NASA Earth Observation Programs and Small Satellites

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Abstract NASA's strategic goal in Earth science is motivated by the fundamental question: "How is the Earth changing and what are the consequences for life on Earth?" NASA's mission in Earth science as mandated by the U.S. Space Act is to "... conduct aeronautical and space activities so as to contribute materially to ... the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space". Therefore, NASA's role is unique and highly complements those of other U.S. Federal agencies by continually advancing Earth system science from space, creating new remote sensing capabilities, and enhancing the operational capabilities of other agencies and collaborating with them to advance Earth science goals. NASA's Earth Science Division (ESD) currently has a system of spacecraft collecting observations of the Earth system and in the months and years ahead will deploy new satellites and constellations with advanced measurement capabilities. Small satellites (~500 kg or less) have been crucial contributors to achieving NASA's Earth science measurements and will continue to be so in the future. The U.S. National Research Council (NRC) is just now completing its first decadal survey for Earth science and applications from space. This survey will be used to set priorities for future missions to 2017 and beyond. Current status of ESD flight programs, preparations for the NRC decadal survey, and the role of small satellites will be discussed.

1 NASA Earth Science

The complexity of the Earth system requires that an organized scientific approach be developed for addressing the complex, interdisciplinary problems that exist, taking good care that in doing so there is a recognition of the objective to integrate science across the programmatic elements towards a comprehensive understanding of

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the Earth system. In the Earth system, these elements may be built around aspects of the Earth that emphasize the particular attributes that make it stand out among known planetary bodies. These include the presence of carbon-based life; water in multiple, interacting phases; a fluid atmosphere and ocean that redistribute heat over the planetary surface; an oxidizing and protective atmosphere, albeit one subject to a wide range of fluctuations in its physical properties (especially temperature, moisture, and winds); a solid but dynamically active surface that makes up a significant fraction of the planet's surface; and an external environment driven by a large and varying star whose magnetic field also serves to shield the Earth from the broader astronomical environment.

The resulting structure is comprised of six interdisciplinary Science Focus Areas:

Atmospheric Composition	Weather
Carbon Cycle and Ecosystems	Water and Energy Cycle
Climate Variability and Change	Earth Surface and Interior

These six focus areas include research that not only addresses challenging science questions but drives the development of an Earth observing capability and associated Earth system models as well. In concert with the research community, NASA developed a hierarchy of science questions. The fundamental question: "How is the Earth changing and what are the consequences for life on Earth?" leads to five associated core questions, representing a paradigm of variability, forcing, response, consequences and prediction mitigate natural hazards? Figure 1 illustrates the cross-cutting and interdisciplinary nature of the science questions and their links to each science focus area.

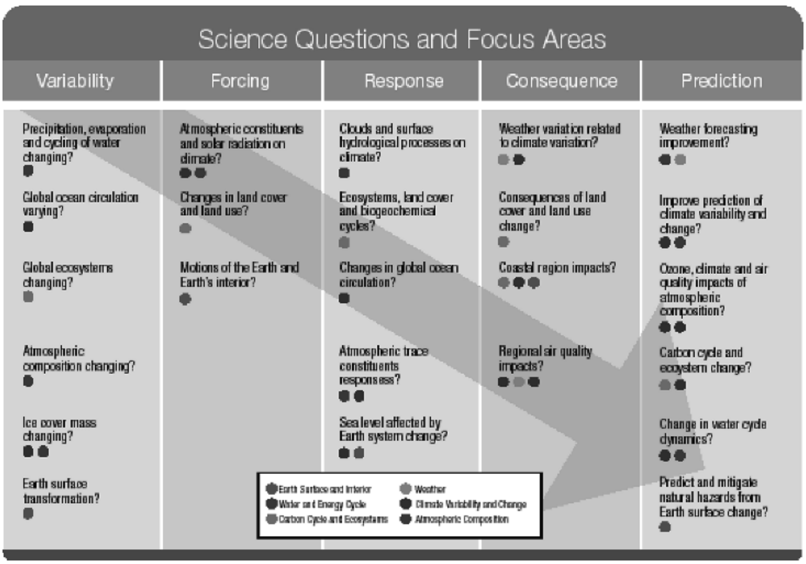

Fig. 1 Links and interrelationships between science focus areas and science questions

NASA's Earth science programs are essential to the implementation of three major Presidential initiatives: Climate Change Research (June 2001), Global Earth Observation (July 2003), and the U.S. Ocean Action Plan (December 2004).

