Satellite Observations to Benefit Science and Society: Recommended Missions for the Next Decade

Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, Robert Henson, Editor, National Research Council

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SATELLITE OBSERVATIONS TO BENEFIT SCIENCE AND SOCIETY

RECOMMENDED MISSIONS FOR THE NEXT DECADE

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[1]Term ended January 2006.
[2]The committee notes with deep regret Anthony Hollingsworth's death on July 29, 2007.

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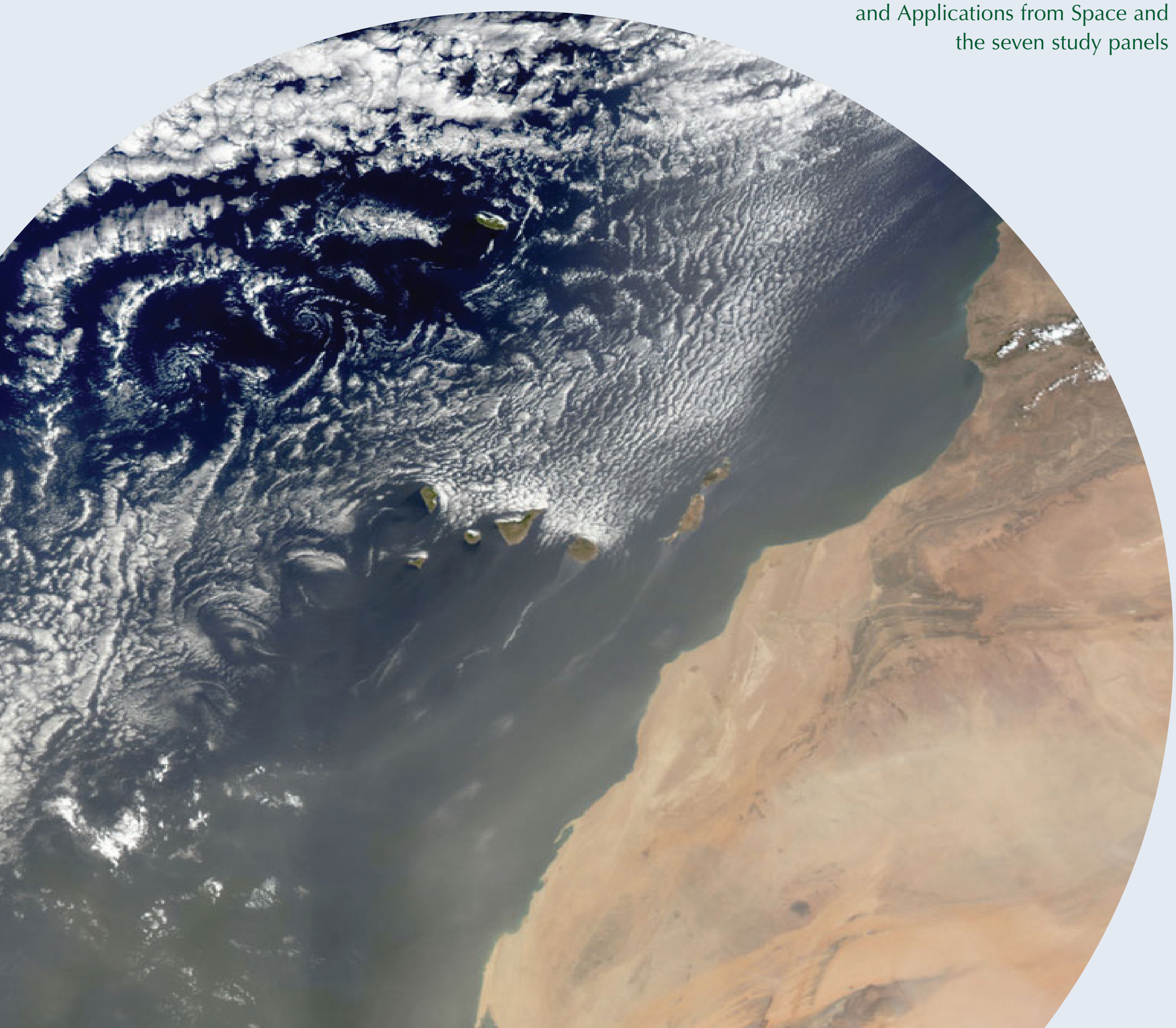
[1]Through May 2005.
[2]Through June 2006.
[3]From August 2006.

ANTHONY HOLLINGSWORTH

It was with great sadness that the committee and the panels of the decadal survey learned of the death of Anthony Hollingsworth on July 29, 2007. Tony was one of the leaders of the decadal survey, arguing for the importance of diverse observations from satellites and other platforms to produce the most accurate and consistent analysis of the Earth system possible for initializing prediction models of the atmosphere, oceans, and land.

A longtime scientist at the European Centre for Medium-Range Weather Forecasts, Tony was a giant among his peers in numerical weather prediction and analysis, data assimilation, and the use of weather forecasts to meet broad societal needs. Tony was dedicated to the use of satellite observations of Earth to improve weather predictions for the benefit of society. He worked tirelessly in the scientific and political trenches of the world, always sharing his knowledge and valuable ideas with others in his gentle, unselfish way. He inspired people of all ages throughout his long and productive career, which still ended all too soon. He was a close friend of all who were fortunate enough to know him well. We will miss him greatly.

Richard A. Anthes and Berrien Moore III, *Co-chairs,*
on behalf of the Committee on Earth Science
and Applications from Space and
the seven study panels



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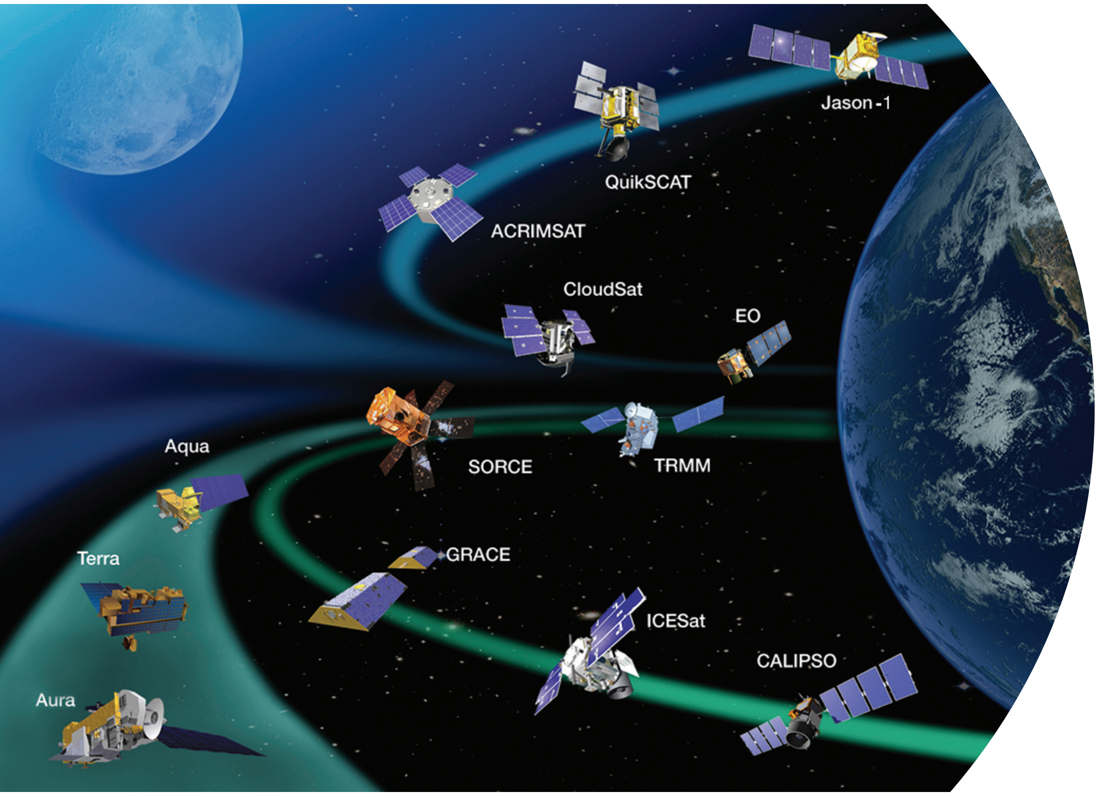
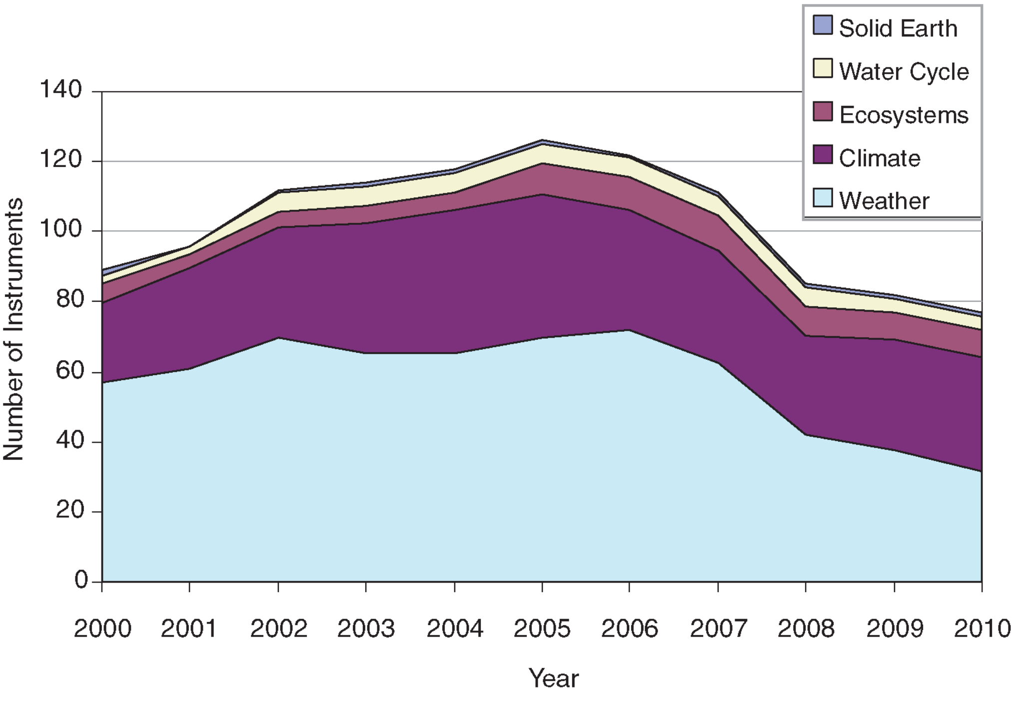


Together with spacecraft operated by NOAA and U.S. international partners, NASA's Earth Observing System, a coordinated series of low-Earth-orbiting satellites, provides observations of the land surface, biosphere, solid Earth, atmosphere, and oceans that are essential to understanding and predicting global environmental change. (Not shown: SeaWiFS.)



Number of U.S. space-based Earth observation instruments in the current decade, based on information from NASA and NOAA Web sites for mission durations.

AN INTEGRATED STRATEGY

SATELLITE OBSERVATIONS TO BENEFIT SCIENCE AND SOCIETY

Natural and human-induced changes in the Earth system—from our planet's interior to the land surface, atmosphere, and oceans—affect all aspects of life. If we are to understand and respond to these changes, we need a foundation of observations collected from the land, sea, air, and space, integrated for maximum usefulness in forecast models and other tools for decision making.

The United States has made great strides in building and deploying a sophisticated set of Earth-monitoring satellites. In 2004, the National Aeronautics and Space Administration (NASA) completed its Earth Observing System (see facing page), whose centerpiece is three multi-instrumented spacecraft—Terra, Aqua, and Aura—that together provide data for characterizing most of the major Earth system components. For decades, Earth's landscape has been studied and documented through the Landsat mission, a long-term collaboration between NASA and the U.S. Geological Survey (USGS). Steady improvement in U.S. weather forecasts and climate projections is due in large part to the network of operational satellites managed by the National Oceanic and Atmospheric Administration (NOAA) and the NASA research satellite fleet.

