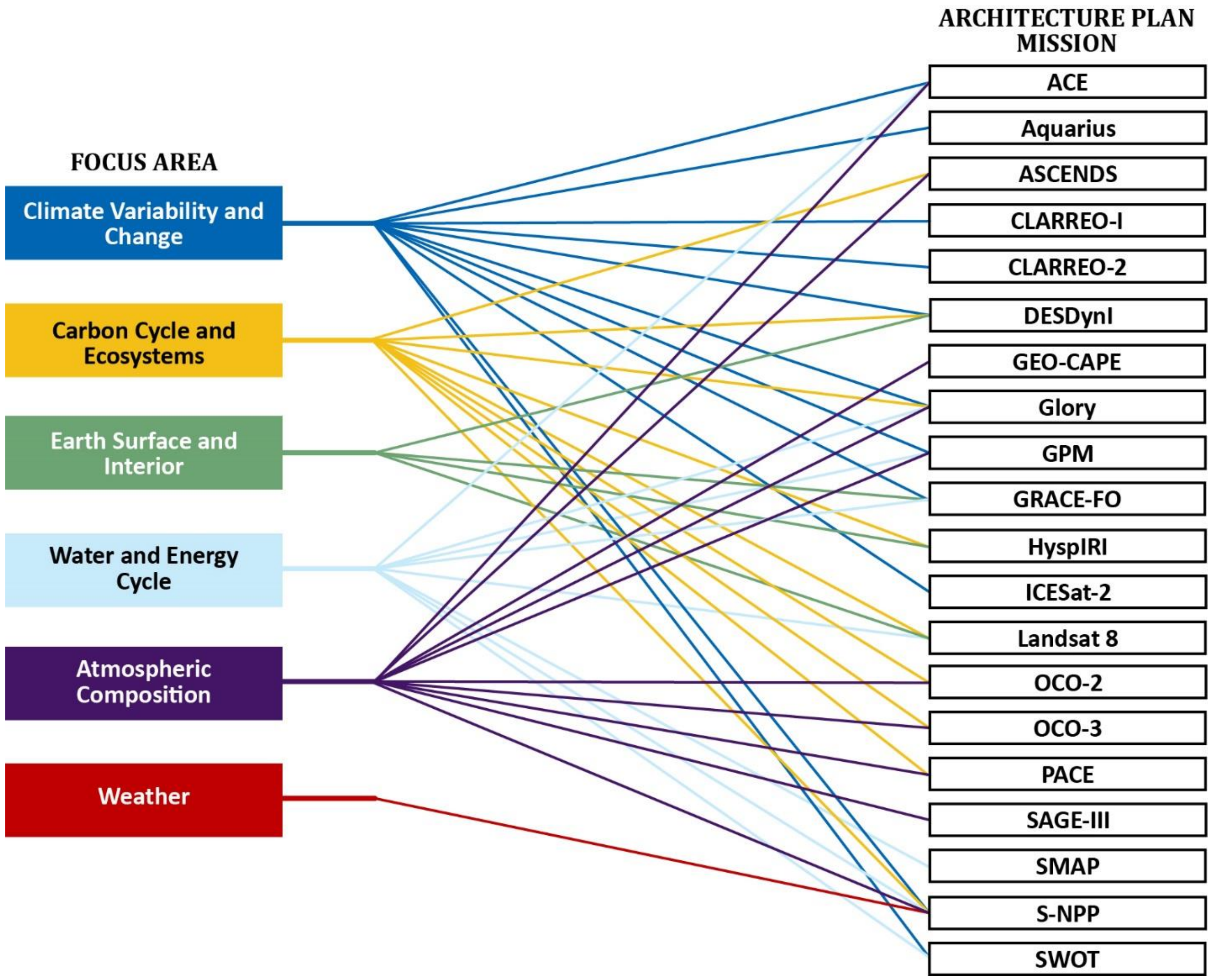
The Architecture Plan also included several management practices NRC had recommended to improve the affordability and operation of NASA's Earth science portfolio. For example, ESD expanded its Earth Venture Program, which provides competitive opportunities for missions that cost less than $150 million.[35] Earth Venture missions currently under development include Cyclone Global Navigation Satellite System (CYGNSS), aimed at improving extreme weather prediction; ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which will study plant-water dynamics; Global Ecosystem Dynamics Investigation Lidar (GEDI), which characterizes the effects of changing climate and land use on ecosystems; and Tropospheric Emissions: Monitoring of Pollution (TEMPO), which will measure atmospheric pollution over North America.

Architecture Plan Addresses All of NASA's Science Research Focus Areas

The Architecture Plan includes missions that support each of NASA's Earth science focus areas. Because Earth science is a study of multiple interrelated systems, a single mission may address multiple focus areas. For example, the ACE mission addresses Climate Variability and Change, Carbon Cycle and Ecosystems, and Water and Energy Cycle. We noted the Plan places more emphasis on the focus area of Climate Variability and Change (11 missions) than on Weather (1 mission). However, this emphasis is consistent with the various laws and policies calling for NASA to focus on climate studies and with NOAA's primary responsibility for weather monitoring. Figure 6 maps the primary focus areas of the missions listed in the Architecture Plan and illustrates areas of overlap.

[35] The Earth Venture Program resides under the Earth System Science Pathfinder Program and currently includes 17 suborbital missions, spaceflight missions, and instruments.

Figure 6: Architecture Plan Missions by Focus Area



Source: NASA OIG presentation of ESD information.

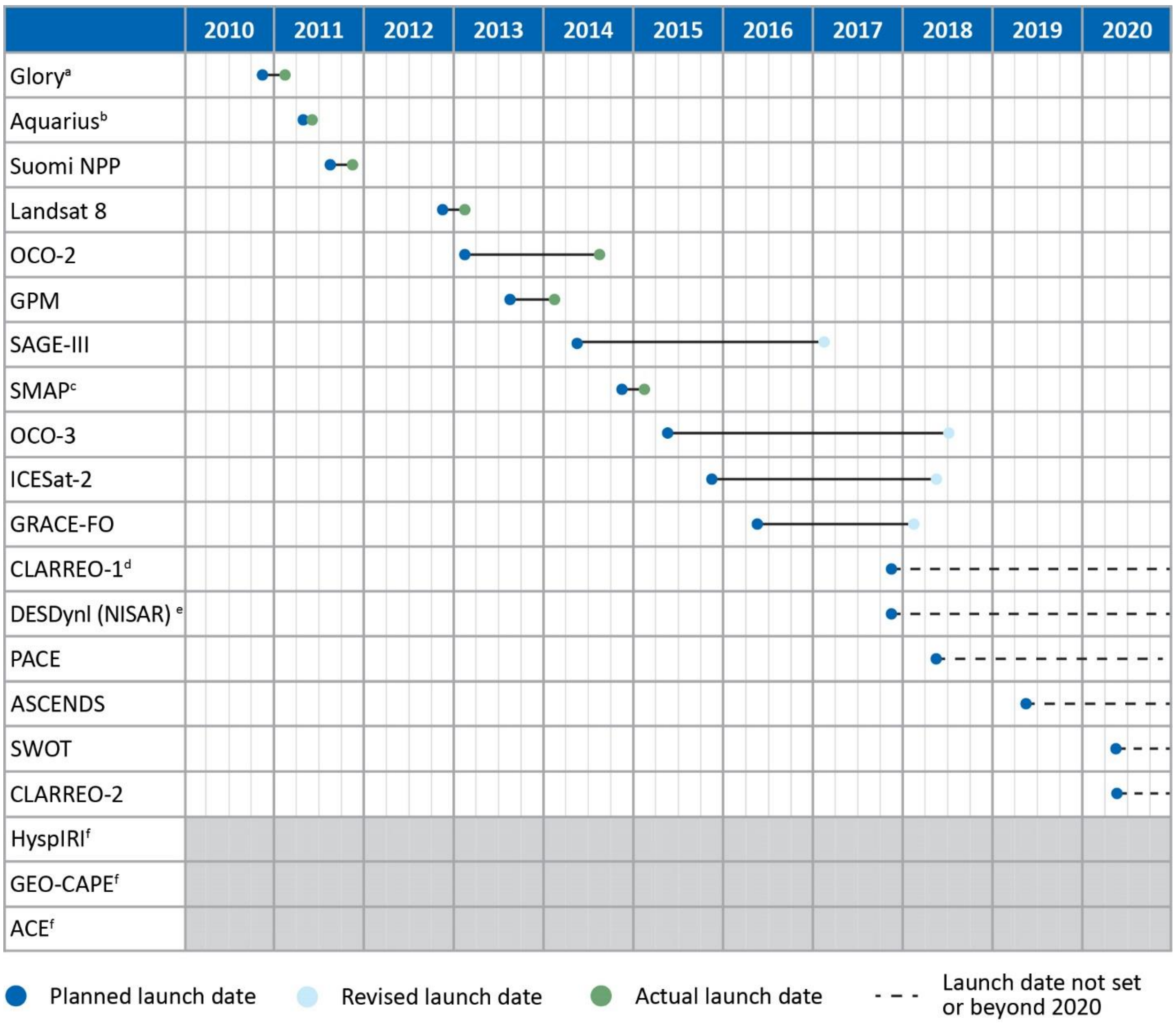
Most Missions Will Miss Their Planned Launch Dates

The Architecture Plan established a schedule whereby 17 of the 20 missions would launch by 2020, including 11 by the end of 2016. However, as of September 2016 NASA had launched only seven of the missions and it is unlikely the others will launch on the schedule outlined in the Plan. ESD officials attributed the delays to a variety of factors, including budget constraints and the availability, reliability, and affordability of launch vehicles. The delays have increased the risk of a data gap as Earth observation assets continue to operate past their designed lifespans.

ESD Making Slower than Expected Progress Implementing Architecture Plan

The Architecture Plan envisioned 11 new Earth science missions in orbit by 2016, only 7 of which have launched or are scheduled to launch by the end of 2016. Four missions – ICESat-2, GRACE-FO, CLARREO, and DESDynI – missed or will miss their targeted launch dates by more than a year. For example, the Plan listed 2015 and 2016 launch dates for ICESat-2 and GRACE-FO, respectively, but neither will launch until 2018. Similarly, ASCENDS and SWOT were slated to launch in 2019 and 2020, respectively; however, as of September 2016, ASCENDS was still in pre-formulation, making its planned launch date unlikely and SWOT's launch has slipped to 2022. Figure 7 illustrates the status of the 20 missions outlined in the Architecture Plan.

Figure 7: Architecture Plan Missions by Planned Launch Date



Source: NASA OIG presentation of ESD data.

[a] Post-launch, the Glory mission failed to reach orbital velocity, reentered the atmosphere, and was destroyed.

[b] Aquarius successfully launched and operated through its prime mission until June 2015 when an essential part of the power and attitude control system stopped functioning.

[c] In July 2015, SMAP's L-band radar stopped transmitting, reducing the resolution of the mission's data.

[d] CLARREO Pathfinder, a technology demonstration will be launched no earlier than 2020 and mounted on the ISS.

[e] Funding for DESDynI was cut in FY 2016 and the primary instrument incorporated into a joint mission between NASA and the Indian Space Research Organisation, known as the NISAR satellite.

[f] According to the Architecture Plan, HyspIRI, GEO-CAPE, and ACE planned launch dates will occur after 2020.