NASA's Earth science program is an end-to-end one that starts with the development of observational techniques and the instrument technology needed to implement them; tests them in the laboratory and from an appropriate set of suborbital (surface, balloon, aircraft) and/or space-based platforms; uses the results to increase basic process knowledge; incorporates results into complex computational models that can be used to more fully characterize the present state and future evolution of the Earth system; and develops partnerships with other national and international agencies that can use the generated information in environmental forecasting and in policy and resource management. Accordingly, ESD is divided into the following major program elements: Research and Analysis, Flight, and Applied Sciences, and Technology [1].

2 ESD Flight Program Status

ESD's Flight Program encompass the space based and suborbital remote sensing observational capabilities supporting NASA's Earth science activities. Ground segment elements such as data and information systems are an important part of the Flight Program in addition to space and suborbital missions. Synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies is the hallmark of the. Three types of space flight missions were distinguished in the recent past: systematic observation missions (SYSP), exploratory missions (PI-led), and operational precursor or technology demonstration missions. The identification of these categories represents a significant evolution of the original architecture of the Earth Observing System, which combined studying basic processes, assembling long-term measurement records, and introducing innovative measurement techniques. The Flight Program also develops geostationary-orbiting meteorological and polar-orbiting environmental satellites for the National Oceanic and Atmospheric Administration (NOAA) through the Geostationary Operational Environmental Satellite (GOES) and the Polar Operational Environmental Satellite (POES) programs.

Figure 2 provides the timeline of Earth science systematic and exploratory missions, including placeholders for future missions. 14 ESD missions are currently operating while 7 are in formulation or development. Of these 21 missions, 9 fall into the small satellite ($\sim$500 kg or less) category. The Ocean Surface Topography Mission (OSTM), Orbiting Carbon Observatory (OCO), Glory, and Global Precipitation Measurement (GPM) are related upcoming missions. This emphasis reflects advancements in compact sensor, small satellite bus, and launch vehicle technologies, in addition to management innovations (e.g. Principal Investigator mission management and streamlined "catalog" acquisition approaches). Advanced planning suggests this trend will continue including their use in constellations as is

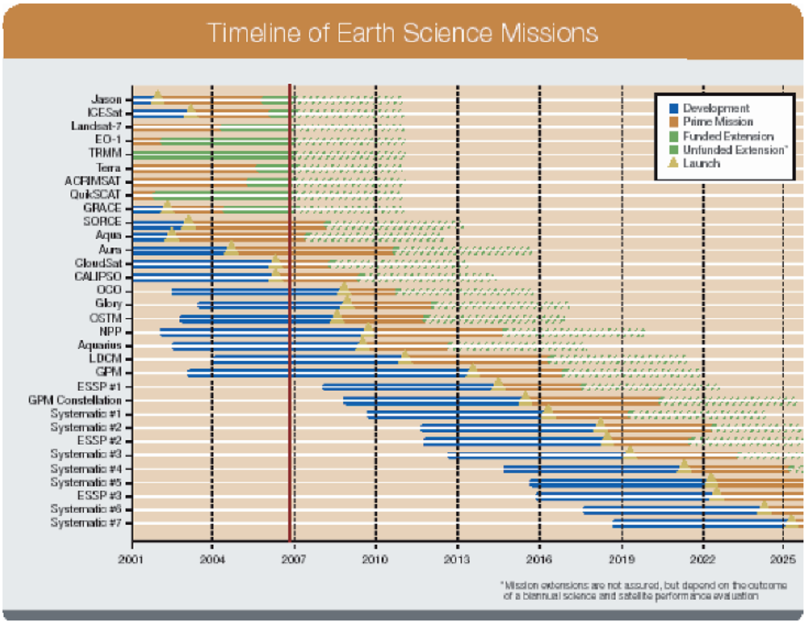

Fig. 2 Earth science mission timeline (includes placeholders for future missions)

now the case in the five satellite A-Train. Descriptions of the four upcoming small satellite missions follow.