But this extraordinary legacy of global observations and benefits is now in serious danger. Many NASA satellites are well past their originally projected lifespan. Funding pressures are affecting plans for operational and research missions at both NASA and NOAA. Between 2006 and 2010 the overall number of U.S. space-based sensors will likely decrease by 35 to 40 percent (see graph on facing page). As a result, forecasts of hurricanes and other severe weather events could suffer, and major gaps may develop in some of the data sets most crucial to monitoring the Earth system and detecting changes in global climate.

In 2004, NASA, NOAA, and the USGS asked the National Research Council to conduct a decadal survey of the Earth sciences community. The charge was to recommend a prioritized list of flight missions and supporting activities for space-based Earth observation over the next decade (through the 2010s) and to identify key factors in planning for the decade beyond (into the 2020s). This booklet highlights the key points made in the final report of the survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (available at http://books.nap.edu/catalog.php?record _id=11820). The study was led by the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, a group of experts from the natural and social sciences that drew on the work of seven crosscutting panels as well as input from more than 100 community members.

As discussed in the survey report, scientific and technical advances make it possible to design a highly productive and integrated suite of satellite-based Earth sensors, capable of providing observations that address a broad range of societal needs. The desire for an integrated observing capability reflects both the increasingly interdisciplinary nature of Earth science and the growing complexity and interrelated nature of the knowledge and information required to meet pressing national needs. Our Earth observing system must also become more efficient to meet these needs within challenging budgetary constraints. The needed capabilities can be achieved as long as upcoming missions are coordinated and structured to complement each other and timed to ensure an unbroken record of key environmental variables. Otherwise, there is a serious risk that important yet aging capabilities will go unreplaced, that potential benefits to society will go unrealized, and that the United States will lose its global standing as a leader in Earth observation.

CRITICAL AREAS FOR EARTH SYSTEM OBSERVING

IMPROVING WEATHER AND CLIMATE FORECASTS

European agencies have overtaken their U.S. counterparts in an array of pivotal capabilities, such as 3- to 10-day weather forecasts. New observing tools are critically needed, along with enhanced computing capacity, improved atmospheric models, and techniques for assimilating the new data into those models.

PROTECTING AGAINST SOLID-EARTH HAZARDS

Scientists who study the solid Earth are hampered by a lack of data, much like weather forecasters before the satellite era. Scientists cannot reliably tell which tectonic faults are most likely to rupture and produce earthquakes and tsunamis. They are also constrained in their ability to detect and interpret precursors of volcanic eruptions and landslides.

ENSURING OUR WATER RESOURCES

The nation's water supply is of paramount importance to economic development, public health and safety, food production, and recreation. Severe drought over the last few years has struck parts of the West and Southwest where population growth is among the nation's most rapid. Yet our ability to observe, predict, and adapt to large variations in the hydrologic cycle is inadequate.

Mindful of these issues, the committee thus offers the following overarching recommendation: *The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications.*

The committee and its panels assert that the effort to obtain practical benefits for humankind can and should play an equal role with the quest to acquire new knowledge about Earth. The overarching objective is a program of science and applications that will protect life and property, enhance economic competitiveness, address profound scientific questions, and assist in the stewardship of our home planet for present and future generations.

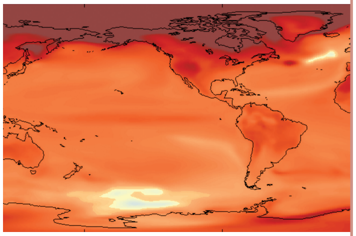
In support of this vision, the committee recommends a set of 17 Earth observing missions, summarized on pages 8 and 9 of this booklet and described in more detail on pages 10–26. The effort to select and prioritize these missions, as discussed on pages 5–7, involved researchers from an unusually broad set of specialties—geology, oceanography, atmospheric science, ecology, and others. Bringing representatives of these disciplines together was itself a landmark effort, as many of the disciplines had no tradition of working together to forge a set of common research priorities.

MAINTAINING HEALTHY, PRODUCTIVE OCEANS

Satellite measurements have revolutionized our understanding of ocean circulation, biology, and interactions with the atmosphere. Many of the sources of these measurements, however, are now at risk because of budget constraints and programmatic choices. Climate change brings new risks for marine life due to ocean warming, changes in circulation, and acidification from increased atmospheric carbon.

ASSESSING AND MITIGATING CLIMATE CHANGE

There are major weaknesses in national and global systems for monitoring climate, and there is no plan for producing a benchmark record of critical variables. Reliable global data are required to test difficult and important research questions, such as how clouds and radiation will interact in a warming climate. Also, nations attempting to regulate and manage their greenhouse emissions need regional data on carbon sources and sinks.

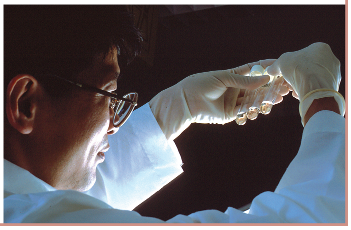


PROTECTING ECOSYSTEMS

Space-borne sensors have helped to quantify dramatic changes to Earth's surface, including the conversion of more than 20 percent of land areas to cropland, the loss of half the world's wetlands and mangrove forests, and the clearing of some 25 percent of the planet's forests. Yet more data are needed to answer key questions. For example, we lack adequate region-by-region estimates of total biomass and how it is changing.

IMPROVING HUMAN HEALTH

Decision makers in public health now use satellite-derived data and information on land, oceans, weather, climate, and atmospheric pollutants. With improved satellite observations, specialists will be able to detect health-threatening environmental change more quickly, identify areas at risk in more detail, and carry out targeted interventions to preserve life and health.



The survey report reflects the committee's best judgment—informed by the work of the cross-cutting panels and discussion with the scientific community—about which Earth observation missions are most important for developing and sustaining the Earth system enterprise. Participants strove to create a program of integrated and complementary observations that will remain robust despite inevitable program changes due to budgetary considerations as well as evolving scientific and societal needs. Missions were selected and phased so as to produce a balanced and integrated program, and the overall range of observations was carefully chosen to accommodate a variety of research goals and provide important societal benefits. Obtaining the necessary *range* of continuous observations, rather than implementing individual missions, is the top priority.

To achieve a fully integrated system capable of providing the desired scientific and societal benefits, the observational tools recommended in the survey report cannot stand alone. They must be part of an Earth information system that connects satellite-retrieved data to forecasting models, information dissemination tools, and other important components. The committee also recommends that the prioritized missions be integrated with in situ observational systems and accompanied by a strong program of Earth science research and analysis. Steps in these directions are discussed on pages 27–31.

EARTH SENSING TO INFORM SOCIETY

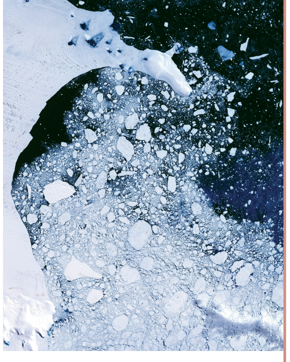
HURRICANE KATRINA

The nation's worst natural disaster in modern times, Katrina was responsible for more than 1,700 deaths, more than $100 billion in damage, and countless other impacts on southeast Louisiana and coastal Mississippi. The human toll could have been far worse were it not for timely and accurate warnings from NOAA, based on computer models that incorporated space- and aircraft-based observations. Forecasters also consulted new data sources recently incorporated into forecast models, such as upper-ocean heat content derived from satellite observations. For example, altimetry readings from NASA satellites showed that the sea-surface height along Katrina's path in the central Gulf of Mexico was up to 70 centimeters above average, a sign of unusually deep warm water that may have contributed to the hurricane's growth to Category 5 status. Although Katrina's track was well predicted, forecasts of the location and magnitude of the storm surge were less accurate, indicating the need for continued research and better observations.

Following Katrina, high-resolution satellite imagery showed where flood waters had receded, providing valuable assistance to relief and recovery efforts. Satellite data are also being used to identify the rate of subsidence in the Mississippi Delta, including New Orleans—valuable information for use in efforts to rebuild and also to address long-term environmental challenges.

ICE SHEET DECAY

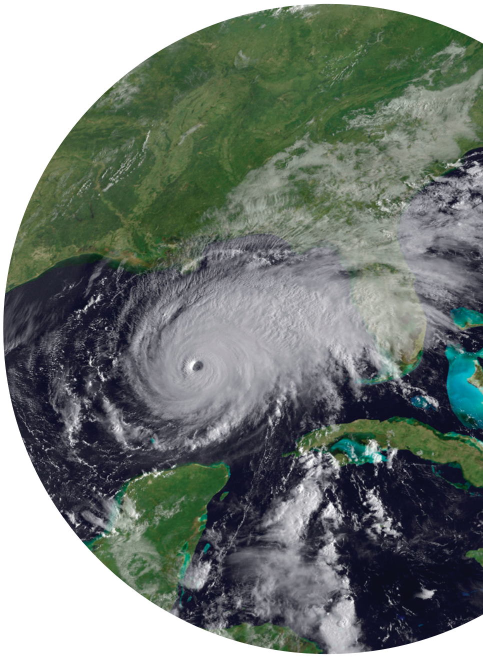
One of the greatest risks of human-induced climate change is the possibility that some of the world's major ice sheets, including those atop Greenland and West Antarctica, could melt partially or completely if global average temperature rises by as little as 3°C. These ice sheets are now being monitored from space by the Gravity Recovery and Climate Experiment (GRACE), a collaboration between NASA and the German Aerospace Center. By measuring tiny changes in the separation between the two GRACE spacecraft, the system generates precise maps of month-to-month changes in the gravitational pull exerted by Earth, including its major ice sheets. In 2006, scientists used GRACE data to confirm that the melting of the Greenland ice sheet had accelerated over the last few years.



OZONE DEPLETION

In 1978, NASA satellites began to provide reliable, high-resolution maps of global ozone on a daily basis. These data proved critical in verifying and analyzing the seasonal ozone hole discovered above Antarctica in the mid-1980s. Recent missions have clarified seasonal and geographic variations in ozone concentrations over Antarctica and elsewhere around the globe. Although implementation of the Montreal Protocol and its limits on chlorofluorocarbon emissions should allow the Antarctic ozone hole to heal in the next few decades, satellite monitoring of ozone remains vital. U.S. and European observations showed that the 2006 ozone hole was as large as any ever observed, with more ozone eroded (as measured by mass deficit) than in any prior year for which data were available.

SELECTING AND PRIORITIZING THE MISSIONS



Policymakers and the public are asking Earth scientists new questions about the vulnerabilities of a planet facing population growth, industrialization, environmental degradation, climate change, and other serious concerns. Past advances in Earth remote sensing have led to spectacular progress in areas such as weather forecasting; during the next 20 years it is essential that we extend our capabilities in new directions and further integrate our understanding of Earth system components in order to answer such pressing questions as:

- Will there be a catastrophic collapse of the Greenland or West Antarctic ice sheets, and if so, how rapidly will this occur?
- How will high-latitude forests change because of long-term warming and precipitation changes?
- Will droughts become more widespread in semiarid regions such as the western United States, Australia, and sub-Saharan Africa?
- How will economic development affect air pollutants and their movement among regions and continents?
- Can we better predict the risk of avian flu outbreaks or the potential spread of mosquito-borne viruses as climate evolves?
- Will heat waves and tropical cyclones intensify or become more frequent with climate change?
- Will the Arctic Ocean become ice-free each summer and, if so, how will this affect ecosystems and people?

The committee considered these and many more questions in selecting the 17 missions summarized on pages 10–26. Much of the initial work took place within the seven crosscutting, thematically organized panels (see box on page 6). Six of the panels prioritized observations and candidate missions, using a set of criteria that included affordability, degree of readiness, relationship to other proposed systems, and ability to contribute to more than one theme or discipline and to a long-term record of the Earth system. The seventh panel, which focused on Earth science applications and benefits to society, provided a framework that the other six panels used in evaluating societal benefits of the proposed observations.