To date, the delays have not prevented NASA from substantially meeting stakeholder needs for Earth observation data. First, most of the Presidential and congressional guidance focused on research areas rather than specific missions. Second, NASA's and NOAA's 26 currently operating missions are providing information for all Earth science focus areas. Finally, the Agency has implemented interim missions to help mitigate data gaps. For example, in October 2009 NASA began aircraft flights over Antarctica (Operation IceBridge) so the Agency could continue to monitor ice sheet mass and height changes during the period between cessation of operations of the first ICESat satellite in August 2010 and launch of ICESat-2 in June 2018. Although these interim measures have been sufficient to prevent data gaps to date, further delays in the launch of planned missions increase the risk of critical data loss and gaps in long-term observations.

External Influences Affecting the Architecture Plan

Issuance of the next Earth Science Decadal Survey in 2017 is likely to affect implementation of the Architecture Plan. ESD officials told us that missions already in development will not be affected because NASA has already committed funds to them. However, the NRC committee will review missions NASA has not yet begun and may ultimately recommend the Agency undertake different missions based on priorities outlined in the 2017 Decadal Survey. Accordingly, some of the missions in the Architecture Plan may never be completed.

Moreover, the Architecture Plan will become increasingly outdated as missions slip and perhaps become a lower priority for the science community. For example, although the 2007 Decadal Survey placed the HyspIRI on its list of Tier 2 missions, the mission is still in pre-formulation and will not be ready to launch for many more years. Additionally, several new instruments previously in NOAA's portfolio, including a Radiation Budget Instrument (RBI) and the Total Solar Irradiance and Spectral Solar Irradiance Instrument (TSIS), were transferred to NASA during the FY 2016 budget process and will take precedence over HyspIRI.[36]

Finally, new efforts to consolidate Earth observation needs are underway that may add to the obsolescence of the Architecture Plan. Specifically, the U.S. Group on Earth Observations is establishing the Satellite Needs Working Group as a forum for Federal agencies to identify their needs and present them to ESD for consideration.

Constraints Limit NASA's Ability to Deliver Missions

Since its first forays into Earth observation, NASA has faced constraints affecting the management and balance of its portfolio, including limited funding, changing Presidential and congressional direction, cost growth, and project failures. While the Agency has tried to minimize their impact, these constraints are likely to continue affecting the Agency's Earth science portfolio.

[36] RBI is a scanning radiometer capable of measuring Earth's reflected sunlight and emitted thermal radiation. Observations from RBI will help measure the effect of clouds on the Earth's energy balance, which strongly influences both weather and climate. TSIS will acquire measurements of total and spectral solar irradiance, a long-standing measurement for climate data records.

Constraints Impacting the Earth Science Portfolio

We identified six main constraints that have affected NASA's Earth science portfolio: (1) unrealistic cost estimates, (2) cost growth, (3) budgetary realities, (4) changing priorities and direction from the President and Congress, (5) launch vehicle issues, and (6) mission and instrument failures.

Unrealistic Cost Estimates

NASA has struggled with identifying realistic cost estimates for Earth science missions, tending to build large, complex projects that incorporate multiple technologies and objectives. In an effort to address this issue, the 2007 Decadal Survey called for smaller, less complex missions. However, as previously noted, the Survey tended to underestimate the costs of the recommended missions, and although NASA tried to incorporate more realistic estimates in the Architecture Plan, the Agency could not support all the projects in the Plan on the proposed schedule. For example, between FYs 2011 and 2013 funding constraints limited development of DESDynI, forcing NASA to look for partnership opportunities and ultimately reach an agreement to develop the mission with India. Additionally, CLARREO, which the Plan described as two satellite launches – CLARREO-1 in 2017 and CLARREO-2 in 2020 – has been redesigned as the CLARREO Pathfinder mission, an instrument technology demonstration that will fly on the ISS no earlier than 2020 to reduce risk for a future CLARREO mission, which will be launched no earlier than 2023.

Cost Growth

Several Earth science missions proved to be significantly more expensive than initial budget estimates. For example, the 2007 Decadal Survey estimated the total cost of a CLARREO mission at $265 million in FY 2006 dollars; however, once NASA and NOAA agreed on requirements for the mission, costs increased to more than $1 billion.[37] To address this cost growth, the Architecture Plan called for two separate missions – CLARREO-1 to be followed by CLARREO-2 – however, according to ESD officials the mission has been redesigned for as a future CLARREO mission, and as noted earlier, NASA decided to proceed in the meantime with the less expensive CLARREO Pathfinder mission. In another example, the 2007 Decadal Survey estimated costs for ICESat-2 at $300 million, but in 2012, NASA baselined the Project's life-cycle costs at $860 million. The Project's cost has subsequently increased by another $204 million to a total life-cycle cost of almost $1.1 billion – nearly four times the original Decadal Survey cost estimates. NASA attributed the increase to development of the Advanced Topographic Laser Altimeter System instrument, which was not part of the first ICESat mission and which NRC did not recommend for the follow-on mission. Similarly, NASA delayed the GPM mission multiple times over 7 years, and after experiencing cost growth, removed an instrument from the mission.

Budgetary Realities

NASA does not have the resources to replace many of its current missions collecting data crucial to Earth science efforts that are operating long past their expected lifetimes, including Aqua and CloudSat. For example, when developing the Architecture Plan NASA anticipated receiving about $10.3 billion between FYs 2011 and 2015 as requested in the President's FY 2011 budget request, but instead received about $8.8 billion – about 15 percent less – which impacted implementation of the Plan as designed. In 2012, NRC noted that aging Earth observation infrastructure placed the Nation at risk of

[37] The 2007 Decadal Survey cost estimate included $200 million from NASA and $65 million from NOAA.

experiencing serious gaps in observational capability, both for operational forecasting missions and for key climate records. Appropriately, NASA takes gap mitigation into consideration when deciding whether to extend operating missions, which it does every 2 years in its Senior Review process.[38] For example, in recommending continued operation of the Solar Radiation and Climate Experiment (SORCE) mission, the 2015 Earth Science Senior Review cited the importance of continuing measurements of total solar irradiance until the TSIS-1 becomes operational in 2018. Additionally, although NASA conducts gap analysis of scientific needs across the portfolio, due to budgetary limits this type of analysis typically only occurs after a mission failure.

Changing Priorities and Direction from the President and Congress

Changes in policy direction and resource levels by the President and Congress affect NASA's Earth Science portfolio. For example, in June 2001 President Bush launched the Climate Change Research Initiative to reduce uncertainties in climate science, improve global observing systems, develop science-based information resources to support policymaking and resource management, and communicate findings broadly among the international scientific community. However, in 2004 the Bush Administration announced a new focus on space exploration that required additional resources and left fewer dollars for NASA's science efforts.[39]

More recently, during the FY 2016 budget process NASA assumed responsibility for several climate-related projects previously run by NOAA – TSIS-1 and -2, RBI, Ozone Mapping and Profiler Suite-Limb Profiler, and Altimetry Follow-On.[40] In addition, NASA will take responsibility for any future ocean altimetry satellites in the Jason series. According to ESD officials, this change will result in additional costs of approximately $82 million that will not be fully covered by the Agency's FY 2017 budget request.

Launch Vehicle Issues

The availability, reliability, and affordability of launch vehicles has also complicated execution of NASA's Earth science portfolio. In its 2012 assessment, NRC noted the lack of reliable, affordable, and predictable access to space had become a key impediment to implementing NASA's Earth science program, pointing out that the Agency was limited primarily to a choice of two launch vehicles: the medium class Taurus or the more powerful and more expensive Atlas V. For example, after Taurus suffered back-to-back failures attempting to launch OCO and Glory, NASA planned to launch ICESat-2 on the Atlas V in tandem with a U.S. Air Force weather observatory. However, after the Air Force decided to postpone its mission until at least 2020, NASA negotiated for ICESat-2 to launch on a Delta II rocket, raising the project's overall cost by $84 million. In an attempt to mitigate launch issues, ESD has designed satellites that can be launched on more than one type of vehicle, including relatively new vehicles under development by companies such as Space Exploration Technologies Corporation.

[38] The Science Mission Directorate's Senior Review assesses the costs and benefits of extending missions that have exceeded their planned operational lives and is further discussed later in this report.

[39] President George W. Bush, "A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration," January 2004.

[40] The Ozone Mapping and Profiler Suite-Limb Profiler will be incorporated onto JPSS-2 to measure the concentration of ozone in the Earth's atmosphere. The Altimetry Follow-On, recently renamed Sentinel-6, will continue ocean altimetry measurements beyond the Jason-3 mission.

Mission and Instrument Failures

Unanticipated events have affected NASA's Earth science portfolio and execution of the Architecture Plan, resulting in data interruptions, re-evaluation of needs, and reprioritization of resources. For example, following the OCO and Glory launch failures, ESD established a commission to study the technical and scientific needs for replacement missions. Based in part on input from the science community, NASA flew a replacement mission for OCO, but not for Glory. More recently, in July 2015 a high-power amplifier on the SMAP mission failed rendering its radar – one of two primary instruments – inoperative. According to NASA, SMAP continues to deliver high-quality measurements albeit at a lower resolution than planned.

Efforts to Minimize Constraints

ESD has taken steps to address the issues discussed earlier by forming partnerships, improving the statement of task for the next NRC Decadal Survey, and extending current missions.

Partnerships

ESD has sought out partnerships with other Federal agencies and foreign space agencies to help decrease mission costs, and 23 of the 49 missions ESD is currently managing involve partnerships. For example, GPM is a partnership between NASA and the Japan Aerospace Exploration Agency (JAXA), with JAXA providing two radar instruments, the launch vehicle, and related launch services. GPM officials told us that without Japanese support they could not have proceeded with the mission. Partnerships can also provide alternative sources of data or modeling systems when an instrument fails or a project has been descoped or delayed. Case in point, delivery of soil moisture data by the European Space Agency's Sentinel is helping alleviate data lost due to the failure of the synthetic aperture radar instrument on SMAP. Although partnering has been beneficial, as we reported in May 2016 it also poses challenges, including securing approval from the Department of State and complying with U.S. export control regulations.[41]

Improvements for the 2017 Decadal Study

NASA has revised the Statement of Task for the 2017 Decadal Survey in the hope the resulting document will produce more realistic cost estimates than the 2007 Decadal Survey. Specifically, NASA requested NRC (1) use the cost and technical evaluation process to calculate estimates, (2) evaluate means of cost reduction including partnerships and alternative observation capabilities, and (3) base the 2017 Decadal Survey budget caps on current budget levels.[42] The 2017 Decadal Survey will also take superseding events into account, including launch vehicle availability, the creation of JASD, and new Federal directives to prioritize mission recommendations.

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[41] NASA OIG, "NASA's International Partnerships: Capabilities, Benefits, and Challenges" (IG-16-020, May 5, 2016).

[42] The cost and technical evaluation process was developed in response to the 2008 NASA Authorization Act, which required life-cycle costs for proposed NASA projects. The process, implemented by the Aerospace Corporation and NRC, uses historical cost estimates and incorporates cost growth, technical risks, and readiness to assess the technical risks and readiness of proposed missions.