OSTM will measure sea surface height to an accuracy of < 4 cm every ten days. Its primary objectives are to provide continuity of ocean topography measurements beyond the Jason mission and to provide a bridge to an operational mission to enable the continuation of multi-decadal ocean topography measurements. OSTM uses a Thales Alenia PROTEUS minisatellite bus. It is a collaboration with CNES, EUMETSAT, and NOAA. OSTM is in implementation (Phase C/D) and is scheduled for 2008 launch with a 3 year lifetime.

OCO provides space-based observations of atmospheric Carbon Dioxide (CO2), the principal human-initiated driver of climate change. It will generate precise global maps of the abundance of CO2 in the Earth's atmosphere using an optical spectrometer. OCO uses an Orbital Sciences Corporation LeoStar-2 minisatellite bus. OCO is in implementation (Phase C/D) and is scheduled for launch in 2008 with a 2 year lifetime.

The Glory mission will increase our understanding of black carbon soot and other aerosols as causes of climate change as well as continue the measurement of the total solar irradiance. Aerosol properties will be measured by an advanced polarimeter. The total solar irradiance measurement will be made based by a SORCE-heritage instrument. Glory uses an Orbital Sciences Corporation LeoStar minisatellite bus. It will carry two optical instruments. Glory is in implementation (Phase C/D) and is scheduled for launch in 2008 with a 3 year lifetime.

Fig. 3 Ocean Surface Topography Mission

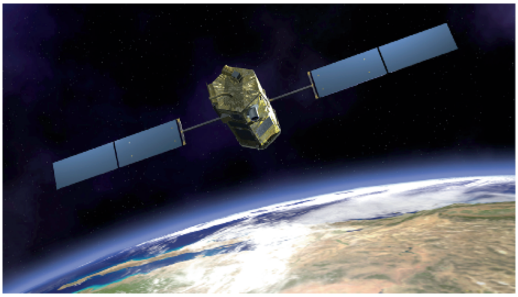

Fig. 4 Orbiting Carbon Observatory

The Global Precipitation Measurement (GPM) mission initiates the measurement of global precipitation, providing uniformly calibrated measurements every 3 hours for scientific research and societal applications through a constellation of dedicated and operational satellites carrying active and passive microwave sensors. It is a collaboration with JAXA and other international partners. In addition to the precipitation radar carrying Core Spacecraft, NASA supplies a single instrument minisatellite observatory. The GPM Constellation Spacecraft flies in a low-inclination orbit to improve spatial coverage and sampling frequency, near real-time monitoring and prediction of hurricanes/typhoons, diurnal sampling of precipitation, cross-calibration of polar-orbiting constellation satellites. GPM Constellation will use a RSDO catalog minisatellite bus. GPM Constellation is in formulation (Phase B) and is scheduled for launch in 2014.