THEMES AREAS ADDRESSED BY THE SEVEN STUDY PANELS

Earth science applications and societal benefits
Land-use change, ecosystem dynamics, and biodiversity
Weather science and applications
Climate variability and change
Water resources and the global hydrologic cycle
Human health and security
Solid-Earth hazards, natural resources, and dynamics

Working from the panel reports, the committee further narrowed the list of candidate missions. In doing so, it considered the importance of:

- *Establishing and maintaining balance* in a number of areas (types of measurements, size and complexity of missions, range of science disciplines, and levels of technological maturity);
- *Emphasizing cross-benefiting observations* that range widely in their spatial and temporal resolution and in their use of different parts of the electromagnetic spectrum; and
- *Leveraging a broad set of partners,* including other agencies, international partners, and the private sector.

To develop its plan, the committee exploited both science and measurement synergies among the various priority missions of the individual panels to create a more capable and affordable observing system. For example, the committee recognized that ice sheet change, solid-Earth hazards, and ecosystem health objectives are together well addressed by a combination of radar and lidar instrumentation. As a result, a pair of missions, flying in the same time frame, was devised to address those three societal issues.

In view of the uncertainties attached to cost, technology readiness, and international involvement, the committee chose to sequence the recommended missions across three broad periods: 2010–2013, 2013–2016, and 2016–2020. The committee considered the maturity of key technologies as part of the sequencing process. Missions requiring a significant amount of technology development were targeted for the later time frames. Enhanced funding will be needed to bring technology to fruition in time for these later missions.

Given the limits on recent and near-future funding for new U.S. observing missions, it is clear that the relative fraction of Earth-sensing satellites launched and managed by other countries will increase over the next few years. The committee took the schedules of major international missions into account when setting the time frames for recommended U.S. missions.

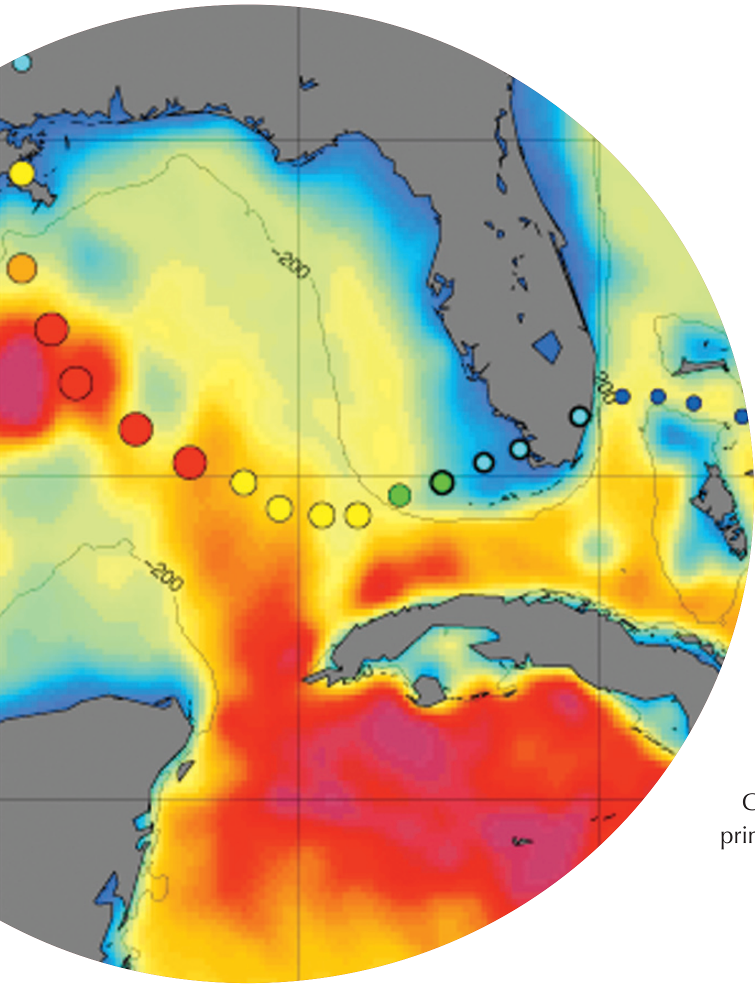
The uncertain state of many current U.S. observing systems, and the fiscal uncertainty within key agencies, added to the challenge of developing a strategy for the next decade and beyond. Costs for each mission, in constant 2006 dollars, were estimated in consultation with NASA mission designers, based on known costs for many current and past missions. Final costs will hinge on how each mission is ultimately implemented. For the configurations recommended here, the committee expects that cost estimates should hold to within plus or minus 50 percent for smaller missions and plus or minus 30 percent for larger ones.

To implement the full set of missions, the NASA Earth science budget will have to increase from around $1.5 billion per year in fiscal year 2007 (in constant 2006 dollars) to $2 billion per year between 2008 and 2010, which would reinstate support at the level that existed as recently as 2000. The missions recommended for NOAA can be accomplished with relatively small budget increases, keeping in mind that NOAA budgets are likely to be constrained due to the recent large cost overruns of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program (supported jointly by NOAA and the U.S. Department of Defense).

Among the many key measurements made by NOAA and NASA missions expected to end over the next few years, the committee identified several that are essential to sustain into the next decade—both to ensure a continuous supply of critical data and to provide a foundation for the observations to be made by recommended new missions. For instance, several instruments originally planned but more recently dropped from the NPOESS and Geostationary Operational Environmental Satellites (GOES-R) programs should be restored or their measurements obtained by other means. These include instruments to measure the incoming components of radiation from the Sun and the outgoing components of radiation from Earth (both needed to determine the energy balance of the planet); ocean wind speed and direction; sea surface temperature; and ozone. Without these sensors, gaps may develop in the observing record as soon as 2008.

In addition, the committee emphasizes the need to bring selected research instruments to operational status and to foster leadership and innovation through new opportunities in space-based observing. The committee thus recommends that NOAA increase its investment in transferring research tools and observations to operational use and that NASA create a new line of comparatively low-cost "Venture" missions (costing from $100 million to $200 million, with new starts every 2 years). Venture missions could range from standalone missions with simple, small instruments and spacecraft to more complex instruments launched on partner or shared spacecraft; all would be designed to answer targeted questions.

RECOMMENDED MISSIONS



Tables 1 and 2 show launch, orbit, and instrument specifications for the missions recommended to NOAA and NASA by the survey committee with input from the seven panels. Colors denote mission cost categories as estimated by the committee. Blue, green, and yellow shading represents missions classified respectively as small (less than $300 million), medium ($300 million to $600 million), and large ($600 million to $900 million). The missions are listed in order of ascending cost within each launch time frame. The full names for each mission are given in the one-page descriptions that follow. To augment the measurements of temperature and water vapor from GPSRO and other operational radio occultation missions, all appropriate NASA low-Earth-orbit missions should carry a Global Positioning System receiver in addition to the primary instruments listed in Tables 1 and 2.

TABLE 1 Launch, Orbit, and Instrument Specifications for Missions Recommended to NOAA

Decadal Survey Mission	Mission Description	Orbit[a]	Instruments	Rough Cost Estimate (FY 06 $million)
2010-2013				
CLARREO (instrument reflight components)	Solar and Earth radiation characteristics for understanding climate forcing	LEO, SSO	Broadband radiometer	65
GPSRO	High-accuracy, all-weather temperature, water vapor, and electron density profiles for weather, climate, and space weather	LEO	GPS receiver	150
2013-2016				
XOVWM	Sea surface wind vectors for weather and ocean ecosystems	LEO, SSO	Backscatter radar	350

[a]LEO, low Earth orbit; SSO, Sun-synchronous orbit.

TABLE 2 Launch, Orbit, and Instrument Specifications for Missions Recommended to NASA

Decadal Survey Mission	Mission Description	Orbit[a]	Instruments	Rough Cost Estimate (FY 06 $million)
2010-2013				
CLARREO (NASA portion)	Solar and Earth radiation; spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally resolved interferometer	200
SMAP	Soil moisture and freeze-thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	300
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	300
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	700
2013-2016				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	300
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	400
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka- or Ku-band radar Ku-band altimeter Microwave radiometer	450
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High-spatial-resolution hyperspectral spectrometer Low-spatial-resolution imaging spectrometer IR correlation radiometer	550
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	800
2016-2020				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	300
PATH	High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea surface temperature[b]	GEO	Microwave array spectrometer	450
GRACE-II	High-temporal-resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	450
SCLP	Snow accumulation for freshwater availability	LEO, SSO	Ku- and X-band radars K- and Ka-band radiometers	500
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	600
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	650

[a]LEO, low Earth orbit; SSO, Sun-synchronous orbit; GEO, geostationary Earth orbit.
[b]Cloud-independent, high-temporal-resolution, lower-accuracy sea surface temperature measurement to complement, not replace, global operational high-accuracy sea surface temperature measurement.

ACE AEROSOL-CLOUD-ECOSYSTEMS

LAUNCH: 2013–2016 **MISSION SIZE:** Large
ORBIT: LEO, SSO **AGENCY:** NASA
ESTIMATED COST: $800 million
AREAS OF INTEREST: Climate, Ecosystems, Health, Weather
INSTRUMENTS: Backscatter lidar, multiangle polarimeter, Doppler radar, multiband spectrometer
BENEFITS:
Improved climate models
Prediction of local climate change
Monitoring of ocean health and productivity and management of fisheries
Early warning of harmful algal blooms
Improved air-quality models and forecasts

Aerosols (airborne particles) affect the formation of clouds and the amount of rain or snow they produce. They can make clouds brighter, which reduces the amount of sunlight reaching Earth. Aerosols remain in the air for only a few days, and they vary greatly in size and other properties. A number of studies have highlighted the need for improved data on aerosols in order to reduce uncertainty in climate prediction and generate more precise local and regional projections of climate change. Aerosols also play a major role in air quality and thus have a direct impact on human health.

By deploying a variety of coordinated sensors, ACE will assess both clouds and aerosols and clarify the relationships between them. The data it gathers will help lead to improvements in the models that predict air quality. ACE is also designed to assist in assessing the health of ocean ecosystems by sensing ocean color and the amount of organic material close to the sea surface. Observations from ACE will help scientists provide early warning of harmful algal blooms in coastal areas. These data also will help scientists calculate the amount of carbon dioxide (CO_2) entering and leaving the oceans. Increases in absorbed CO_2 are linked to ocean acidification, which in turn threatens the health of coral reefs and marine ecosystems.

The four main instruments for ACE consist of a lidar, for measuring cloud and aerosol heights and the thickness of certain layers; a cloud radar, to detect droplet size and cloud height; a polarimeter, to measure cloud and aerosol properties; and a multiband spectrometer, to sample ocean properties. Some prelaunch development will be needed so that the lidar, radar, and polarimeter can carry out multibeam and cross-track sampling.

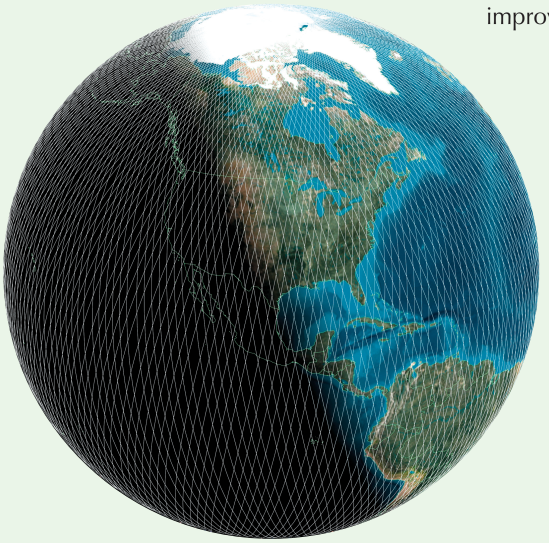
ASCENDS ACTIVE SENSING OF CO_2 EMISSIONS OVER NIGHTS, DAYS, AND SEASONS

LAUNCH: 2013–2016
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $400 million
AREAS OF INTEREST: Ecosystems, Health
INSTRUMENTS: Multifrequency laser
BENEFITS:
Improved climate models and predictions of atmospheric CO_2
Identification of human-generated CO_2 sources and sinks to enable effective cabon trading
Closing of the carbon budget for improved policy and prediction

Fossil fuel burning, deforestation, and other human activities have driven a 40 percent increase in atmospheric CO_2 since the mid-1800s. Of the CO_2 released by human action, about half remains in the atmosphere. Land ecosystems and oceans absorb the remainder in roughly equal amounts. However, this process varies over time and space in ways that remain poorly understood. Direct measurements of carbon and CO_2 fluxes across the land and sea surface are expensive, scarce, and difficult to extrapolate.