Mission Extension

In 2005, NASA began implementing a biennial Senior Review process in the Science Mission Directorate to assess the costs and benefits of extending missions that have exceeded their planned operational lives. Extended missions help ensure data continuity when newer systems are not yet available and can lessen the impact of instrument degradation and failures. For example, program officials told us that users relied on Moderate Resolution Imaging Spectroradiometer data collected by Aqua and Terra missions to fill gaps after an instrument failure on Landsat 7 in 2003.[43]

However, as we have previously reported, extended missions also pose greater operational risks, may be less efficient at data collection, and are more prone to instrument degradation due to aging.[44] The most recent Earth Science Senior Review occurred in 2015 and examined 10 of the 14 missions in extended operations.[45] Only the Earth Observation (EO)-1 mission, which had already been in extended operations for 12 years, was terminated as a result of the Review. Continuation of the remaining nine missions will bring the average length of their extended operations to 11 years. Given that NASA and other agencies rely on many Earth science missions that have been in extended operations for a decade or more and that many planned missions have experienced delays and descoping, the Earth science portfolio is at increased risk of experiencing data gaps.

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43 In May 2003, almost 4 years after Landsat 7 launched, its Scan Line Corrector failed resulting in degraded images.

44 NASA OIG, "The Science Mission Directorate's Mission Extension Process" (IG-15-001, October 9, 2014).

45 The 10 missions were Aqua, Aquarius, Aura, CALIPSO, CloudSat, EO-1, GRACE, OSTM, SORCE, and Terra. "NASA Earth Science Senior Review 2015," June 22, 2015, available at https://science.nasa.gov/earth-science/missions/operating (last accessed October 13, 2016).

RESEARCH AND OTHER USES FOR EARTH SCIENCE DATA

Since 2000, the use of data from NASA's Earth observation program has risen dramatically. Government agencies, scientists, private entities, and other stakeholders increasingly rely on EOSDIS to process raw information received from Earth observation systems into useable data collections. For example, over the past 15 years the number of EOSDIS products delivered to users increased from about 8.14 million to 1.42 billion. Moreover, NASA's Earth observation data is routinely used by government agencies, policymakers, and researchers to expand understanding of the Earth system and to enhance economic competitiveness, protect life and property, and develop policies to help protect the planet. In addition, NASA has been tasked with examining how commercially-provided data can be used to augment the Agency's data.

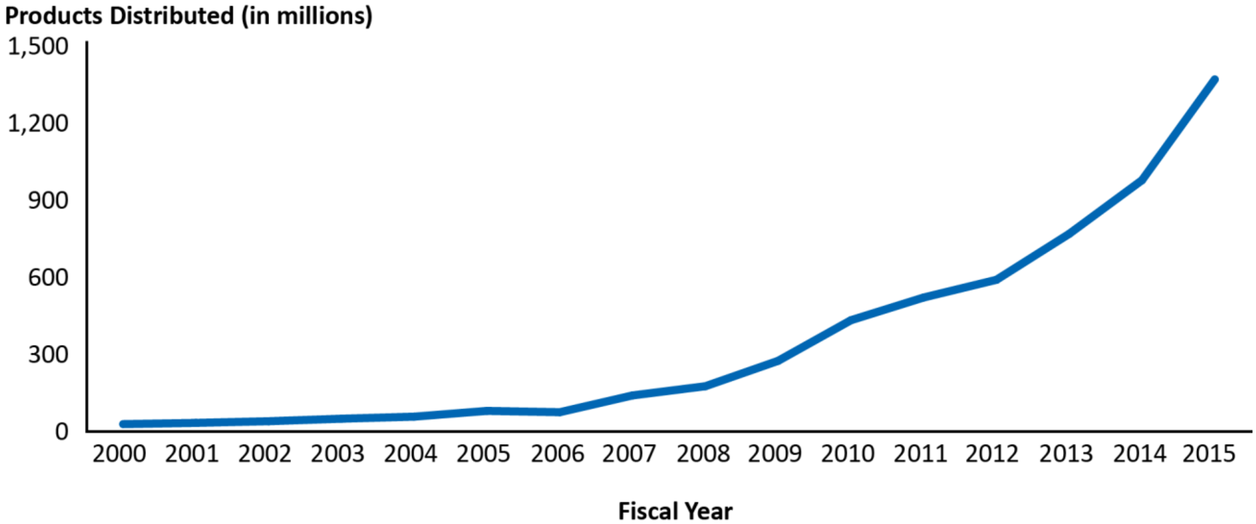
Increase in Usage of Earth Observation Data

Processing and distribution of most of the data collected by ESD missions occurs through EOSDIS. EOSDIS managers coordinate with project managers, scientists, and Science Definition Teams to ensure products are best suited for the science community.[46] Once a mission is launched and operating, data from the Earth observation instruments is processed and sent to the appropriate DAAC where the raw and processed data is archived and distributed to researchers through the Internet. For example, the DAAC for data related to land cover and elevation (e.g., global forest cover and digital elevation models) is located in Sioux Falls, South Dakota, which has a large community of land scientists. If a mission produces data relevant to multiple scientific disciplines, data is sent to multiple DAACs for processing before release to users. In addition to processing, data is also archived at the DAACs.

In FY 2015, NASA reported EOSDIS had 9,462 unique data sets available for use, 2.6 million user accounts, and 1.42 billion products requested and delivered. These figures represent a significant increase in available data products, users, and downloads since the system was established in 1994 (see Figure 8).

[46] Science Definition Teams are responsible for developing the science requirements of the mission.

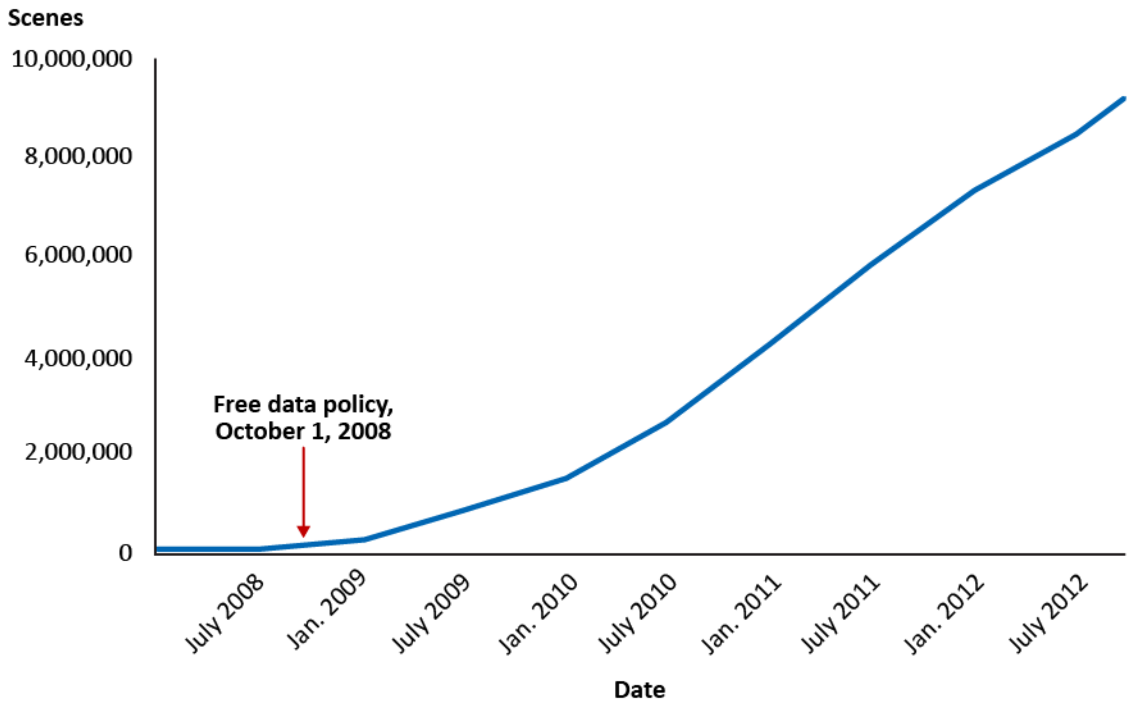
Figure 8: EOSDIS Product Distribution from FY 2000 to FY 2015



Source: NASA OIG analysis of EOSDIS Annual Metrics, FYs 2000 through 2015.

ESD officials attribute the increase in part to NASA's open data policy, and USGS's experience with adopting a free data policy for the Landsat program supports this correlation. In 1985, a commercial company – Earth Observation Satellite Company – was awarded a 10-year contract pursuant to which it built and operated Landsat 4 and 5 and could market and collect fees for distributing Landsat data. Data costs under the contract were up to $4,400 per "scene" – an image of roughly 45,000 acres – for the public and $2,500 for the Government. After expiration of the contract, USGS began providing Landsat data at no cost. Since then, data downloads have increased by more than 4,000 percent, as shown in Figure 9.

Figure 9: Rate of Landsat Data Access



Source: NASA OIG presentation of NASA data.

ESD has also undertaken efforts to increase the efficiency of EOSDIS in response to recommendations from NASA's Technical Capability Assessment Team and the President's Big Data Research and Development Initiative.[47] For example, ESD is exploring commercial cloud capabilities to improve data dissemination, establishing a standardized software development for its DAACs, and implementing a policy that would allow other agencies and governments to use its software. ESD is also developing new guidance to incorporate potential user applications into mission planning, document the utility of data, and decrease the time between data receipt and creation of new applications.

ESD also has an ongoing initiative – referred to as "early adopters" – to expedite access to data for users. The 2007 Decadal Survey noted that better coordination between the missions and users would help maximize the utility of collected data. For example, since 2011 the Early Adopters Program provided simulated SMAP data to more than 50 organizations for pre-launch applications research.[48] Additionally, the Program encouraged early feedback on products and formats that would increase the value to researchers of the data collected by the mission. The Applied Sciences Program Director told us he viewed the Early Adopters Program for SMAP as successful and pointed to development of the U.S. Department of Agriculture's National Agricultural Statistical Service – a web-based crop vegetation condition assessment and monitoring application – produced using SMAP data as an example. He said ESD plans to have similar engagements for GRACE, ICESat-2, and SWOT that will help end users more easily assimilate the projects' data into applications and operations.

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[47] NASA established the Technical Capability Assessment Team in 2012 to examine ways to ensure the Agency has the right skills, facilities, and equipment to execute its missions. The Big Data Research and Development Initiative, created in 2012, aims to improve the discoverability, accessibility, and usability of Federal data and information products derived from civil Earth observations.

[48] The simulated SMAP data is presented in terms of viewing angle, resolution, soil moisture data, vegetation properties, soil temperature, and surface roughness.

Other Sources of Earth Observation Data

In FY 1997, Congress appropriated $50 million to NASA to purchase commercial remote sensing data and information products. Managed by the Commercial Remote Sensing Program Office at Stennis Space Center in Mississippi, NASA issued 15 contracts to commercial companies to provide data and services through September 2001.[49] Although by some measures the Program was successful – that is, data was delivered on or ahead of schedule and its quality verified – overall, NASA found commercial avenues could not meet all of the Agency's data requirements. Except for initial development of a commercial data procurement strategy for Landsat 8 that was abandoned in the early 2000s, NASA has not funded a commercial Earth science data purchase strategy.

While the President, Congress, and NRC have encouraged NASA to use commercially provided Earth observations to promote private-sector innovation and complement data provided by Government systems, challenges remain. Although the 2007 Decadal Survey recognized a role for commercially obtained data, it noted "most of what is important scientifically will not be provided in the foreseeable future by commercial providers." For example, while an increasing number of private companies, including DigitalGlobe, Inc. and Satellite Imaging Corporation, offer high-resolution geospatial imaging, they generally do not offer such specific measures as ocean salinity or height desired by the science community. In addition, NASA must reconcile its data and information policy, which promotes open sharing of all data at minimal cost to users, with a business model that supports commercial enterprises while keeping fees from creating a barrier to data use. Furthermore, ESD officials noted that even if they collect specific data required by the scientific communities, current commercial systems rely on NASA's systems for data calibration and validation, and as a result, replacing NASA Earth observation systems with commercial systems is not currently feasible.