Fig. 5 Glory

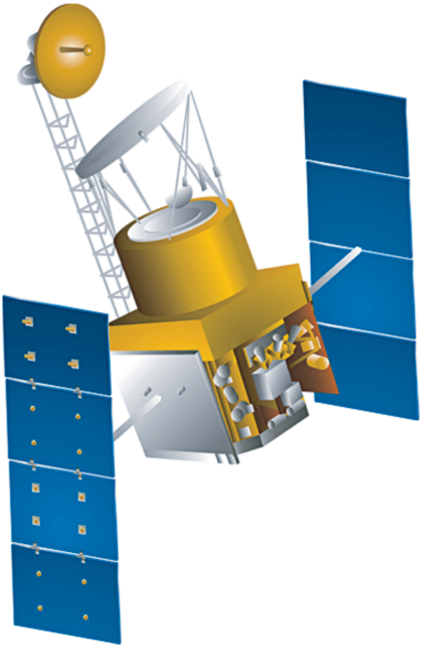

Fig. 6 GPM Constellation

3 NRC Decadal Survey and ESD Preparations

The U.S. NRC recently completed its first decadal survey for Earth science and applications from space [2].This survey will be used by ESD to set priorities for future missions and research and develop an integrated strategic roadmap of its space activities. Among its recommendations, the decadal survey prioritized 15 missions for ESD to launch during 2010–2020. During the latter half of 2006, in preparation for the decadal survey and to facilitate strategic roadmapping, ESD conducted "building block" mission concept definition studies under NASA Headquarters direction at the Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), and the Langley Research Center (LaRC). These consisted of 13 individual and 6 integrated mission concepts based on earlier Science Focus Area roadmaps. ESD is presently using the engineering, programmatic, and budgetary data from the "building block" studies to construct the priority order of its space science missions through the next decade. In both the decadal survey missions and the ESD "building block" studies a number of concepts used small satellites in individual or multi-satellite configurations. Four small satellite concepts from the 15 missions recommended by the NRC decadal survey follow.

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) will provide a global, accurate, and tested climate benchmark. Key observations include incident and reflected solar irradiance and spectrally resolved radiance emitted to space that carries the spectral signature of IR forcing of climate and the resulting response of that climate system. The observing elements are shared between NASA and NOAA. The NASA component consists of three microsatellites in polar orbits separated by 60 degrees in orbit plane, two carrying redundant IR interferometers and the third carrying in addition a UV/VNIR/SWIR redundant interferometer. GPS occultation receivers are carried on all three microsatellites. CLARREO is recommended to launch in the 2010–2013 timeframe. The NOAA component of CLARREO is the reflight of the TSIS incident solar irradiance and CERES broadband Earth radiation instruments on NPP and NPOESS.

Soil Moisture Active-Passive (SMAP) will provide global high-resolution 3–10 km soil moisture mapping. It addresses critical science questions in the water and energy cycle and enhances the forecasting and mitigation of flash-floods, severe storms, and regional droughts. Additionally, it extends the predictability of processes influenced by surface moisture states and fluxes. SMAP is based on a single minisatellite in low Earth orbit and includes both active and passive L band microwave measurements. Its technology readiness benefits from the recent Hydros risk reduction efforts. SMAP is recommended to launch in the 2010–2013 timeframe.

Surface Water and Ocean Topography (SWOT) will address science and applications questions related to the storage and movement of inland waters, the circulation of the oceans and coastal waters, and the fine-scale bathymetry and roughness of the ocean floor. SWOT carries a Ka band swath altimeter that will produce high resolution measurements of water surface elevations over inland waters, as well as near-coastal regions and the open ocean. It also carries a Ku band nadir altimeter, a microwave radiometer, and a precision GPS receiver. It uses a minisatellite bus and is recommended to launch in 2013–2016 to overlap with the NOAA-recommended ocean vector winds mission.

Gravity Recovery and Climate Experiment-II (GRACE-II) will measure temporal variations in Earth's gravity field at a higher resolution than that demonstrated by the NASA-DLR GRACE mission. For the hydrological cycle, GRACE-II will observe large-scale evapotranspiration, soil moisture inventory, and depletion of large aquifers; detect changes in deep ocean currents to differentiate between sea