ASCENDS will provide long-term, accurate global CO_2 data using a multifrequency laser to measure the total amount of CO_2 in atmospheric columns. ASCENDS data will allow for weekly mapping of CO_2 sources and sinks at 1° longitude and latitude. These data will assist society in predicting future CO_2 concentrations, monitoring CO_2 sequestration efforts, and supporting future carbon and energy policies.

ASCENDS will provide measurements by day, when photosynthesis occurs, as well as at night, when plant respiration dominates. Simply going from a single daily measurement to two readings, one taken by day and the other at night, can provide a greatly improved picture of CO_2 fluxes.

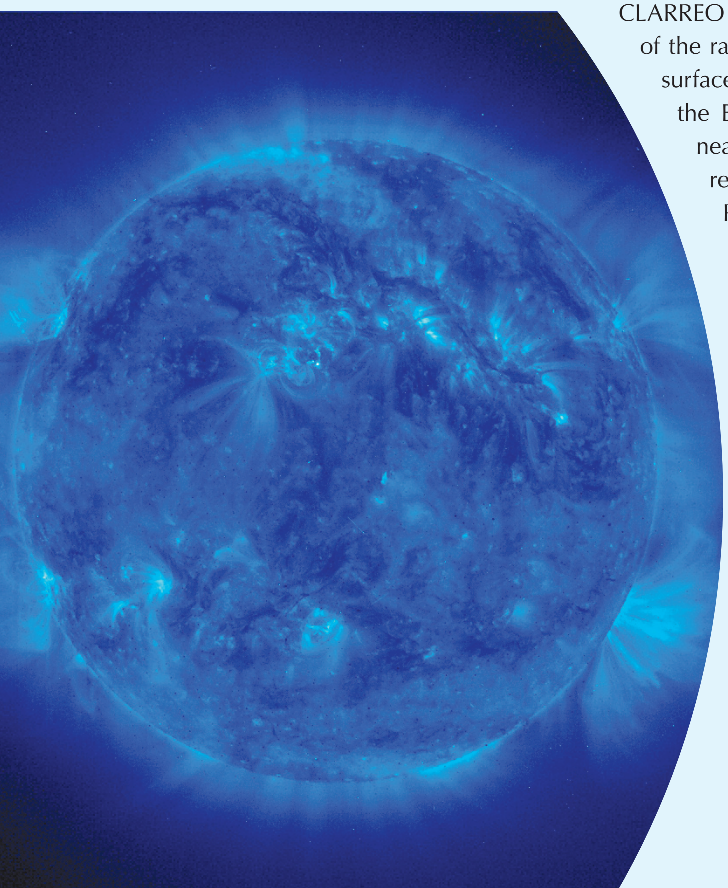


The time frame for ASCENDS was chosen to allow overlap with the Orbiting Carbon Observatory. Simultaneous lidar-based measurement of oxygen (O_2) would correct for variations in atmospheric pressure. Ideally, coordinated observations from a carbon monoxide (CO) sensor would provide additional data to distinguish the CO_2 emitted by plant life from that produced by fires and fossil fuels. Extensive aircraft flights will be needed to test the CO_2 and O_2 sensing techniques under a variety of conditions.

CLARREO CLIMATE ABSOLUTE RADIANCE AND REFRACTIVITY OBSERVATORY

LAUNCH: 2010–2013
MISSION SIZE: Small
ORBIT: LEO, Precessing
AGENCY: NASA, NOAA
ESTIMATED COST: $200 million (NASA), $65 million (NOAA)
AREAS OF INTEREST: Climate, Health
INSTRUMENTS: Absolute, spectrally resolved interferometers (NASA), broadband radiometers (NOAA)
BENEFITS:
Benchmarking of climate record to produce accurate trends and improve climate predictions
Verification and improvement of climate models
Ozone and surface radiation forecasts and public advisories

Decisions to address a wide range of societal concerns rely on accurate climate records and credible long-term outlooks. A vital element in climate monitoring and assessment is the amount of radiation entering and leaving the Earth system. The CLARREO mission will measure incoming and outgoing radiation using independent, well-established methods as part of a single mission. The result will be a benchmark record of global climate consistent with international standards. Because human-induced climate change is expected to produce a recognizable signature of radiative effects by wavelength, the data will also help to verify the quality of global climate models.



CLARREO will employ interferometers to measure two key parts of the radiation budget: infrared radiation emitted from Earth's surface and atmosphere, and solar radiation reflected from the Earth system to space in near-ultraviolet, visible, and near-infrared wavelengths. The mission will also include a receiver to intercept and analyze signals from the Global Positioning System (GPS) after they pass through Earth's atmosphere along the horizon (a technique known as radio occultation). The delay induced in these signals by atmospheric refraction can yield data on pressure, temperature, and water vapor.

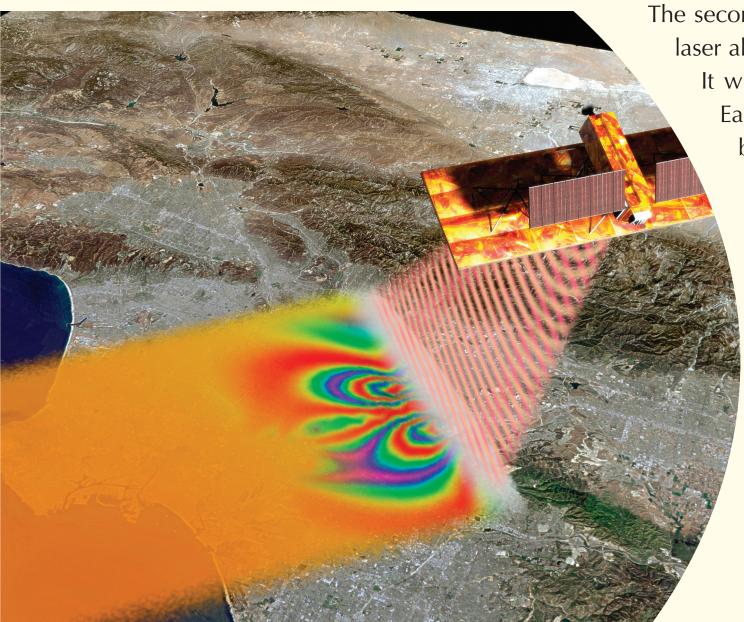
The NASA component of CLARREO will include three satellites, all of which carry redundant thermal infrared interferometers and a GPS receiver, and one of which also includes redundant ultraviolet, visible, and near-infrared interferometers. The NOAA component of CLARREO involves the reflight of the incident solar-irradiance and CERES broadband instruments on the NPOESS Preparatory Project (NPP) and NPOESS spacecraft.

DESDynI — DEFORMATION, ECOSYSTEM STRUCTURE, AND DYNAMICS OF ICE

LAUNCH: 2010–2013
MISSION SIZE: Large
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $700 million
AREAS OF INTEREST: Solid Earth, Ecosystems, Climate, Health, Water
INSTRUMENTS: L-band interferometric synthetic aperture radar, laser altimeter
BENEFITS:
Observations of the effects of changing climate and land use on species habitats, ecosystems, and carbon storage in vegetation
Data on the response of ice sheets to climate change and the resulting impact on sea level
Improved forecasts of earthquakes, volcanic eruptions, and landslides

Changes in the height of features on Earth's surface serve as important indicators of crucial geophysical processes. Surface deformation is linked directly to earthquakes, volcanic eruptions, and landslides; it can also occur when fluids are injected underground to stimulate production from oil and gas reserves. Ice sheets deform in response to changes in temperature and precipitation, providing clues to large-scale melt that can raise global sea levels. The changing height of a forest canopy can serve as a proxy for the amount of carbon it stores.

Each of these variables will be assessed globally through DESDynI. The key instrument is an interferometric synthetic aperture radar (InSAR). The InSAR's resolution of better than 35 meters will allow it to depict tectonic faults and surface deformation with high precision. These data will help scientists to better calculate the near-surface strain that accumulates between earthquakes, the migration of magma toward volcanos, and the kinematics of landslides. InSAR data will also help document the dynamics that shape the Greenland and Antarctic ice sheets, as well as their melt rates and resulting sea-level rise.



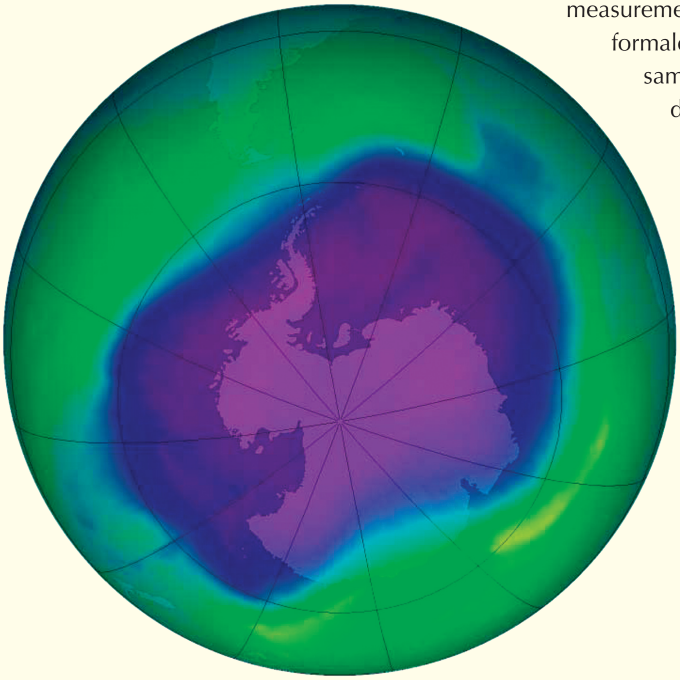
The second DESDynI instrument is a multibeam laser altimeter, operating in the infrared range. It will collect data from specific points on Earth's surface to supplement the InSAR's broader sweep. Together, the instruments will be able to characterize the three-dimensional structure of forests, from which estimates of carbon storage can be obtained.

GACM GLOBAL ATMOSPHERIC COMPOSITION MISSION

LAUNCH: 2016–2020
MISSION SIZE: Large
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $600 million
AREAS OF INTEREST: Ecosystems, Health, Water, Weather
INSTRUMENTS: Ultraviolet spectrometer, infrared spectrometer, microwave limb sounder
BENEFITS:
Identification of sources and sinks of harmful pollutants
Better forecasts of ozone and surface radiation
Better forecasts of dangerous pollution events

The composition and chemistry of our atmosphere must be observed, modeled, and predicted in order to understand and mitigate potentially harmful impacts on society and ecosystems. Current satellite instruments provide critical data at low resolution. However, to obtain the more precise data needed to improve models and predictions, a new generation of instruments and observing strategies must be developed.

The suite of sensors aboard GACM will advance understanding of chemical weather processes on regional to global scales and help improve models and predictions of air pollution and ground-level ultraviolet radiation. GACM includes a unique combination of passive sensors gathering data on the altitudes and concentrations of key trace gases and aerosols (airborne particles) that are related to ozone formation or that serve as tracers of pollution and airflow. These sensors include a spectrometer in the ultraviolet/visible range that will collect daytime measurements of ozone (O_3), nitrogen dioxide, sulfur dioxide, formaldehyde, and aerosols. An infrared spectrometer will sample carbon monoxide through the atmosphere by day and in the mid-troposphere at night, while an advanced microwave spectrometer will sample gases and aerosols in the upper troposphere and lower stratosphere.