Applied Sciences Program Turns Data into Societal Benefits

NASA's Applied Sciences Program aims to help the United States better manage its resources, improve quality of life, and strengthen the economy through the use of Earth observation data. The Program develops Earth science applications in collaboration with end-users in public, private, and academic organizations and enables near- and long-term uses of Earth science data to enhance economic competitiveness, protect life and property, and develop policies to help protect the planet. For example, the Program helped the California Department of Water Resources use NASA satellite data to decrease water use in crop irrigation tests by 30 percent.

However, calculating the socioeconomic value of Earth observations is difficult. In 2003, NRC estimated their socioeconomic value at about $1 trillion annually. In 2012, NASA issued a primer on techniques to calculate the socioeconomic value of Earth observations.[50] More recently, ESD solicited proposals to develop, implement, and manage a program of activities to articulate the socioeconomic benefits of Earth science applications directly attributable to Earth observations.

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[49] During Phase I, the Program awarded 10 contracts totaling about $4.3 million. Subsequently, the Program awarded 5 contracts totaling about $42.8 million to Phase I companies whose products were validated, accepted, and recommended for follow-on awards by NASA Earth scientists.

[50] NASA, "Measuring Socioeconomic Impact of Earth Observations," 2012.

In a recent report, the International Group on Earth Observations identified eight areas that benefit from Earth observation data: (1) agriculture and food security, (2) ecological forecasting, (3) water resources, (4) health and air quality, (5) disasters and wildland fires, (6) energy, (7) urban resilience, and (8) transportation and infrastructure.[51] Although NASA's Earth science efforts touch all of these areas in some way, the Agency has focused primarily on four: ecological forecasting, water resources, health and air quality, disasters and wildland fires. Below we discuss examples of how NASA's Earth observation efforts are being integrated into applications for decision makers in these areas.

Biodiversity and Ecosystems

In April 2016, NASA reported that researchers had examined 15 years of cloud data from the Terra and Aqua satellites and found that variations in cloud cover sharply delineated the boundaries of ecological biomes, which are regions of the world with similar weather, temperature, animals, and plants. Specifically, researchers found that clouds influence such environmental factors as rain, sunlight, surface temperature, and leaf wetness – all of which dictate where plants and animals can survive. With this data, conservation policies can be tailored to specific regions.

Besides locating the areas in which species live, Earth observation data can also identify ecosystems threatened by pollution. For example, using data from Landsat 8 researchers have detected shipwreck sites from sediment plumes visible from space. Leaking fuel and corroded heavy metals from these sites can negatively impact ecosystems and pose navigational hazards.[52] In another example, the National Marine Fisheries Service uses data from Aqua, Jason-2, and other sources to characterize whale habitats and predict whale presence. This information is critical to helping prevent endangered whales from being struck by ships along the west coast of the United States, the site of more than 50 percent of domestic container shipping traffic.

Water Resources

GPM, GRACE, Landsat, SMAP, and SWOT are among NASA missions that help improve understanding and management of the water cycle, which has wide-ranging implications for water resources, food security, energy development, and protection of human health and critical habitat. For example, research conducted at the University of California, Irvine using data from the GRACE satellites concluded that approximately one third of Earth's largest groundwater basins are being rapidly depleted by human consumption. This type of information can help inform decisions about preservation of water resources. In addition, the California Department of Water Resources used Landsat imagery to map drought effects on agricultural production in the State's Central Valley and help inform allocation of drought emergency funds to support farmworkers and their families. In another example, SWOT data is used to measure monthly and seasonal changes in water resources.

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[51] Although not identified as a separate area, climate and weather data play an important role across the eight benefit areas.

[52] The potential negative environmental impacts of modern-era shipwrecks are substantial enough that the Council of Europe's Parliamentary Assembly has recommended they be mapped and monitored.

Health and Air Quality

Aqua, Aura, GPM, and SMAP are among the missions informing public health policy. For example, the Louisiana Department of Health and Hospitals used Aqua sea surface temperature data to predict the risk of oyster norovirus outbreaks. In another example, GPM's global coverage and high frequency observations help locate areas at risk from hurricane-induced flooding, which can cause sewage and waste-related health issues. Likewise, GPM and SMAP benefit the emerging field of landscape epidemiology aimed at identifying and mapping habitats for human diseases such as malaria and for which direct observations of soil moisture and freeze/thaw status can provide valuable information. For example, NASA's Malaria Modeling and Surveillance Project's Global Situational Awareness Tool combines data sets from a number of satellites, including rainfall data from the Tropical Rainfall Measuring Mission, to evaluate the risk of malaria worldwide.

With respect to air quality, NASA's Air Quality Applied Sciences Team has used Aura satellite images of nitrogen dioxide to demonstrate reductions in air pollution across the United States. Other researchers used Aura data to identify 75 non-erupting volcanoes, which are sources of the toxic gas sulfur dioxide that also contributes to acid rain. Because volcanoes are often in remote locations and not regularly monitored, this satellite-based data set is the first to provide regular annual information on volcanic emissions, which can be used to help inform regulatory policies and anticipate future emission risks that may evolve with changing economic and population growth.

Natural Disasters

SMAP's soil measurements provide a key variable to modeling water-related natural hazards such as floods and landslides. Similarly, SWOT will provide data on in situ water levels and therefore additional insight into the dynamics of floods and their impacts, which will surpass current floodplain measurements that are often made after the event has occurred and are based on high water marks that provide limited data. In addition, the U.S. Forest Service used data from S-NPP, which collects land surface temperature measurements, to enhance fire detection and fire progression prediction as well as make post-fire assessments. S-NPP also serves as a tool for wild fire managers to determine fire scene boundaries, monitor outbreaks, protect firefighters and resources, and advance timely ecosystem restoration. Moreover, scientists are developing predictive wildfire models based, in part, on data collected over the years from S-NPP.

CONCLUSION

We found NASA's 2010 Architecture Plan for Earth science missions responsive to stakeholders' needs and the Agency's overall approach to selecting missions appropriate and reasonable. However, due primarily to budget constraints and the availability and affordability of launch vehicles, NASA has not carried out the Architecture Plan on the schedule envisioned, leaving the Agency and other stakeholders increasingly reliant on an aging Earth observation infrastructure susceptible to failure that could result in crucial data gaps. Moreover, since establishing an Earth science observation program in 1987, the Agency has faced challenges affecting the management and balance of its portfolio, including funding limitations, changing Presidential and congressional direction, cost growth, and project failures. While NASA has tried to minimize their impact, these constraints are likely to continue to affect the Agency's Earth science portfolio. Notwithstanding these challenges, researchers and policymakers have increasingly used NASA's Earth science observations to expand understanding of the Earth system, inform decisions regarding economic competitiveness and protection of life and property, and develop policies to help protect the planet.

RECOMMENDATIONS

To improve NASA's management of its Earth science portfolio, we recommended the Associate Administrator for the Science Mission Directorate direct the Earth Science Division Director to

1. update the Architecture Plan every 5 years to align with the release of Earth Science Decadal Surveys and mid-term Surveys and account for portfolio changes, and
2. develop strategies to engage with commercial companies to investigate cost-beneficial acquisition, disposition, and use of Earth observing data.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider the proposed actions responsive to our recommendations and will close the recommendations upon verification and completion of the proposed actions.

Management's full response to our report is reproduced in Appendix C. Their technical comments have been incorporated, as appropriate.

Major contributors to this report include, Raymond Tolomeo, Science and Aeronautics Research Directorate Director; Rebecca W. Pselos, Project Manager; Dr. Noreen Khan-Mayberry; Sarah McGrath; and Alyssa M. Sieffert.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from October 2015 through September 2016 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

This review evaluated NASA's 69 Earth satellite and instrument missions in low Earth orbit managed by ESD or overseen by JASD. We sought to determine whether NASA is achieving established goals and priorities and meeting stakeholder needs. We also sought to review internal controls as they related to the overall objective. Specifically, we evaluated (1) the Agency's current Earth science strategic plan, (2) the Agency's current progress towards its strategic plan and other identified missions, (3) the utilization of data gathered as part of the strategic plan and any additional missions, and (4) internal controls related to the process. Our review of NASA's Earth science portfolio was conducted at NASA Headquarters, Goddard Space Flight Center, the Jet Propulsion Laboratory, and Langley Research Center. Additionally, we engaged Federal agencies who are responsible for delivering space-based Earth science data, including NOAA and USGS, and NRC representatives of the 2007 and 2017 Decadal Surveys for Earth science.

To evaluate the Agency's strategic plan for Earth science, we reviewed NASA Policy Directives (NPD) and NASA Procedural Requirements (NPR) related to strategic planning, NASA strategic plans at the Agency and Mission Directorate level between 2007 and 2016, and the Architecture Plan. To determine how ESD addressed stakeholders' priorities, we compared the Architecture Plan to (1) the 2007 Decadal Survey, (2) strategic plans for the U.S. Group on Earth Observations, (3) strategic plans for the U.S. Global Change Research Program, (4) Earth science-related legislation, and (5) the National Space Policy of the United States of America (2010 National Space Policy). Finally, we reviewed the procedures used to develop the Decadal Surveys in the context of standards used for setting research policies within NASA. To gather this information, we viewed ESD mission profiles in program documentation and at program mission websites and reports for the 2007 and 2017 Decadal Surveys and spoke with members of the 2007 and 2017 Decadal Surveys.

To determine the progress of current Earth science projects, we gathered publicly-available data regarding missions currently in planning, development, implementation, or operations. We identified 69 satellite and instrument missions in low Earth orbit under ESD and JASD and those operated by NOAA and USGS that NASA developed. Of note, Quick Scatterometer is utilized as a calibration instrument for ESD, but was not included in our study because the mission ended on November 23, 2009. Additionally, we spoke with a sample of project and program managers and staff. We selected a sample of projects that represented different phases of projects' life cycles from both ESD and JASD, the Earth Systematic Missions and the Earth System Science Pathfinder Programs, domestic and international partnerships, and the different relationships to the 2007 Decadal Survey. Our sample included ECOSTRESS, GOES, GPM, JPSS, Landsat, NISAR (DESDynI), OCO-2, OSTM, PACE, and SMAP. To represent missions arising from the 2007 Decadal Survey, we selected PACE and SMAP. Conversely, we selected OCO-2 because it lacked a link to the 2007 Decadal Survey. Missions with international and domestic partnerships included NISAR (DESDynI) and Landsat, respectively. ECOSTRESS was selected for its relation to the Earth System Science Pathfinder Program and GPM was selected for its relation to Earth Systematic

Missions. Finally, we selected GOES-R, JPSS, and OSTM for their relation to JASD. Additionally, we requested and reviewed project status information via Key Decision Point memorandums or similar documentation.

To determine the prioritization process and accounting for stakeholders' interests, we spoke to relevant officials from Science Mission Directorate's ESD, JASD, Strategic Integration and Management Division, and Resource Management Division regarding the management of the Earth science portfolio. We also spoke with the directors for ESD's Flight Programs, Research Program, Applied Sciences Programs, Earth System Science Pathfinder Program, and the Earth Systematic Missions Program to understand the decision-making process for the creation, management, cancellation, or continuation of Earth science projects. Due to their previous work on the subject, we spoke with the members of NRC's Space Studies Board, including chairs of the 2007 and 2017 Earth Science Decadal Survey committees. Additionally, we reviewed all legislative and executive mandates issued to NASA since 2007.