Fig. 7 CLARREO

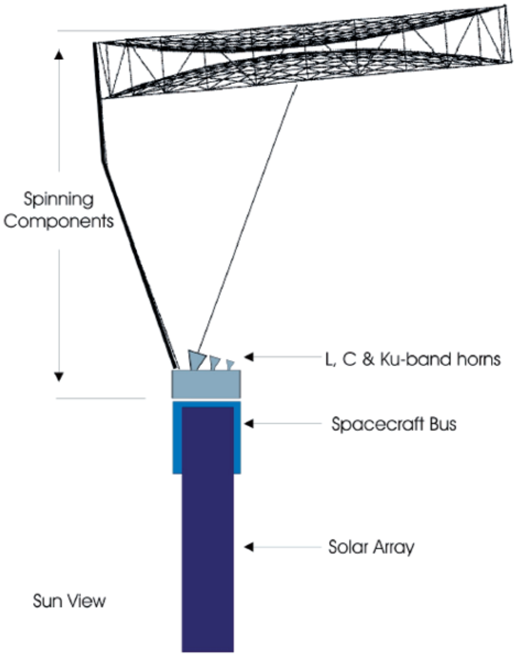

Fig. 8 SMAP

level rise and addition of freshwater from the continents; and detect changes in the mass and global spatial distribution of ice and permafrost. In addition, GRACE-II will identify constraints on the strength of Earth's interior by observing changes in the flow in Earth's core. GRACE-II will have more accurate measurement of inter-satellite range using either an improved version of the GRACE microwave ranging system or a laser satellite-to-satellite interferometer. The pair of microsatellites is recommended to be launched in 2016–2020.

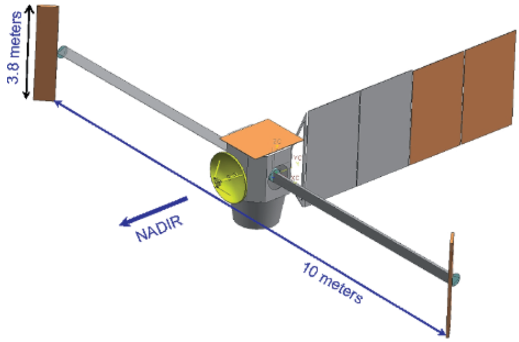

Fig. 9 SWOT

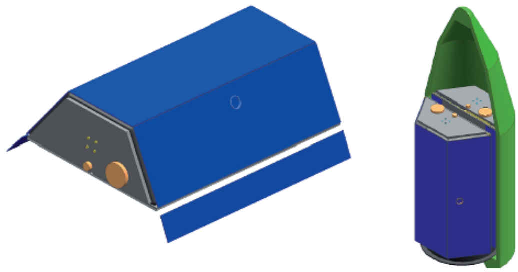

Fig. 10 GRACE-II

4 Role of Small Satellites

In the decade 2007–2017, ESD will develop and demonstrate new sensors and interacting constellations of satellites. Expanded operational capabilities will be complemented with the delivery of reliable data products from the space observing system and the continual improvement of predictive models based on emerging scientific research. In the future, as more data is collected and analyzed from a multi-disciplinary viewpoint and as predictive model development moves toward increased coupling of Earth system components, there will be increasing requirements for scientific research. Likewise, the number of space-based observations required for assimilation into the coupled models will also grow with the complexity of the system. In order to meet the increasing demands of data volume and model complexity, ESD will pursue the following strategies:

- *Work with the scientific community to create interdisciplinary teams that help focus research and resources on key uncertainties and model deficiencies;*

- *Develop in concert with commercial partners, new, decentralized approaches to data archiving and management that emphasizes broad, creative uses of multi-disciplinary data sets;*
- *Develop, launch and operate a cost effective suite of space-borne missions that observe multiple key Earth system parameters; and,*
- *Coordinate with other U.S. and international partners to ensure that a core set of key measurements are made on a sustained basis.*

In implementing the third of these strategies, ESD anticipates using the increasing capabilities of small satellites and their constellations.

References

1. NASA, Science Plan for NASA's Science Mission Directorate 2007–2016, 42–71 (2007)
2. National Research Council, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (2007)