The committee also recommends focused technology development for a second-phase mission featuring an active differential absorption lidar (DIAL) system that would be launched in 2022 or thereafter. It would measure O_3 with a vertical resolution better than 2 kilometers and aerosols and atmospheric structure at resolutions better than 150 meters.

GEO-CAPE GEOSTATIONARY COASTAL AND AIR POLLUTION EVENTS

LAUNCH: 2013–2016
MISSION SIZE: Medium
ORBIT: GEO
AGENCY: NASA
ESTIMATED COST: $550 million
AREAS OF INTEREST: Ecosystems, Health, Water, Weather
INSTRUMENTS: High-spatial-resolution hyperspectral spectrometer, low-spatial-resolution imaging spectrometer, infrared correlation radiometer
BENEFITS:
Predictions of impacts from oil spills, fires, water pollution from sewage and other sources, fertilizer runoff, and other environmental threats
Detection and tracking of waterborne hazardous materials
Monitoring and improvement of coastal health
Improved forecasts of air quality

The growing concentration of people living near coasts is exerting enormous pressure on coastal ecosystems. The impacts include declining fisheries, harmful algal blooms, and more than 20 persistent “dead zones” worldwide, including the Mississippi Delta. The twin stressors of climate change and population growth create an imperative to monitor changes in coastal oceans. At the same time, poor air quality threatens human and ecosystem health in many parts of the world. The current observation system for air quality is inadequate for measuring human exposure to pollutants and for crafting emissions control strategies.

The suite of instruments aboard GEO-CAPE will improve observations of coastal ocean health and air quality across the Americas. From a point in space above roughly 80°W longitude, two spectrometers will sense reflected sunlight within several narrow wavelength bands. One spectrometer will scan at the continental scale, providing hourly data at a resolution of 7 kilometers. It will measure natural and human-produced substances in rivers and oceans as well as gases and aerosols in the atmosphere, including those that react in sunlight to form polluting low-level ozone. The other spectrometer is a steerable imager that can gather data at a resolution of 250 meters on high-impact events such as large-scale fertilizer runoffs, industrial accidents, and other environmental disasters.

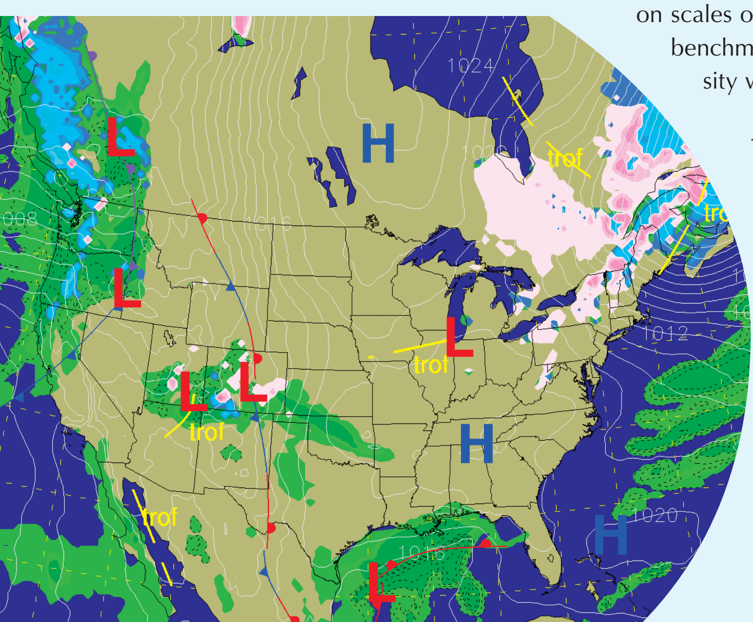
An infrared correlation radiometer will measure carbon monoxide (CO) in tandem with the continental-scale spectrometer. Together, they will allow for vertical CO profiles that help trace the long-range transport of pollution.

GPSRO OPERATIONAL GPS RADIO OCCULTATION

LAUNCH: 2010–2013
MISSION SIZE: Small
ORBIT: LEO
AGENCY: NOAA
ESTIMATED COST: $150 million
AREAS OF INTEREST: Climate, Health, Water, Weather
INSTRUMENTS: GPS receivers
BENEFITS:
- Benchmarking of climate observations for establishing trends and variability in climate
- More accurate, longer-term weather forecasts
- Improved forecasts of space weather

Forecasts of weather at ground level as well as prediction of "space weather"—the impacts of solar storms and other high-altitude disturbances—are limited by inadequate three-dimensional data, especially over the oceans and other hard-to-sample areas. This not only hinders the accuracy of weather forecast models but also complicates the effort to monitor long-term changes in global climate. At higher altitudes, a lack of data adds to the challenge of predicting space-weather impacts that can range from communications blackouts to power grid disruptions.

GPSRO will benefit forecasts of weather, climate, and space weather by employing approximately six satellites in low Earth orbit, each intercepting signals from GPS satellites. By measuring the delays induced in these signals as they pass through the atmosphere, GPSRO will produce precise, accurate soundings of atmospheric refractivity at high vertical resolution. In turn, these profiles can yield three-dimensional information on electron density in the ionosphere, temperature in the stratosphere and upper troposphere, and temperature and water vapor in the lower troposphere. These data will improve the analyses that feed into weather forecasts on scales of hours to many days, while also serving as an ideal benchmark for climate monitoring. The data on electron density will enhance the quality of space-weather forecasts.



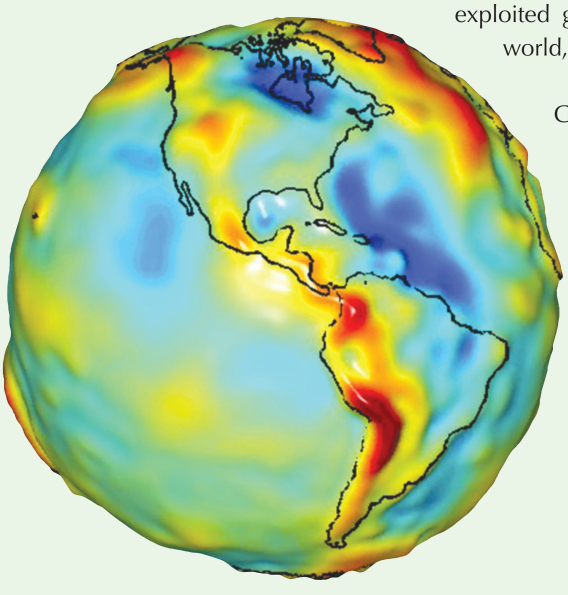
The techniques in GPSRO have been tested and verified through several successful proof-of-concept missions involving single satellites and through the six-satellite Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), launched in 2006. The committee recommends that GPSRO be launched near the end of the COSMIC mission, around 2012.

GRACE-II GRAVITY RECOVERY AND CLIMATE EXPERIMENT II

LAUNCH: 2016–2020
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $450 million
AREAS OF INTEREST: Climate, Water
INSTRUMENTS: Microwave- or laser-based ranging system
BENEFITS:
Improved measurement of changes in Earth's mass distribution due to dynamic processes
Data on changes in volume of ice sheets due to climate change, leading to better climate models and estimates of sea-level rise
Improved understanding of groundwater dynamics on continental scales
Improved prediction of changes in sea level

GRACE, twin satellites launched in March 2002, is making detailed measurements of Earth's gravity field. Analyses of data from GRACE have led to important discoveries about gravity and Earth's natural systems, which in turn have far-reaching benefits to society and the world's population.

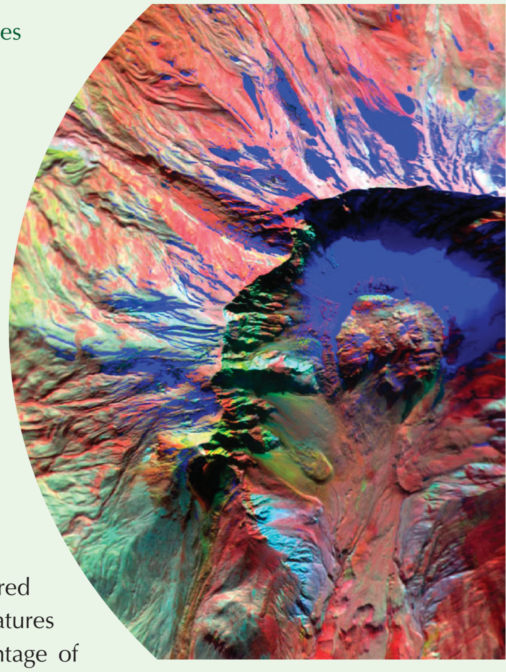
Data from GRACE are providing scientists with a globally consistent measurement of the distribution of Earth's mass and its variability in time and space. This variability in mass is due primarily to water motion. Thus, measurements from GRACE provide an integral constraint on many geophysical processes related to land, ocean, atmosphere, and glaciological subsystems. A record of time variations in Earth's gravity field reflects the redistribution and exchange of mass within and between these reservoirs. Over one-quarter of the world's population relies on groundwater as its principal source of drinking water. Yet global observations of this critical resource are highly variable in density, with most in situ observations located within heavily exploited groundwater basins in the developed world, and few elsewhere.



GRACE-II would extend and improve on the first GRACE mission. Resolution would be increased to around 100 kilometers. Accuracy could be boosted by development of a laser-based satellite-to-satellite interferometer and a drag-free propulsion system, with boosters continually fired to minimize orbital degradation caused by atmospheric drag. The resulting data would foster major breakthroughs in a number of areas of Earth science.

HyspIRI HYPERSPECTRAL INFRARED IMAGER

LAUNCH: 2013–2016 **MISSION SIZE:** Medium
ORBIT: LEO, SSO **AGENCY:** NASA
ESTIMATED COST: $300 million
AREAS OF INTEREST: Ecosystems, Health, Solid Earth
INSTRUMENTS: Hyperspectral spectrometer
BENEFITS:
Data on changes in vegetation type and deforestation for ecosystem management and monitoring of changes in carbon sinks
Early warnings of drought
Improved exploration for natural resources
Predictions of the likelihood of volcanic eruptions and landslides



Highly detailed images of Earth's surface are invaluable for studying and managing ecosystems and other natural resources. Satellite-based sensors can detect early signs of drought, soil types prone to landslides, volcanic unrest that may precede eruptions, and changes in the health and extent of coral reefs. Forest and agricultural managers can make use of timely, high-resolution images from space in responding to fires, the effects of invasive species, and other ecosystem threats. This imagery also helps scientists analyze climate variability and longer-term climate change.

HyspIRI will employ a hyperspectral imager and a thermal infrared scanner to monitor a variety of ecological and geological features at a wide range of wavelengths. The system will take advantage of recent advances in detectors, optics, and electronics to provide global coverage every 30 days at a resolution of 45 meters. Both instruments would be pointable, to allow for frequent high-resolution sampling of volcanic activity, wildfires, droughts, and other critical events. The system would also map surface rock and soil composition, in many cases with a quality close to that provided by laboratory X-ray diffraction analysis. These data would benefit exploration for natural resources as well as environmental remediation activities.