We also evaluated the use and dissemination of Earth science data through interviews with key personnel within ESD's Applied Sciences Program and NASA's Earth Observing System Project Science Office. We reviewed the Data Management Plans for these projects to determine how their data was disseminated to the public. Additionally, we reviewed the annual reports produced by ESD's Applied Sciences Program and EOSDIS.

For Appendix B, we reviewed the Key Decision Point documents and publicly available information related to each mission's description, measurements, societal benefits, operations platform, status, and cost. We obtained each mission's focus area, domestic and international partnerships, ESD division, and source of mission requirements from ESD officials. Compiled information was then reviewed by NASA's Office of the Chief Financial Officer and Science Mission Directorate who confirmed life-cycle costs for missions in pre-formulation through prime operations and total investment for missions in extended operations.

We obtained and examined internal and external applicable documents related to the Earth science portfolio as well as NASA policy. The documents we examined included the following:

- Title 51, "National and Commercial Space Programs," December 18, 2010
- Pub. L. No. 111-267, "'National Aeronautics and Space Administration Authorization Act of 2010," October 11, 2010
- President of the United States, "National Space Policy of the United States Of America," June 28, 2010
- Office of Science and Technology Policy, "The National Global Change Research Plan 2012-2021: A Strategic Plan for the U.S. Global Change Research Program (USGCRP)," April 2, 2012
- Office of Science and Technology Policy Executive Office of the President, "National Plan For Civil Earth Observations," July 2014
- NPD 1000.0B, "NASA Governance and Strategic Management Handbook," November 26, 2014
- NPD 1001.0B, "2014 NASA Strategic Plan," March 12, 2014
- NPR 1080.1A, "Subject: Requirements for the Conduct of NASA Research and Technology (R&T)," May 30, 2008
- NASA, "2014 Science Plan," 2014

- NASA, "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space," June 2010
- NRC, "Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey," 2012
- NRC, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," 2007

Use of Computer-Processed Data

We used computer-processed data to perform this audit. Specifically, we reviewed publicly-available lists of Earth science missions obtained primarily from NASA's, the Committee on Earth Observation Satellites', and the European Space Agency's websites, and obtained computer processed financial data from NASA's Office of the Chief Financial Officer. We confirmed missions in planning, development, implementation, or operations with ESD officials and performed manual testing of the data by reviewing Key Decision Point documentation, and interviewing project management for a sample of the missions. We concluded the data was valid and reliable for the purposes of review.

Review of Internal Controls

We evaluated internal controls, including organizational structures and policies that (1) provide reasonable assurance that programs meet their objectives, (2) safeguard assets and resources, and (3) provide relevant and reliable data to the public, and concluded that the internal controls were generally adequate.

Prior Coverage

Since 2010, the NASA OIG, the Government Accountability Office (GAO), and NRC have issued 22 reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/reports/FY17/index.html, http://www.gao.gov, and http://www.nap.edu, respectively.

NASA Office of Inspector General

NASA's International Partnerships: Capabilities, Benefits, and Challenges (IG-16-020, May 5, 2016)

NASA's Management of the Near Earth Network (IG-16-014, March 17, 2016)

The Science Mission Directorate's Mission Extension Process (IG- 15-001, October 9, 2014)

NASA's Use of Research Announcement Awards for Aeronautics Research (IG-12-011, April 30, 2012)

NASA's Management of the NPOESS Preparatory Project (IG-11-018, June 2, 2011)

Government Accountability Office

NASA: Assessments of Major Projects (GAO-16-309SP, March 30, 2016)

NASA: Assessments of Selected Large-Scale Projects (GAO-15-320SP, March 24, 2015)

Geostationary Weather Satellites: Launch Date Nears, but Remaining Schedule Risks Need to be Addressed (GAO-15-60, December 16, 2014)

NASA: Assessments of Selected Large-Scale Projects (GAO-14-338SP, April 15, 2014)

Geostationary Weather Satellites: Progress Made, but Weaknesses in Scheduling, Contingency Planning, and Communicating with Users Need to Be Addressed (GAO-13-597, September 9, 2013)

NASA: Assessments of Selected Large-Scale Projects (GAO-13-276SP, April 17, 2013)

NASA: Assessments of Selected Large-Scale Projects (GAO-12-207SP, March 1, 2012)

Polar Satellites: Agencies Need to Address Potential Gaps in Weather and Climate Data Coverage (GAO-11-945T, September 23, 2011)

NASA: Assessments of Selected Large-Scale Projects (GAO-11-239SP, March 3, 2011)

NASA: Assessments of Selected Large-Scale Projects (GAO-10-227SP, February 1, 2010)

National Research Council

Enhancing Participation in the U.S. Global Change Research Program (2016)

Developing a Framework for Measuring Community Resilience: Summary of a Workshop (2015)

Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program (2013)

Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey (2012)

A Review of the U.S. Global Change Research Program's Strategic Plan (2012)

Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions (2011)

Controlling Cost Growth of NASA Earth and Space Science Missions (2010)

Appendix B: Earth Science Missions

Table 2 provides a description of NASA's six Earth science focus areas. In addition, the appendix includes a brief overview of the 69 satellite and instrument missions in NASA's Earth science portfolio as of September 2016, including launch dates, life-cycle cost estimates, and the primary and secondary focus areas for each mission. Pre-formulation activities, which primarily consist of concept and trade studies to determine the feasibility of a mission, are not included in life-cycle costs and therefore NASA has not established launch dates or life-cycle cost estimates for these missions.

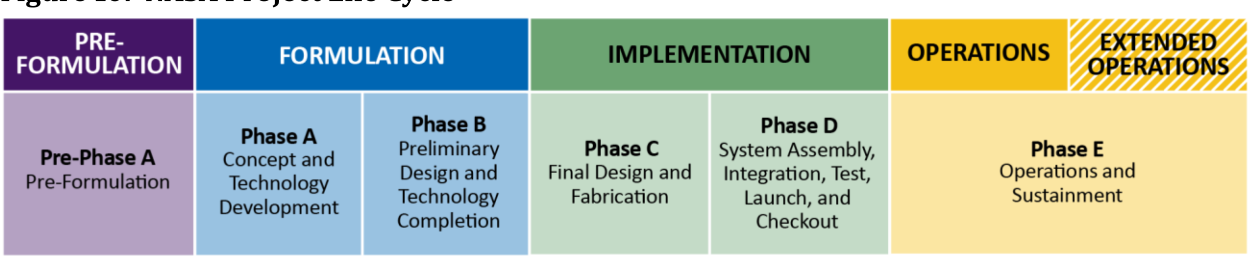
Table 2: Science Focus Area Descriptions and Icons

Science Focus Area	Description	Primary Focus Icon	Secondary Focus Icon
Atmospheric Composition	Advance the understanding of changes in the Earth's radiation balance, air quality, and ozone layer that result from changes in atmospheric composition.		
Weather	Improve the capability to predict weather and extreme weather events.		
Climate Variability and Change	Improve the ability to predict climate changes by improving understanding of the roles and interactions of the oceans, land, and ice in the climate system.		
Carbon Cycle and Ecosystems	Detect and predict changes in Earth's ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle.		
Global Water and Energy Cycle	Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change.		
Earth Surface and Interior	Characterize the dynamics of the Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events.		

Source: NASA OIG presentation of NASA information.

NASA Earth science missions follow NASA's project life cycle.[53] Figure 10 shows each step of the cycle.

Figure 10: NASA Project Life Cycle



Source: NASA OIG presentation of NASA information.

[53] NPR 7120.5E, "NASA Space Flight Program and Project Management Requirements w/Changes 1-14," August 14, 2012.

3D-WINDS

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

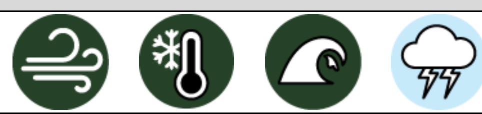
The Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds) mission studies winds found in the troposphere – the lowest layer of the Earth's atmosphere and site of all weather on Earth. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	More accurate, long-term weather forecasts and better storm tracking prediction to allow for improved storm evacuation planning and planting and harvesting schedules to increase food supplies.

ACE

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Aerosol-Cloud-Ecosystems (ACE) mission will study the direct and indirect effect of aerosols (airborne particles) on cloud formation and measure and quantify the relationship among aerosols, cloud and precipitation systems, and ocean ecosystems. This is a 2007 Decadal Survey Tier 2 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	By improving climate models and air-quality forecasts, ACE data will assist individuals in planning their daily activities.

AQUA

Status	Launch Date	Life-Cycle Cost
Extended Operations	2002	$2.1 billion

The Aqua satellite mission collects data on the Earth's water cycle in its liquid, solid, and vapor forms using six different instruments. More accurate than any previous satellite sensor, Aqua is able to extend rainfall characterization beyond the tropics in concert with other satellite measurements and produce global soil moisture distribution records for regions with little vegetation.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Japan and Brazil
Earth Science Focus Area	
Societal Benefit	Makes critical contributions to monitoring terrestrial and marine ecosystem dynamics and is used by operational agencies to improve weather prediction.

ASCENDS

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission will make global carbon dioxide measurements without a seasonal, latitudinal, or daily bias, as well as measure ambient air pressure and temperature. As a result, researchers will be able to better quantify global spatial distributions of atmospheric carbon dioxide and provide a scientific basis for future projections of carbon dioxide sources and sinks. This is a 2007 Decadal Survey Tier 2 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Improved predictions of atmospheric carbon dioxide help identify human-generated carbon dioxide sources and sinks to enable effective carbon trading policy globally, regionally, and locally.

AURA

Status	Launch Date	Life-Cycle Cost
Extended Operations	2004	$1.22 billion

The Aura satellite mission studies the chemistry and dynamics of Earth's atmosphere to investigate questions about ozone trends and air-quality changes and their linkage to climate change. Aura's four instruments measure five of the six commonly known air pollutants – carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, and aerosols.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Finland, the Netherlands, and the United Kingdom
Earth Science Focus Area	
Societal Benefit	Provides data for improved daily air quality forecast models and information for local and Federal Government agencies monitoring and enforcing air quality standards.

CALIPSO

Status	Launch Date	Life-Cycle Cost
Extended Operations	2006	$265 million

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission measures direct and indirect impacts from clouds and aerosols (airborne particles) on climate and improves understanding of the role aerosols and clouds play in regulating the Earth's climate, in particular how aerosols and clouds interact.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	France, NOAA, NRL, and EPA
Earth Science Focus Area	  
Societal Benefit	Will improve aerosol tracking for weather, climate, pollution, and air quality models and predictions and provide international and national leaders accurate information to make informed policy decisions about global climate change.

CATS

Status	Launch Date	Life-Cycle Cost
Extended Operations	2015	$18 million

Flown on the ISS, the Cloud-Aerosol Transport System (CATS) investigation uses a light detection and ranging instrument to measure atmospheric clouds and aerosols. CATS provides continuity for the CALIPSO mission, which launched in 2006 and has been in extended operations since 2009.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Improved weather and climate change modelling and prediction.

CLARREO

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission measures solar and Earth radiation to provide long-term benchmarking data for the detection, projection, and attribution of changes in the climate system.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Establish a multi-decade global climate record and provide climate forecasting that informs international commerce, societal stability, and security decisions and policy.

CLARREO PATHFINDER

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder mission measures solar and Earth radiation to provide long-term benchmarking data for the detection, projection, and attribution of changes in the climate system. NASA funded the mission to demonstrate measurement technologies required for the full mission described previously.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Establish a multi-decade global climate record and provide climate forecasting that informs international commerce, societal stability, and security decisions and policy.

CLOUDSAT

Status	Launch Date	Life-Cycle Cost
Extended Operations	2006	$139 million

Studies clouds and aerosols in detail to improve understanding of their role in regulating Earth's climate, weather, and air quality. CloudSat is providing the first direct, global measurement of the vertical structure and overlap of cloud systems and their liquid and ice-water contents, measuring cloud properties, and studying the indirect effect of aerosols on clouds.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	Canada and USAF
Earth Science Focus Area	
Societal Benefit	Improved cloud representations in atmospheric models to help improve the accuracy of weather forecasts and climate models.

CYGNSS

Status	Launch Date	Life-Cycle Cost
Implementation	2016	$174.2 million

The Cyclone Global Navigation Satellite System (CYGNSS) mission will use a constellation of eight micro-satellite observatories to measure ocean surface roughness, which is used to help determine wind speed. The mission will study the relationship among ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics to determine how a tropical cyclone forms and strengthens.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Improved forecasting of hurricane intensification resulting from the ability to observe the air-sea interaction processes that take place near the inner core of storms.

DSCOVR

Status	Launch Date	Life-Cycle Cost
Operating	2015	$117.3 million

Located approximately one million miles from Earth, the Deep Space Climate Observatory (DSCOVR) maintains real-time solar wind monitoring capabilities by measuring the radiation reflected and emitted by Earth. In addition, DSCOVR will provide images of the sunlit side of Earth for science applications. The life-cycle cost is for the two NASA-funded instruments on this NOAA mission.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission (mission operated by NOAA)
Partners	NOAA and U.S. Air Force
Earth Science Focus Area	 
Societal Benefit	Without timely and accurate warnings, space weather events like geomagnetic storms caused by changes in solar wind have the potential to disrupt nearly every major public infrastructure system, including power grids, telecommunications, aviation, and Global Positioning System. Data collected by DSCOVR will improve the accuracy and lead time of geomagnetic storm warnings and forecasts.

ECOSTRESS

Status	Launch Date	Life-Cycle Cost
Implementation	2019	$56 million

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission will measure the temperature of plants and use that information to improve understanding of their water needs and response to stress. ECOSTRESS will (1) identify critical thresholds of water use and water stress in key climate sensitive biomes; (2) detect the timing, location, and predictive factors leading to plant water uptake, decline, and/or cessation over the daily cycle; and (3) measure agricultural water consumptive use over the contiguous United States to improve drought estimation accuracy.

Operations Platform	Instrument
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Data will be used to produce the Evaporative Stress Index – a leading drought indicator that can indicate if plants are stressed and whether a drought is likely to occur and therefore provide benefits for food security, water management, and agriculture.

EO-1

Status	Launch Date	Life-Cycle Cost
Extended Operations	2000	$177 million

The Earth Observing-1 (EO-1) mission provides detailed spectral mapping of the Earth's surface. A technology demonstration mission, the overall objective is to perform remote land sensing and explore new remote sensing technologies (instruments, spacecraft, ground segment, etc.).

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	USGS
Earth Science Focus Area	
Societal Benefit	Improve Earth imagery used for classifying land utilization.

GACM

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Global Atmosphere Composition Mission (GACM) will measure ozone and related gases for intercontinental air-quality and stratospheric ozone layer prediction. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	 
Societal Benefit	Help inform the air-quality index.

GEDI

Status	Launch Date	Life-Cycle Cost
Implementation	2019	$127 million

The Global Ecosystem Dynamics Investigation Lidar (GEDI) mission will characterize the effects of changing climate and land use on ecosystem structure and dynamics to improve understanding of the Earth's carbon cycle and biodiversity. Focused on tropical and temperate forests from its vantage point on the ISS, GEDI uses light detection and ranging to examine the forest structure and its relationship to habitat quality and biodiversity and potential ability to sequester carbon dioxide under changing land use and climates.

Operations Platform	Instrument
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Improve climate change monitoring.

GEO-CAPE

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission will measure tropospheric trace gases and aerosols and coastal ocean phytoplankton, water quality, and biogeochemistry from geostationary orbit. The mission will provide multiple daily observations that explore the physical, chemical, and dynamical processes that determine tropospheric composition and air-quality over spatial scales ranging from urban to continental and temporal scales ranging from daily to seasonal. This is a 2007 Decadal Survey Tier 2 recommendation and will be will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Environmental Protection Agency and NOAA
Earth Science Focus Area	 
Societal Benefit	Advance the monitoring, assessment, and forecasting of the health of ocean ecosystems and air quality in the United States and support research and applied or operational efforts in assessments of climate variability and change through improved understanding of biogeochemical cycles and food web impacts.

GOES 13–15

Status	Launch Date	Life-Cycle Cost
Operating	2009 and 2010	n/a

The Geostationary Operational Environmental Satellite, Series (GOES) 13–15, known as GOES N, O, and P before launch, are part of the GOES/Polar Operational Environmental Satellite (POES) Program, a key element in National Weather Service operations.

Operations Platform	Satellite
Associated NASA Program/Division	Missions operated by NOAA
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Provide real-time weather data for use in short-term weather forecasting (warnings of severe weather) and space environment monitoring, as well as research and development.

GOES-R SERIES

Status	Launch Date	Life-Cycle Cost
Implementation	2016	$10.9 billion

Part of the GOES/POES Program, GOES-R through U, are primary tools for the detection and tracking of hurricanes and severe weather.

Operations Platform	Satellite
Associated NASA Program/Division	JASD
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Improved weather forecasting that directly affects public safety, protection of property, and ultimately, economic health and development.

GPM

Status	Launch Date	Life-Cycle Cost
Operating	2014	$928 million

The Global Precipitation Measurement (GPM) mission is part of an international network of satellites that provide global observations of rain and snow every 3 hours.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Primarily Japan Aerospace Exploration Agency along with several other nations
Earth Science Focus Area	  
Societal Benefit	Improve understanding and forecasting of tropical cyclones, extreme weather, floods, landslides, land surface models, the spread of water-borne diseases, agriculture, freshwater availability, and climate change.

GRACE

Status	Launch Date	Life-Cycle Cost
Extended Operations	2002	$162 million

The Gravity Recovery and Climate Experiment (GRACE) mission uses Global Positioning System receivers and a microwave ranging system to measure variations in gravity over Earth's surface, producing a new map of the gravity field every 30 days. GRACE shows how the Earth's gravity differs not only from one location to another, but also from one time period to another. The gravity variations GRACE studies include surface and deep currents in the ocean, runoff and ground water storage on land masses, exchanges between ice sheets or glaciers and the oceans, and variations of mass within the Earth. Another goal of the mission is to create a better profile of the Earth's atmosphere.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	Germany
Earth Science Focus Area	
Societal Benefit	Results from GRACE yield information about how water is transported and stored within the Earth's environment, which provides decision makers details for drought and flood predictions; water usage and availability; and agricultural and maritime industries.

GRACE-FO

Status	Launch Date	Life-Cycle Cost
Implementation	2018	$432 million

The GRACE Follow-on (GRACE-FO) mission will provide scientists with new insights into the dynamic processes in Earth's interior, currents in the oceans, and variations in the extent of ice coverage. In addition to using the same kind of microwave ranging system as GRACE, GRACE-FO will test an experimental instrument that uses lasers to make gravity field measurements 20 times more precise. GRACE-FO data is vital to ensuring continuation of gravitational field measurements began by the GRACE mission.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Germany
Earth Science Focus Area	
Societal Benefit	Data from GRACE-FO, combined with other existing sources of data, will improve scientific understanding of glaciers and hydrology.

GRACE-II

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

Grace-II will track large-scale water movement through the study of Earth's gravity fields using high-temporal-resolution technology. The GRACE missions measure variations in gravity over the Earth's surface, producing a new map of the gravity field every 30 days. GRACE-II will extend and improve on the first GRACE mission. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Germany
Earth Science Focus Area	
Societal Benefit	Improve climate change and variability prediction by tracking sea levels, water storage, and ice formations.

HYSPIRI

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Hyperspectral Infrared Imager (HyspIRI) mission will study Earth's ecosystems, providing a benchmark against which future changes can be assessed. The mission will identify presence, type, and health of vegetation and assess the pre-eruptive behavior of volcanoes, the likelihood of future eruptions, and carbon and other gases released from wildfires. This is a 2007 Decadal Survey Tier 2 recommendation and will be will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Improve food security monitoring, weather forecasting, environmental contaminant monitoring, and exploration of natural resources.

ICESAT-2

Status	Launch Date	Life-Cycle Cost
Implementation	2018	$1.1 billion

The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission measures ice sheet mass balance, cloud and aerosol heights and land topography and vegetation characteristics. As envisioned by the 2007 Decadal Survey, the follow-on ICESat-2 mission will continue to assess polar ice changes.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Allows estimation of sea-level rise which can impact coast communities.

JASON-3

Status	Launch Date	Life-Cycle Cost
Operating	2015	$364 million

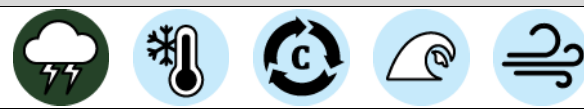
The fourth in a series of U.S.-European satellite missions, Jason-3 provides continuity of coverage related to extreme weather events, operational oceanography, climate applications, and forecasting. The mission will take highly detailed measurements of sea surface height to examine sea level rise and currents – a critical factor in understanding Earth's dynamic climate.

Operations Platform	Satellite
Associated NASA Program/Division	Mission operated by NOAA
Partners	NOAA and France
Earth Science Focus Area	
Societal Benefit	Provides information vital to the public and maritime community regarding hurricane intensity, tsunami dynamics, El Niño Southern Oscillation, eddy dynamics, ocean boundary currents, coastal and shallow water tides, and weather and climate forecasting.

JPSS 1–4

Status	Launch Date	Life-Cycle Cost
Implementation (JPSS 1)	2017	$1.6 billion
Formulation (JPSS 2)	–	–
Pre-Formulation (JPSS 3 and 4)	–	–

The Joint Polar Satellite System (JPSS) is the next-generation polar-orbiting operational environmental satellite system for the United States. A collaboration between NOAA and NASA, JPSS satellites will provide global coverage of the Earth twice a day and use microwave and infrared data to measure rainfall rates, sea ice, snow and surface temperatures, atmospheric chemistry, and cloud properties. JPSS will also use visible/infrared imagery to provide information on chlorophyll, cloud imagery, cloud products, sea surface temperatures, fires, smoke, ice, and oil spills.

Operations Platform	Satellite
Associated NASA Program/Division	JASD
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Used to provide early warnings on hazardous weather conditions, enhanced weather prediction capabilities, and real-time storm tracking, thus reducing potential loss of human life and property and advancing the national economy. Will also allow for improved understanding of Earth's ecosystems, which will inform resource management decisions, and improved coastal water quality support, which will enable coastal communities to more effectively manage resources.