ICESat-II ICE, CLOUD, AND LAND ELEVATION SATELLITE II

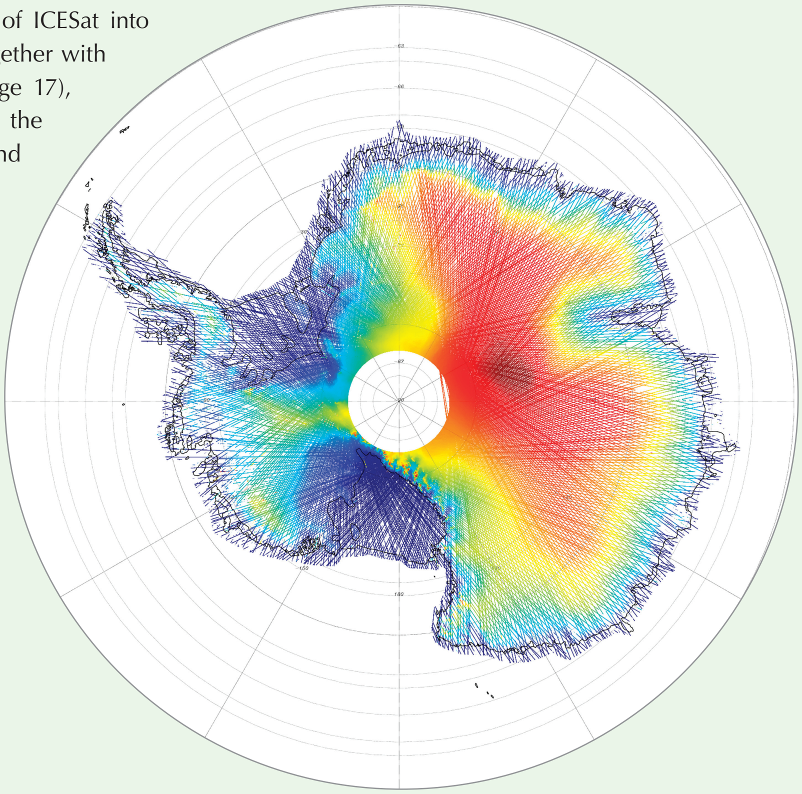
LAUNCH: 2010–2013
MISSION SIZE: Medium
ORBIT: LEO, non-SSO
AGENCY: NASA
ESTIMATED COST: $300 million
AREAS OF INTEREST: Climate, Ecosystems, Water
INSTRUMENTS: Laser altimeter
BENEFITS:

Data on changes in ice sheet volume due to climate change to improve forecasts of sea-level rise

Data on land carbon storage to understand responses of vegetation to changing climate and land use

Laser altimetry is a proven method for measuring the height and inferring the volume of glaciers, ice sheets, and sea ice. The topographic data obtained by the ICESat mission since 2003 have led to the first basin-wide estimates of sea ice thickness, a critical measure for the Arctic Ocean in a warming climate. Although sea ice extent has been monitored by satellite since the 1970s, no comparable record exists for ice thickness. Laser altimetry is also the preferred technique for measuring ice volume over large areas and long time periods. It has also proven useful for measuring the depth of forest canopies, an indicator of biomass.

ICESat-II will extend the unique record of ICESat into the next decade to provide data that, together with the data provided by GRACE-II (see page 17), will enable scientists to monitor both the mass and the thickness of the Greenland and Antarctic ice sheets and clarify their contributions to sea-level rise. ICESat-II will also complement the ice data from DESDynI (see page 13) and contribute to studies of vegetation.



The payload will include a single-channel lidar with GPS navigation and pointing capability to allow for repeated high-accuracy sampling of ice elevation. Limitations to the lidar technology now being used in ICESat will be corrected in ICESat-II.

LIST LIDAR SURFACE TOPOGRAPHY

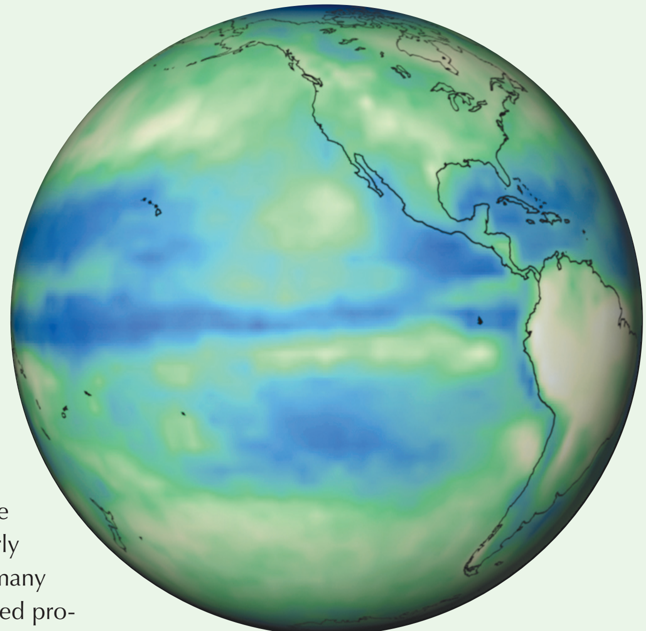
LAUNCH: 2016–2020
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $300 million
AREAS OF INTEREST: Health, Solid Earth
INSTRUMENTS: Laser altimeter
BENEFITS:
Quantified assessment of wildfire risk
Monitoring of changes due to land use and land management
Predictions of the likelihood of volcanic eruptions and landslides

Until recently, the coarse resolution of topographic mapping has been a major impediment to understanding the forces and processes that shape Earth's surface. Although airborne lidar is useful for surveying small areas, a space-based sensor is essential for worldwide mapping. Global topographic data are now available at 30- to 90-meter horizontal resolution, with a vertical precision of about 10 meters. Much better data are needed in order to predict the location and timing of landslides, floods, tsunami run-ups, and lava and mud flows.

Using laser altimetry, LIST will carry out the most precise global topographic survey to date, with a resolution of 5 meters and a precision in the tenths of meters. This will permit mapping of landslide, earthquake, and flood hazards at a small enough scale to be useful for site-specific land use decisions as well as research. Observations from LIST 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.

PATH — PRECIPITATION AND ALL-WEATHER TEMPERATURE AND HUMIDITY

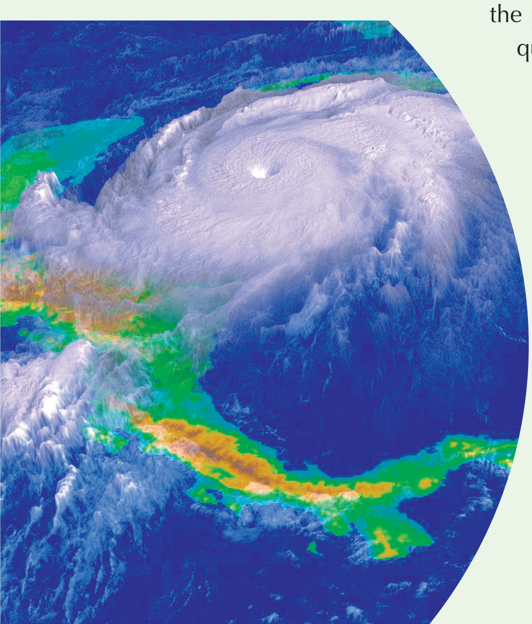
LAUNCH: 2016–2020
MISSION SIZE: Medium
ORBIT: GEO
AGENCY: NASA
ESTIMATED COST: $450 million
AREAS OF INTEREST: Health, Water, Weather
INSTRUMENT: Microwave array spectrometer
BENEFITS:
More accurate weather forecasts and warnings
Improved prediction of storm track and intensity and improved evacuation planning
Improved forecasts of hurricane storm surge and rainfall accumulation



Frequently updated temperature and moisture data are critical to high-quality forecasts of weather, particularly hurricanes, floods, and other high-impact events. For many years, satellites in low Earth orbit have routinely gathered profiles of temperature, water vapor, and the amount of liquid water within clouds using microwave spectrometers and infrared sounders. Infrared sounders can be used in geostationary orbit to enable more frequent regional observations, although their performance is limited by clouds and precipitation. Limits on microwave technology have thus far kept these spectrometers from accessing the vantage point of geostationary orbit to enable more frequent regional observations under all weather conditions.

PATH will provide the first geostationary platform for a microwave spectrometer and infrared sounder in tandem. The mission will analyze temperature and water vapor in three dimensions, as well as sea surface temperature and precipitation. Data will be gathered every 15 to 30 minutes in both clear and cloudy conditions. PATH will lead to more accurate weather forecasts through greatly improved models of the atmosphere's lowest kilometer and the processes that shape clouds, rainfall, and snowfall. The frequently updated observations of wind speed and sea surface temperature will increase the accuracy of hurricane track, intensity, and storm surge forecasts. Water vapor and rainfall data will enhance flood prediction.

A geostationary orbit will allow PATH to carry out sampling that would otherwise require an impractically large constellation of satellites. A platform in mid-Earth orbit is another possibility; however, additional instrument development would be needed for this option.



SCLP SNOW AND COLD LAND PROCESSES

LAUNCH: 2016–2020
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $500 million
AREAS OF INTEREST: Water
INSTRUMENTS: Ku- and X-band radars, K- and Ka-band radiometers
BENEFITS:
Improved management of water resources in snowmelt-dominated river basins
Assessment of the risk of snowmelt-induced floods and flows of debris
Predictions of the impact of climate change on seasonal snowpacks

Seasonal snowpacks and glaciers provide water for one-sixth of the world's population and affect weather and climate on local, regional, and global scales. Climate change seriously threatens the global abundance and timing of snow. Runoff from western U.S. snowfall now peaks several weeks earlier in the spring than it did in the 1950s. Despite the importance of snow to society, there are major gaps in snow-cover observations globally. Scientists and water resource managers need to know where and how much snow has fallen, how much water it holds, and how fast it is melting.

Through a combination of active and passive microwave sensors, SCLP will provide a detailed and frequently updated record of snow cover. A pair of synthetic aperture radars will be able to characterize both deep and shallow snowpacks. A dual-frequency passive radiometer will provide additional detail and allow for comparison with snow data from similar sensors on other platforms. The mission will provide observations on two needed timescales: 15-day observation intervals will capture seasonal change, and more frequent (3- to 6-day) observations will track the effects of individual weather events.

The passive microwave component of SCLP could provide a source of interim data to users affected by the removal of the passive microwave instrument from the first National Polar-orbiting Operational Environmental Satellite System (NPOESS) platform.

SMAP SOIL MOISTURE ACTIVE-PASSIVE

LAUNCH: 2010–2013
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $300 million
AREAS OF INTEREST: Health, Water
INSTRUMENTS: L-band radar, L-band radiometer
BENEFITS:
More accurate weather and climate forecasts, especially over interior continental areas
Improved early warning and decision support for droughts
Better predictions of agricultural productivity
Improved flood forecasts, especially in the developing world

Although soil moisture strongly affects plant growth and the evolution of both weather and climate, there is no global network to measure it. When accurate readings of soil moisture are fed into weather and climate models, the forecast quality improves and longer lead times become possible. Soil moisture is one of the leading factors in flood and landslide risk, and it also plays an important role in the global carbon cycle through its effects on plant growth.

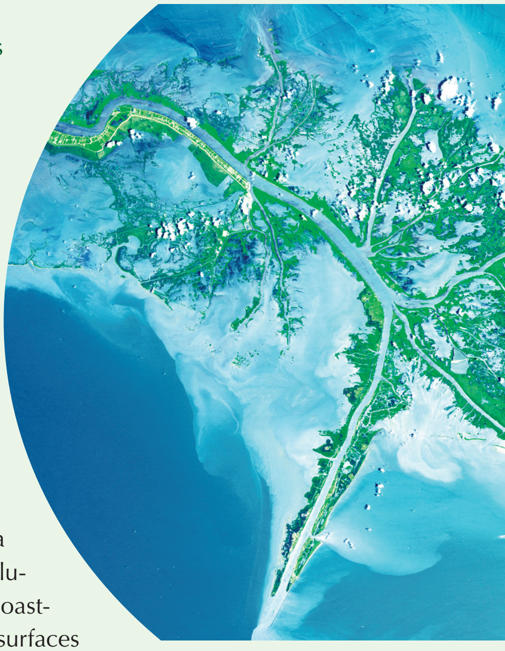
Many field studies have shown that microwave radars provide useful data on soil moisture. SMAP combines an active radar with a passive radiometer, allowing soil moisture to be measured and analyzed globally at a resolution of 3 to 10 kilometers every 2 to 3 days. The results will help Earth scientists to better represent the water, energy, and carbon cycles in global models of weather and climate. Significant advances in long-range weather and seasonal forecasting will become possible, and the data will help build a new generation of hydrologic models for predicting and studying floods and droughts.