LAGEOS 1 AND 2

Status	Launch Date	Life-Cycle Cost
Operating	1976 and 1992	n/a

The Laser Geodynamics Satellites (LAGEOS) 1 and 2 monitor the motion of the Earth's tectonic plates, gravitational field, and the "wobble" in the Earth's axis of rotation. At the time of development, these missions were budgeted outside of ESD; therefore life-cycle cost could not be verified.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Italy
Earth Science Focus Area	
Societal Benefit	Used to improve determinations of the length of a day on Earth and provide insight into the causes of earthquakes.

LANDSAT 7

Status	Launch Date	Life-Cycle Cost
Extended Operations	1999	$500 million

The seventh in a series of satellites, Landsat 7 is a joint mission between NASA and USGS that provides multispectral, medium resolution, seasonal global coverage of Earth's land surfaces. The Earth observing instrument on Landsat 7 measures changes to permit studies of land cover and land use change over multi-decadal periods. Landsat data constitute the longest continuous record of the global land surface as seen from space.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission (mission operated by USGS)
Partners	USGS
Earth Science Focus Area	
Societal Benefit	Landsat data is critical for understanding and managing forests, changes in farming technologies, monitoring changes in urban landscapes, responding to wild fires, measuring the extent of flood and storm damage, examining wildlife habitat, measuring glacial retreat, and mapping the Antarctic ice sheet.

LANDSAT 8

Status	Launch Date	Life-Cycle Cost
Operating	2013	$931 million

Landsat 8 is a joint mission between NASA and USGS that provides multispectral, medium resolution, seasonal global coverage of the Earth's land surfaces. The Earth observing instrument on Landsat 8 measures changes in the Earth's landscape to permit studies of land cover and land use change over multi-decadal periods. Landsat data constitute the longest continuous record of the global land surface as seen from space.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission (mission operated by USGS)
Partners	USGS
Earth Science Focus Area	
Societal Benefit	Landsat data is critical for understanding and managing forests, changes in farming technologies, monitoring changes in urban landscapes, responding to wild fires, measuring the extent of flood and storm damage, examining wildlife habitat, measuring glacial retreat, and mapping the Antarctic ice sheet.

LANDSAT 9

Status	Launch Date	Life-Cycle Cost
Formulation	No Earlier Than 2020	$851–928 million

Landsat 9 is a joint mission between NASA and USGS that provides multispectral, medium resolution, seasonal global coverage of Earth's land surfaces. The Earth observing instrument on Landsat 9 measures changes in the Earth's landscape to permit studies of land cover and land use change over multi-decadal periods. Landsat data constitute the longest continuous record of the global land surface as seen from space.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	USGS
Earth Science Focus Area	
Societal Benefit	Landsat data is critical for understanding and managing forests, monitoring changes in farming technologies, monitoring changes in urban landscapes, responding to wild fires, measuring the extent of flood and storm damage, examining wildlife habitat, measuring glacial retreat, and mapping the Antarctic ice sheet.

LIS

Status	Launch Date	Life-Cycle Cost
Implementation	2017	$6.4 million

Flown on the ISS, the Lightning Imaging Sensor (LIS) will monitor global lightning for Earth science studies and provide cross-sensor calibration and validation with other space-borne instruments and ground-based lightning networks. LIS will also supply real-time lightning data over data-sparse regions, such as oceans, to support weather forecasting and warning.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Will provide important gap-filling information vital to a wide range of issues, including weather, climate, atmospheric chemistry, and lightning physics.

LIST

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

Using laser altimetry, the Lidar Surface Topography (LIST) mission will provide the most precise global topographic survey to date, permitting the mapping of landslide, earthquake, and flood hazards at a sufficiently small scale to inform site-specific land use decisions. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Observations will help scientists find active faults, map the global loss of topsoil, and detect signs of potential volcanic activity. Global measurements of vegetation height will advance studies of forest and land-cover dynamics and allow quantitative assessment of wildfire risk.

MAIA

Status	Launch Date	Life-Cycle Cost
Formulation	No earlier than 2023	$127.5–130.5 million

The Multi-Angle Imager for Aerosols (MAIA) mission will provide measurements needed to characterize the sizes, compositions, and quantities of particulate matter in air pollution. As part of the MAIA investigation, researchers will combine MAIA measurements with population health records to better understand the connections between aerosol pollutants and health problems such as adverse birth outcomes, cardiovascular and respiratory diseases, and premature deaths.

Operations Platform	Instrument
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	 
Societal Benefit	Studies connection between pollutants and health.

NISAR (DESDYNI)

Status	Launch Date	Life-Cycle Cost
Implementation	2022	$867 million

A component from the cancelled Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynl) mission, the NASA-ISRO Synthetic Aperture Radar (NISAR) mission – a collaboration between NASA and the Indian Space Research Organisation – will acquire radar images of surface changes resulting from ice-sheet collapse, earthquakes, tsunamis, volcanoes, and landslides, and produce images both detailed enough to detect local changes and broad enough to measure regional trends.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	India
Earth Science Focus Area	
Societal Benefit	Allow for improved resource management and improve public health and safety by decreasing exposure to natural hazards.

NOAA-15

Status	Launch Date	Life-Cycle Cost
Operating	1998	n/a

NOAA-15 (known as NOAA-K before launch) is a polar-orbiting satellite developed by NASA for NOAA that collects data on the Earth's atmosphere, surface, and cloud cover.

Operations Platform	Satellite
Associated NASA Program/Division	Mission operated by NOAA
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	The data collected by NOAA-15 aid in environmental studies, such as climate change studies, vegetation monitoring, biomass burning, El Niño effects, pollution and sea ice tracking, as well as both near and long-range weather forecasting information. In addition, the NOAA polar orbiting satellites are major contributors toward international search and rescue operations.

NOAA-18

Status	Launch Date	Life-Cycle Cost
Operating	2010	n/a

A polar-orbiting satellite developed by NASA for NOAA, NOAA-18 (known as NOAA-N before launch) collects data on the Earth's atmosphere, surface, and cloud cover.

Operations Platform	Satellite
Associated NASA Program/Division	Mission operated by NOAA
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	The data collected by NOAA-18 is transmitted to NOAA's Satellite and Information Service, which processes the data for the National Weather Service for its long-range weather and climate forecasts. Forecasters worldwide can access the satellite's images and data.

NOAA-19

Status	Launch Date	Life-Cycle Cost
Operating	2009	n/a

The NOAA-19 satellite (known as NOAA-N Prime before launch) is the fifth in a series of polar-orbiting satellites and includes improved imaging and sound capabilities that measure the Earth's atmosphere, surface, and cloud cover.

Operations Platform	Satellite
Associated NASA Program/Division	Mission operated by NOAA
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	The data collected by NOAA-19 is transmitted to NOAA's Satellite and Information Service, which processes the data for the National Weather Service for its long-range weather and climate forecasts. Forecasters worldwide can access the satellite's images and data.

OCO-2

Status	Launch Date	Life-Cycle Cost
Operating	2014	$467.5 million

The Orbiting Carbon Observatory-2 (OCO-2) is collecting precise, high-resolution measurements of atmospheric carbon dioxide. These measurements are combined with data from the ground-based network to provide scientists with information to better understand the processes that regulate atmospheric carbon dioxide and its role in the carbon cycle. OCO-2 will study how natural sources of carbon dioxide, as well as sinks, are distributed around the globe and how they change over time.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	OCO-2 data is essential for improving predictions of future atmospheric carbon dioxide increases and their impact on Earth's climate, which will enable decision makers to more effectively manage the Earth's natural resources and design and implement strategies that minimize human contribution to increased atmospheric carbon dioxide.

OCO-3

Status	Launch Date	Life-Cycle Cost
Implementation	2018	$115 million

Orbiting Carbon Observatory-3 (OCO-3) is a complete stand-alone payload built using spare parts from OCO-2, with additional elements added to accommodate installation and operation on the ISS. The OCO-3 instrument will collect space-based measurements of atmospheric carbon dioxide with the precision, resolution, and coverage needed to assess the spatial and temporal variability of carbon dioxide over an annual cycle.

Operations Platform	Instrument
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Will provide similar data to OCO-2 but allow for improved tracking of photosynthesis changes over the course of a day.

OMPS-LIMB

Status	Launch Date	Life-Cycle Cost
Formulation	2021	$20 million

The Ozone Mapping and Profiler Suite (OMPS), an advanced suite of two hyper spectral instruments, tracks the health of the Earth's ozone layer and measures the concentration of ozone in the Earth's atmosphere. NASA will provide the OMPS-Limb profiler, which will be integrated onto the JPSS-2 satellite and is designed to provide high-vertical resolution ozone profiles and measure aerosols.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	NOAA for the full OMPS
Earth Science Focus Area	
Societal Benefit	When combined with cloud predictions, data collected by the OMPS-Limb instrument will produce better ultraviolet index forecasts, which help the public take precaution against harmful UV sun rays.

OSTM

Status	Launch Date	Life-Cycle Cost
Extended Operations	2008	$158 million

Mounted on the Jason-2 satellite, the Ocean Surface Topography Mission (OSTM) uses a radar altimeter to measure sea surface height, one of the most important indicators of global climate change.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	NOAA, France, and the European Organization for the Exploitation of Meteorological Satellites
Earth Science Focus Area	 
Societal Benefit	Data is used in a variety of applications, such as routing ships, improving the safety and efficiency of offshore industry operations, managing fisheries, and tracking marine mammals.

PACE

Status	Launch Date	Life-Cycle Cost
Formulation	No earlier than 2022	$805–850 million

Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE) is a satellite mission to study Earth's aquatic ecology and chemistry. The PACE sensor will allow scientists to see the colors of the ocean, from the ultraviolet to near infrared, and obtain more accurate measurements of biological and chemical ocean properties such as phytoplankton biomass and the composition of phytoplankton communities. PACE will also measure clouds and tiny airborne particles like dust, smoke, and aerosols in the atmosphere to supplement measurements from other NASA satellite missions.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Will provide improved monitoring of water quality and water resources. For example, will enable refined detection, tracking, and assessment of the effects of hurricanes, oil spills and seeps, volcanic ash plumes, and fires to improve evaluation of the impact on marine and terrestrial ecosystems and human health.

PATH

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Precipitation and All-weather Temperature and Humidity (PATH) mission will provide the first geostationary platform for a microwave spectrometer and infrared sounder to operate in tandem. PATH will analyze temperature and water vapor as well as sea surface temperature and precipitation. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	PATH will increase the accuracy of weather forecasts through improved models of the atmosphere's lowest kilometer and the processes that shape clouds, rainfall, and snowfall; increase the accuracy of hurricane track, intensity, and storm surge forecasts; and enhance flood prediction.

RAPIDSCAT

Status	Launch Date	Life-Cycle Cost
Operating	2014	$34.8 million

Operating from the ISS, RapidScat measures wind speed and direction over the ocean.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Used for weather forecasting, hurricane monitoring, and observations of large-scale climate phenomena like El Niño.

RBI

Status	Launch Date	Life-Cycle Cost
Implementation	2021	$305 million

Observations from the Radiation Budget Instrument (RBI), which will fly on JPSS-2, will help measure Earth's reflected sunlight and emitted thermal radiation to determine the effect of clouds on the planet's energy balance, a strong influence on both weather and climate. Long-term satellite data from RBI will help scientists and researchers understand the links between the Earth's incoming and outgoing energy and the properties of the atmosphere that affect this energy change.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Data from RBI will provide fundamental inputs to extended range (10-days or longer) weather forecasting.

SAGE-III

Status	Launch Date	Life-Cycle Cost
Implementation	2016	$133 million

From its perch aboard the ISS, the Stratospheric Aerosol and Gas Experiment III (SAGE-III) instrument provides global, long-term measurements of key components of the Earth's atmosphere. Most importantly, SAGE-III measures the vertical distribution of aerosols and the Earth's ozone layer from the upper troposphere through the stratosphere. It also provides unique measurements of temperature in the stratosphere and mesosphere and profiles of trace gases such as water vapor and nitrogen dioxide, both of which play significant roles in atmospheric radiative and chemical processes.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	European Space Agency and NOAA
Earth Science Focus Area	
Societal Benefit	Data from SAGE-III will improve understanding of the Earth's climate, climate change, and human-induced ozone trends.

SCLP

Status	Launch Date	Life-Cycle Cost
Pre-Formulation	–	–

The Snow and Cold Land Processes (SCLP) mission will measure global snow accumulation; snow cover, edge, and depth; and snow surface temperature. This is a 2007 Decadal Survey Tier 3 recommendation and will be revisited by the 2017 Decadal Survey in terms of priority and scope.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Improve management of water resources in snowmelt-dominated river basins; assess the risk of snowmelt-induced floods and flow of debris; and predict the impact of climate change on seasonal snow packs.

SENTINEL-6A AND 6B

Status	Launch Date	Life-Cycle Cost
Pre-Formulation (Sentinel-6A)	No earlier than 2020	–
Pre-Formulation (Sentinel-6B)	No earlier than 2025	–

Formerly known as Altimetry Follow-on (AFO) and a part of the Copernicus Program of Earth observing satellites, Sentinel-6 will provide measurements of global sea-level and ocean topography measurements. NASA will provide the payload and launch the satellites. NASA will also provide three instruments: Advanced Microwave Radiometer-Climate Quality (AMR-C), Laser Retroreflector Array (LRA), and GNSS Receiver for Radio Occultation Science (GNSS-RO).

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	European Space Agency, NOAA, and the European Organization for the Exploitation of Meteorological Satellites
Earth Science Focus Area	
Societal Benefit	Improve monthly and seasonal forecasts of the weather conditions (e.g., heat waves or sustained heavy downpours; a cold winter or a hot summer) as a result of the ocean's influence on the atmosphere.

SMAP

Status	Launch Date	Life-Cycle Cost
Operating	2015	$915 million

The Soil Moisture Active-Passive (SMAP) mission measures water in the top 5 centimeters (2 inches) of soil and distinguishes between ground that is frozen or thawed. Where the ground is not frozen, SMAP measures the amount of water found between the minerals, rocky material, and organic particles found in soil.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Improve understanding of how water and carbon (in its various forms) circulate. Data used to monitor draughts, predict floods, assist crop productivity, and improve weather forecasting.

SORCE

Status	Launch Date	Life-Cycle Cost
Extended Operations	2003	$142 million

The Solar Radiation and Climate Experiment (SORCE) mission measures the Sun's energy via incoming X-ray, ultraviolet, visible, near infrared, and total solar radiation found at the top of Earth's atmosphere.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	None
Earth Science Focus Area	
Societal Benefit	Enables researchers to learn more about how the Sun affects Earth's climate.

S-NPP

Status	Launch Date	Life-Cycle Cost
Operating	2011	$845.2 million

The Suomi National Polar-orbiting Partnership (S-NPP) provides measurements in support of long-term monitoring of climate trends and global biological productivity. The mission provides a bridge between NASA's EOS missions and the JPSS by extending measurements initiated with the EOS Terra and Aqua missions. The five instruments on S-NPP provide visible and infrared multi-spectral global imagery, atmospheric temperature and moisture profiles, total ozone and stratospheric ozone profiles, and measurements of Earth's radiation balance.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission (Mission operated by NOAA)
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Monitor wildfires, volcanic eruptions, snowstorms, droughts, floods, hurricanes, and dust plumes; provide accurate weather prediction; predict and respond to food shortages and famines; and monitor the spread of pollutants.

SWOT

Status	Launch Date	Life-Cycle Cost
Implementation	2022	$755 million

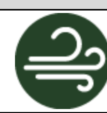
The Surface Water and Ocean Topography (SWOT) mission will contribute to a better understanding of the world's oceans and its terrestrial surface waters by making high-resolution measurements of ocean circulation. SWOT will provide broad-swath sea surface heights and terrestrial water heights for at least 90 percent of the globe using a dual-antenna Ka-band Radar Interferometer.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	France, Canada, and the United Kingdom
Earth Science Focus Area	 
Societal Benefit	Data collected by SWOT will improve flood, draught, and water reservoir management.

TEMPO

Status	Launch Date	Life-Cycle Cost
Implementation	2021	$218 million

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission will measure pollution in North America hourly and at high spatial resolution. TEMPO's measurements of tropospheric ozone, aerosols, and clouds will create a dataset that provides an understanding of and improves prediction of air quality and the amount of energy Earth receives from the Sun and the planet radiates back to space.

Operations Platform	Instrument
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Data will improve emission inventories, monitor population exposure, and enable effective emission-control strategies.

TERRA

Status	Launch Date	Life-Cycle Cost
Extended Operations	1999	$1.58 billion

Terra is the flagship satellite of NASA's Earth observing systems, carrying five instruments that observe Earth's atmosphere, ocean, land, snow and ice, and energy being released and consumed. Taken together, these observations provide unique insight into how the Earth system works and how it is changing.

Operations Platform	Satellite
Associated NASA Program/Division	Earth Systematic Mission
Partners	Canada and Japan
Earth Science Focus Area	
Societal Benefit	Improve emergency management and disaster assessment, air quality measurements, volcanic ash monitoring, forest fire monitoring, and crop assessment.

TCTE

Status	Launch Date	Life-Cycle Cost
Operations	2013	$14 million

Total solar irradiance Calibration Transfer Experiment (TCTE) – funded by NOAA as part of the JPSS mission – is designed to measure light from the Sun and determine whether solar changes influence Earth's climate. TCTE is an interim solution to maintain and extend the solar irradiance data record until the launch of the Total Solar Irradiance Sensor (TSIS). Life-cycle cost accounts for integration on to a spacecraft and 2 years of operations.

Operations Platform	Instrument
Associated NASA Program/Division	JASD
Partners	NOAA and USAF
Earth Science Focus Area	
Societal Benefit	Improve understanding of Earth's present climate and help predict future climate.

TROPICS

Status	Launch Date	Life-Cycle Cost
Formulation	No earlier than 2023	$40–42 million

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) will provide rapid-refresh microwave measurement to observe the thermodynamics and precipitation structure of tropical cyclones over their lifecycle. The measurements will provide nearly all-weather observation of 3D temperature and humidity, as well as cloud ice and precipitation horizontal structure.

Operations Platform	Satellite
Associated NASA Program/Division	Earth System Science Pathfinder
Partners	None
Earth Science Focus Area	
Societal Benefit	Improved understanding of tropical cyclones.

TSIS-1 AND -2

Status	Launch Date	Life-Cycle Cost
Implementation (TSIS-1)	2018	$86 million
Pre-Formulation (TSIS-2)	–	–

To be flown on the ISS, the Total Solar Irradiance Sensor (TSIS) instruments will provide measurements of the total solar irradiance, which is required for establishing Earth's total energy input, and spectral solar irradiance, which is necessary to understanding how the atmosphere responds to changes in the Sun's output. These measurements are important for accurate scientific models of climate change and solar variability.

Operations Platform	Instrument
Associated NASA Program/Division	Earth Systematic Mission
Partners	NOAA
Earth Science Focus Area	
Societal Benefit	Data collected by TSIS instruments will improve understanding of the present climate epoch and be used for predicting the Earth's future climate.

Appendix C: Management's Comments

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

OCT 3 1 2016

Reply to Attn of: Science Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Science Mission Directorate

SUBJECT: Agency Response to OIG Draft Report "NASA's Earth Science Mission Portfolio" (A-15-014-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled "NASA's Earth Science Mission Portfolio" (A-15-014-00), dated September 30, 2016.

The OIG makes two recommendations addressed to the Associate Administrator for Science Mission Directorate (AA/SMD) intended to improve NASA's management of its Earth science portfolio. Specifically, the OIG recommends that the AA/SMD:

Recommendation 1: Update the Architecture Plan every 5 years to align with the release of Earth Science Decadal Surveys and mid-term Surveys and account for portfolio changes.

Management's Response: Concur. The primary objective of the Architecture Plan is to document a realistic, executable, integrated portfolio of mission and non-flight activities for the Earth Science Division (ESD) – a strategic portfolio informed substantially by the National Academies' Decadal Survey but also incorporating Administration priorities and realistic budget constraints.

NASA embraces the OIG's recommendation to update the Architecture Plan on a 5-year cadence. Given the Plan's essential objective to respond to both Decadal Survey and Administration priorities within a realistic budgetary constraint; the upcoming release of the next Earth Science and Applications from Space Decadal Survey at the end of CY2017; and the upcoming Administration transition (with new NASA leadership and Administration budget allocations realistically expected no earlier than the second half of CY2017 and likely even later based on history), NASA/SMD/ESD will target release of the next Architecture Plan for approximately June 2019. This phasing will mesh well with both the OIG's recommendation for 5-year updates and with the statutory requirement that the National Academies provide mid-term reviews of NASA's progress on each Decadal Survey, the third Architecture Plan will be targeted for release in mid-2024, and will, thus, be informed by the expected late CY2022 Academies Mid-Term review of ESD progress.

Estimated Completion Date: June 2019 or approximately 18 months after the release of the 2017 Decadal Survey.

Recommendation 2: Develop strategies to engage with commercial companies to investigate cost-beneficial acquisition, disposition, and use of Earth observing data.

Management's Response: Concur. NASA agrees with the OIG's recognition of the private/commercial sector's potentially beneficial contributions to Earth observation, research, and applications development. We, likewise, agree with the OIG recommendation that NASA/SMD/ESD take proactive steps to investigate and identify specific private sector measurement sets and data products that could cost-efficiently advance ESD's science and applications objectives. To this end, ESD will continue to pursue and expand (insofar as appropriated funds are available) its ongoing programs supporting the private sector, such as: (1) small, low-cost launch vehicle development (the present VCLS [Venture Class Launch Services program] currently funding Firefly, RocketLabs USA, and Virgin Galactic to mature and demonstrate low-cost launch vehicles capable of orbiting ESD cubesat and smallsat payloads by April 2018); and (2) smallsat constellations (the SmallSat Constellation Initiative proposed in the President's FY17 budget request, and building on NASA/ESD's SmallSat Constellation Data Buy Request for Information released in July 2016 and the strong industry responses received). ESD will continue to interact and coordinate closely with National Oceanographic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NESDIS) and other agencies, and with the White House United States Group on Earth Observations (USGEO) observation assessment process, to ensure that NASA both supports appropriately and benefits from data buys and related public-private partnerships that may be developed external to NASA.

Estimated Completion Date: Based on the in-hand results of the SmallSat Constellation RFI and anticipating eventual Congressional appropriation of the SmallSat Constellation Initiative activity in the President's FY17 Budget Request, in 2017-2018 NASA/ESD anticipates competitively soliciting (via a Request for Order or Broad Agency Announcement, as appropriate) one to two pilot data buys of Earth observation products resulting from privately developed and launched small satellite constellations. NASA/ESD will provide OIG a copy of the competitive solicitation by August of 2018.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Peter Meister on (202) 358-1557.

Thomas Zurbuchen

Appendix D: Report Distribution

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