SWOT SURFACE WATER AND OCEAN TOPOGRAPHY

LAUNCH: 2013–2016
MISSION SIZE: Medium
ORBIT: LEO, SSO
AGENCY: NASA
ESTIMATED COST: $450 million
AREAS OF INTEREST: Climate, Health, Water
INSTRUMENTS: Ka- or Ku-band wide-swath synthetic aperture radar interferometer, Ku-band nadir altimeter, microwave radiometer

BENEFITS:

Improved water management in transboundary river basins
Improved prediction of carbon fluxes to and from wetlands
Improved flood and marine forecasts
Identification and forecasts of inundation and malaria zones
Prediction of changes in sea level



More than 75 percent of the world's population relies on drinking water from lakes, rivers, and other surface sources. Yet there is no coordinated global system for measuring supplies of surface water. Key information that affects the flow of water from one nation to another is often not freely available. Data on river discharge are vital in managing water resources as well as predicting floods, one of the world's deadliest natural hazards.

The Jason series of satellites has gathered groundbreaking data on global oceans using radar altimetry. However, the data's resolution is not sufficient to assess water levels on rivers and near coastlines. SWOT will extend the Jason record and analyze water surfaces over both land and ocean at much higher spatial resolution, using a suite of instruments that includes an interferometer, a microwave radiometer, and a radar altimeter. SWOT will produce the first remotely sensed estimates of water storage in lakes, reservoirs, and wetlands across the world. Its vertical accuracy will be a few centimeters, averaged over areas of roughly a square kilometer. In many locations, these will be the first such data ever available, serving as a boon to water managers as well as researchers studying river and water-storage dynamics.

The timing of SWOT may depend on the longevity of the Jason-2 mission, now scheduled for launch in mid-2008. An overlap with XOVWM (see page 26) is highly desirable for measuring winds over the ocean.

3D-WINDS — THREE-DIMENSIONAL TROPOSPHERIC WINDS

LAUNCH: 2016–2020
ORBIT: LEO, SSO
ESTIMATED COST: $650 million (Stage I demonstration)
AREAS OF INTEREST: Water, Weather
INSTRUMENTS: Doppler lidar
BENEFITS:
- More accurate, longer-term weather forecasts
- Improved storm track prediction and evacuation planning
- Improved planting and harvesting schedules and outlooks

MISSION SIZE: Large
AGENCY: NASA

Although weather forecasts have improved steadily over recent decades, the prediction models on which those forecasts are based are limited by a lack of wind measurements over many parts of the globe. Large uncertainties remain in three-dimensional wind data over the oceans, the Southern Hemisphere, and polar and tropical regions. Improved three-dimensional wind data throughout the troposphere (the lowest 8 to 16 kilometers of the atmosphere) would yield concrete benefits, including better day-to-day weather forecasts as well as improved forecasts of hurricane track and intensity, El Niño and La Niña, and the transport of air pollutants.

3D-Winds will measure the tropospheric wind fields using two complementary Doppler wind lidars: one in the near-infrared range, well suited for measuring winds in the presence of dust, pollution, or other airborne particles, and the other in the ultraviolet range, detecting molecular-scale Doppler shifts in order to measure winds in air that is relatively pristine. Together, the system will be able to collect wind data across most tropospheric and stratospheric conditions.

Given the complexity of the hybrid system proposed for 3D-Winds, the committee recommends an early research program to address high-risk components, followed by design, construction, and testing of a prototype, which could be demonstrated in low Earth orbit as early as 2016.

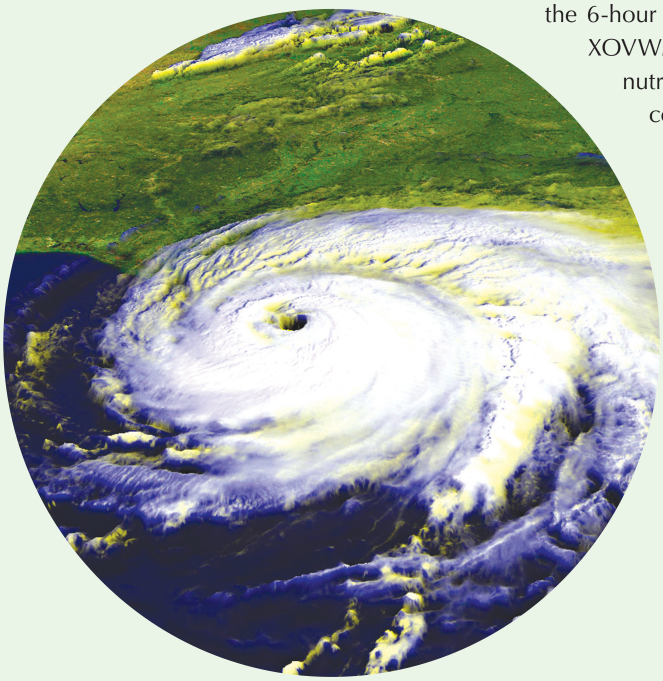
XOVWM EXTENDED OCEAN VECTOR WINDS MISSION

LAUNCH: 2013–2016
ORBIT: LEO, SSO
ESTIMATED COST: $350 million
AREAS OF INTEREST: Climate
INSTRUMENTS: Backscatter radar
BENEFITS:
Prediction of changes in nutrient availability for fisheries and coastal ecosystems
Improved marine hazard prediction and navigation safety
Improved prediction of hurricanes, extratropical storms, coastal winds, and storm surge

MISSION SIZE: Medium
AGENCY: NOAA

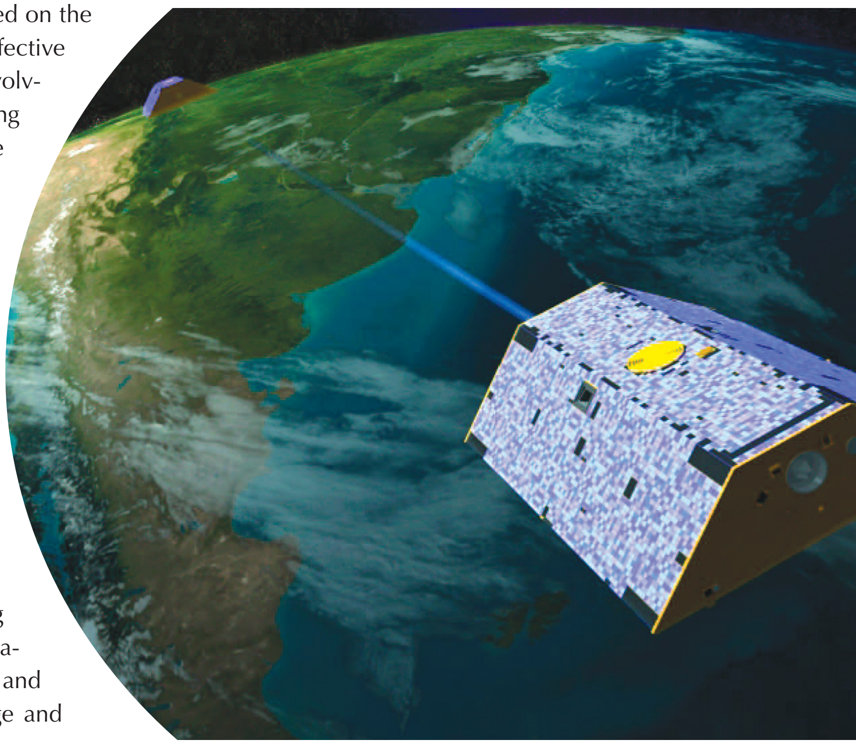
In the last few years, scatterometer data from the QuikSCAT mission have become invaluable for marine warnings and hurricane forecasts, including the location and intensity of storm centers. But ocean currents and winds near coastlines are not being mapped by either scatterometers or altimeters at present, due to low spatial resolution and contamination of the radar signal by nearby land. In addition, there is currently no plan to replace the aging QuikSCAT.

XOVWM will measure wind speed and direction over the ocean surface at a spatial resolution of 5 kilometers or less over an 1,800-kilometer swath, revisiting each location every 18 hours or so. XOVWM will overlap with and supplement the SWOT mission (see page 24), improving our understanding of variability in winds and ocean currents. Data from XOVWM would be combined with data from the European Space Agency's operational scatterometer to futher reduce the average time between wind measurements to 10 hours, approaching the 6-hour goal for weather forecasting. The coastal data from XOVWM will allow for better estimates of upwelling and nutrient supply for fisheries management. Many other coastal activities, from search-and-rescue missions to shipping, will benefit from model improvements made possible by XOVWM.



Compared to the existing QuikSCAT mission, which is operating years beyond its expected lifetime, XOVWM will provide improved wind measurements, especially in rainy conditions, as well as higher-spatial-resolution measurements, better coverage in coastal regions, and more frequent observations.

FROM SATELLITE OBSERVATIONS TO EARTH INFORMATION



The program of observations described on the preceding pages is designed to be effective in its use of resources, resilient to evolving constraints, and open to embracing new opportunities as they arise. The recommended missions can provide a wealth of new and urgently needed data on the Earth system. However, these observations—as important as they are—will prove useful only if they can be effectively analyzed, interpreted, and applied. The missions are one part of a larger program needed to translate raw observations of Earth into useful information. To realize the potential offered by these missions, resources must be focused in the following four areas: ensuring sustained observations for operations, research, and monitoring; obtaining complementary non-space-based observations; turning observations into knowledge and information; and sustaining the knowledge and information system.

THREE TYPES OF OBSERVING

- Exploratory observations are designed mainly to advance scientific understanding. They can lead to unexpected discoveries, test hypotheses, and validate models. They may also reveal changes in parts of the Earth system that are critical to our well-being.
- Operational observations are those designed to serve routine functions such as day-to-day weather prediction. These observations generally must be collected and processed in real time. Sometimes data from exploratory observations are shown to have a large positive impact on weather forecasts and become critical to operational systems.
- Sustained observations of certain key variables, such as sea surface temperature and sea level, atmospheric temperature, and solar radiation, are needed to clarify the long-term implications of a change in the Earth system or to uncover slowly evolving dynamics.

ENSURING SUSTAINED OBSERVATIONS FOR OPERATIONS, RESEARCH, AND MONITORING

Observational systems can be classified into three overlapping categories: *exploratory, operational,* and *sustained* (see box on page 27). Sustained measurements are those that must be made over many years in order to distinguish short-term variability from long-term trends. These observations become part of the climate data record. They are also necessary for research on important natural oscillations in the climate system that have periods of decades or longer.

One reason for the complexity in coordinating space-based Earth remote sensing is that observations frequently serve multiple goals at the same time. Indeed, exploratory missions often produce innovative observations that can be employed in an operational setting and also contribute to a long-term program of sustained observation. The challenge of transitioning missions from exploratory to operational status is well recognized and long studied, but progress to date has been mixed. Moreover, operational sensors do not always provide the type of sustained observations needed to accurately track and analyze climate change. For instance, major uncertainties in the long-term trend of upper-air temperatures exist in part because of the attempt to create climate records from what are essentially weather-focused operational observations.

The committee is concerned that the nation's institutions involved in civil space activities are not adequately prepared to mount a coordinated observing strategy and meet society's long-term needs for sustained observations and Earth information. These institutions have responsibilities that are often mismatched with authorities and resources; mandates inconsistent with their charters; budgets that do not address emerging needs; and shared responsibilities hampered by a lack of mechanisms for cooperation. These fundamental issues need to be addressed through high-level federal policy.

The committee recommends that the Office of Science and Technology Policy, working with partners in agencies and academia, develop and implement a plan for achieving and sustaining global Earth observations. Further, NOAA, working with its partners, should create a data and information system to ensure the production, distribution, and stewardship of high-accuracy climate records.

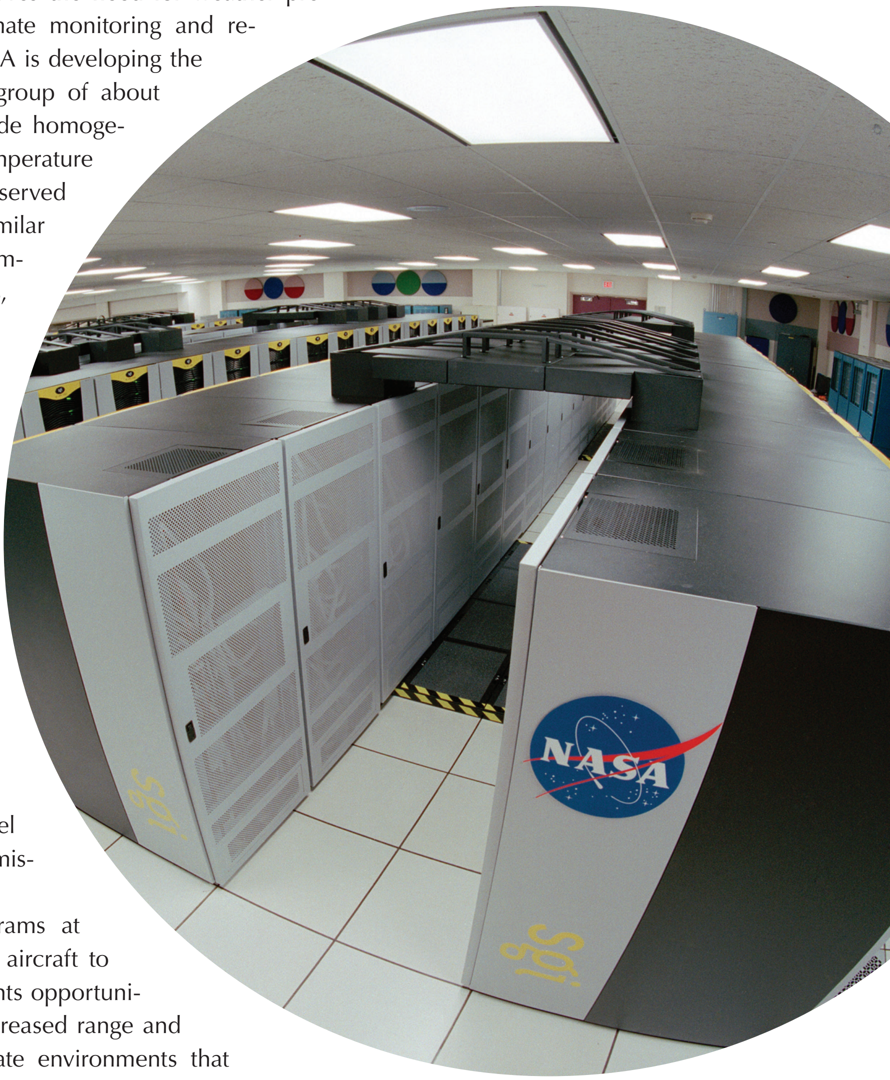
OBTAINING COMPLEMENTARY NON-SPACE-BASED OBSERVATIONS

Observations from the vantage point of space can provide an economical and global view of many Earth system phenomena and processes. However, the laws of physics impose fundamental limitations and require trade-offs in the sensitivity and spatial and temporal resolution that space-based instruments can achieve. Thus, space observations cannot always provide all of the data needed to understand key physical, chemical, and biological processes. In situ instruments (sensors on land, at sea, and aboard aircraft that measure conditions at their immediate locations) remain critical for calibrating and validating satellite observations and for gathering data with levels of accuracy, precision, and resolution that are unavailable from space-based sensors.

Nationally and globally, the core in situ weather observations made for more than 50 years have come from surface stations and radiosondes (balloon-borne instrument packages). Today, however, the number of radiosonde observations is declining in many parts of the world, although satellite data partially compensate for this loss. The surface-based network of U.S. weather observing stations serves the need for weather prediction, but it is inadequate for climate monitoring and research. To remedy this situation, NOAA is developing the U.S. Climate Reference Network, a group of about 100 observing stations that will provide homogeneous long-term observations of temperature and precipitation, helping to place observed trends into historical perspective. Similar surface-based networks exist for streamflow monitoring, seismic measurements, and other purposes; these need to be maintained and enhanced.

Aircraft are another source of routine weather observations and an essential tool in Earth system research. Many satellite-borne sensors for Earth observation were conceived for and tested on aircraft, and airborne field campaigns are a vital training ground for graduate students. Yet NASA's airborne research facilities are in significant jeopardy. The limits on aircraft use are growing, while support for staging field campaigns and developing instruments has decreased and the level of technical infrastructure for airborne missions has declined.

The transition of airborne programs at NASA and NOAA from conventional aircraft to unpiloted aerial vehicles (UAVs) presents opportunities as well as risks. UAVs provide increased range and flight time and the ability to penetrate environments that



might be too hazardous for piloted aircraft. However, issues of cost, reliability, software, and proximity to urban areas have limited the use of UAVs to demonstration missions. For now, conventional aircraft remain more reliable and more cost-effective for Earth sensing, and agencies need to ensure an appropriate balance between these two types of platforms.

Understanding the interaction between human activities and the natural environment is of growing interest. Space-borne and in situ observations greatly enable this understanding, but for maximum usefulness they need to be coordinated with additional information about urban areas and other human-modified landscapes. Much of this information currently falls within the domain of social scientists, economists, geographers, urban planners, and others not traditionally part of the Earth science community. Increased collaboration with these groups is essential.

TURNING OBSERVATIONS INTO KNOWLEDGE AND INFORMATION

A central theme of the decadal survey report is the utility of space-based observations of the planet for addressing important societal needs. Achieving benefits for society will require the development of an integrated process that transforms observations into useful information. We also need to improve our ability to assimilate data from multiple observations and sensors, while addressing well-known challenges of data and information management.

To provide a more direct route from space-based observation to societal benefits requires that social scientists be more involved throughout the entire life cycle of a given mission. Closer ties between physical and social scientists can also help make the resulting mission data more readily available to a broader range of users through improved access, education, and training.

As discussed in several recent National Research Council reports, an increasing challenge is to manage and process the flow of Earth-system data gathered from the above systems. Every mission must have a plan for processing and archiving data and making the data easily accessible at little or no cost to users. Research and analysis efforts such as those at NASA need to be maintained and strengthened. Likewise, support for modeling, computing, and data assimilation is essential in order to maximize the value of our investment in observing systems. NASA should enhance its Research and Analysis (R&A) program to provide this crucial scientific underpinning, ensuring adequate support for R&A as well as operations and data analysis associated with the recommended missions.

Commercial entities are also providing a rapidly growing array of Earth information services, many of them free. While these are not expected to replace government systems, they can serve as a valuable adjunct. The committee recommends that teams of experts be formed to combine and assimilate data from both public and private sources.

SUSTAINING THE KNOWLEDGE AND INFORMATION SYSTEM

A successful long-term plan for monitoring Earth from space must be durable enough to withstand changes in leadership, variations in funding, advances and slowdowns in technology, and other hard-to-predict factors. Such a plan should incorporate mechanisms for adapting to evolving constraints as needed, and it should build the next generation of leaders through committed education and training.

To ensure long-term programmatic stability, the decadal survey report encourages the formation of an independent, community-based advisory body that regularly reviews the status of space-based Earth observing systems as a whole, with an eye to potential problems as well as opportunities. Such a group will need to provide advice consistent with evolving plans for both domestic and international programs. It should also seek opportunities for efficiencies that come from collaboration and data sharing.

To assist with issues that inevitably arise as programs are reprioritized and adjusted and to help guide programmatic decisions, committee members developed the following strategies and rules:

- *Leverage international efforts.* Restructure or defer missions that are largely duplicated by other nations; when appropriate, offer cost-effective additions to international missions to extend their value.
- *Manage technology risk*. Sequence missions according to technological readiness and budgetary risk; invest early in efforts to meet important technological challenges.
- *Develop a mechanism for responding to budget pressures and shortfalls.* Implement an independent review process to ensure that larger objectives are considered; delay or cancel missions if cost overruns grow large; when missions must be dropped, eliminate some within each theme area (see box on page 6), rather than dropping entire themes; if budget shortfalls are large, seek community input and reevaluate the observing program as a whole rather than in a piecemeal fashion.

Ensuring balance is an important high-level principle essential to maintaining the integrity of the overall plan for Earth sensing from space as priorities change and programs are adjusted. Balance should be sought across:

- *Scientific disciplines,* so that the range of expertise needed for interdisciplinary Earth systems science is available and breakthroughs in specific areas are nourished;
- *Mission sizes,* to allow for participation at multiple levels of the scientific community and to balance long-term pursuits with a capability for timely response to emerging ideas;
- *Technology maturity,* so that roadblocks to mission progress are kept to a minimum;
- *Observations, analysis, and modeling,* so that the appropriate tools are available to analyze and understand new data as they become available; and
- *Stability and adaptability,* so that new societal needs can be met while long-term programs of value are protected.

As our nation's approach to observing Earth from space is revitalized, it is exceedingly important that future scientists obtain the education and training they need to interpret new observations and turn them into knowledge that benefits society. Such training can be provided through symposia and workshops for smaller, more specialized communities. Larger audiences can be accommodated through computer-aided distance learning. To ensure the wide and effective use of Earth observation data, opportunities for education and outreach should be emphasized early on so that both the science and the user communities are ready when new data become available. Educators will thus also be able to integrate information on new missions and their benefits into curricula for elementary-school through university levels. Such efforts will expand the science literacy of future scientists, teachers, and the public as a whole.

KEY ELEMENTS OF THE MISSIONS

ORBIT ALTITUDES

Low Earth orbit (LEO): an orbit typically between 300 and 2,000 kilometers above Earth

Sun-synchronous orbit (SSO): an orbit structured so that the satellite passes over a given point on Earth at the same time each day

Medium Earth orbit (MEO): an orbit in the range between LEO and GEO, used by the Global Positioning System (GPS) and other navigational and communications satellites

Geosynchronous Earth orbit (GEO): an orbit that is useful for applications that require a satellite to appear stationary with respect to a fixed point on the rotating Earth. To achieve such an orbit, an object must be placed into a circular orbit in a plane aligned with Earth's equator, and at an altitude such that the orbital period of the satellite is exactly equal to Earth's period of rotation (approximately 24 hours). The altitude for geostationary orbit is approximately 36,000 kilometers above sea level.

WAVELENGTHS

Microwave: 1 millimeter to 30 centimeters; typical wavelengths used by radars, scatterometers, and radiometers; classified into wavelength ranges identified by letter (e.g., X-band or K-band)

Infrared (IR): 750 nanometers to 1 millimeter; useful in detecting clouds, ocean eddies, and other Earth system features, especially those involving water or water vapor

Visible (400 to 700 nanometers) and ultraviolet (1 to 400 nanometers): useful for space-borne remote sensing of molecular species in Earth's troposphere and stratosphere

INSTRUMENT TYPES

Active (sends signals and receives returns)

Radar (radio detection and ranging): detects and characterizes objects by transmitting pulses of radiation, typically in the microwave range, and analyzing the portion of the signal that is reflected and returned to the sensor

Lidar (light detection and ranging): similar to radar, but using laser light instead of radio signals

Scatterometer: specialized radar used mostly to determine wind speed and direction near the ocean surface, but can also be used over land to study ice and vegetation

Altimeter: specialized radar or lidar that measures the height of the land or sea surface

Passive (receives signals from the Sun, the Earth system, or other satellites)

Radiometer: measures the intensity of energy radiated by an object at a given wavelength, typically at infrared or microwave wavelengths

Limb sounder: observes Earth's limb (the horizon from space) and measures radiation emitted by or passing through various heights of Earth's atmosphere

GPS receiver: receives radio waves emitted from GPS satellites; can be used to analyze variations in signal speed and infer atmospheric properties (through a technique called radio occultation), and to determine position

Spectrometer: measures light received in terms of the intensity at constituent wavelengths to determine chemical makeup, temperature profiles, and other atmospheric properties

Interferometer: combines signals from two or more wavelengths in order to produce higher resolution than an individual wavelength could provide

Polarimeter: measures the polarization of incoming light and can, for example, help in the characterization of atmospheric aerosols