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2000 Survey of Distributed Spacecraft Technologies and Architectures for NASA's Earth Science Enterprise in the 2010–2025 Timeframe

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National Aeronautics and
Space Administration

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August 2000

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1 Purpose

The purposes of this study are:

(1) To identify far-term (2010–2025) Earth Science Enterprise (ESE) mission concepts that are candidates for implementation as part of the Earth Science vision and are enabled (i.e., not feasible without) or enhanced (i.e., improved in a meaningful way) by the use of distributed spacecraft architectures or technologies.

(2) To define and characterize the functional attributes (i.e., what to do) and technical performance (i.e., how well to do it) required from distributed spacecraft architectures that support these mission concepts.

(3) To identify distributed spacecraft technology areas where technology developments are needed to implement these mission concepts.

(4) To accumulate data that may be useful in a follow-on effort to develop general technology investment strategy tools.

2 Background

The Cross-Enterprise Technology Development Program (CETDP) develops critical, long range strategic technologies to enable or reduce the cost of future NASA science missions. CETDP, as its name suggest, serves the needs of multiple NASA enterprises: Earth Science, Space Science, and Human Exploration and Development of Space. The program is executed through ten technology thrust areas. One such thrust area is Distributed Spacecraft, a spatially distributed network of individual vehicles or assets, acting collaboratively as a single collective unit and exhibiting a common system-wide capability.

NASA Headquarters released NASA Research Announcement NRA 99-OSS-05 Advanced Cross-Enterprise Technology Development for NASA Missions to solicit new and innovative technology solutions under the Cross-Enterprise Technology Development Program (CETDP). The NRA covers the full range of NASA technology areas including Distributed Spacecraft Technology (DST). The DST Thrust Area Manager has commissioned Goddard to conduct this study of ESE future mission needs for DST to better focus DST technology investment. The Jet Propulsion Laboratory is conducting a complimentary study to determine Space Science Enterprise needs for DST technology.

3 Scope

The study covers ESE needs for DST in the 2010–2025 timeframe. As ESE plans for that period are in the process of being defined, appropriate and current ESE documents and interviews with ESE science and technology personnel provide the necessary framework. In particular, the study focused on the Earth Science Vision Initiative and extrapolation of the ESE measurement architecture for the 2003–2010 time period.

The study provides no recommendations as to investment in a specific technology or implementation, but rather provides information to assist in formulating investment decisions with regard to types of technologies and capabilities strategically appropriate and needed by ESE.

Several of the identified technology needs cross thrust area boundaries. This study notes these areas but does not recommend under which thrust area these technology needs should be addressed.

4 Assumptions

This study assumes that the ESE Post-2002 measurement set is the baseline from which the top level science requirements derive. NASA will implement a set of missions and leverage other data sources (e.g., commercial entities, other agencies) to fulfill these requirements. This study further assumes that the ESE will evolve the Post-2002 mission set into an implementation of the Earth Science Vision. The study also assumes that the ESE will obtain the necessary funds to realize the post-2002 mission set and subsequent vision implementation. Descriptions of the Post-2002 Mission Scenario and the ESE vision are contained in reference documents listed in appendix A.

5 Methodology

A two-prong approach was used. The study investigated DST fundamental principles as applied to Earth observation. This established the technical foundation for study development as well as assisting in logical project categorization. Simultaneously, a survey was conducted to identify ESE measurement driven concepts, which are likely candidates for DST infusion in the study timeframe. The results of the two activities are integrated. Notional architectures enabled or enhanced by DST were developed for each of the project categories. These architectures revolve around DST capabilities needed by ESE in the 2010-2025 period, but remain, as much as possible, non-measurement or implementation specific.

A Technology Formulation Team (TFT) composed of technologists, systems engineers, and Earth scientists utilized the facilities of Goddard's Integrated Mission Design Center and Collaborative Engineering Environment to refine the notional architectures and identify technology drivers and constraints. The TFT developed the initial technology development and infusion roadmaps leading to the notional architectures. A further description of the TFT can be found in appendix C.

6 Earth Science Enterprise Strategy and Vision

6.1 Current Earth science architecture characteristics

Current architectures are characterized by single research spacecraft or campaigns with little or no interaction among space based assets. Modeling and fusion of data occur on the ground sometime after data acquisition. Dynamic scheduling is generally not allowed and there is no provision for time sharing information or rapid reallocation of resources in response to events.

Earth science missions generally fall into one of two groups. Long-term system monitoring and pathfinder or exploratory missions. Long-term system monitoring missions include Terra, Aqua, Landsat 7, and Chemistry. They are characterized by large, multiple instrument platforms and complex, labor intensive ground operations. Exploratory missions such as the Earth Systems Science Pathfinder (ESSP) series provide for one-time scientific discovery campaigns. These missions are generally more focused and lower in cost than the long-term monitoring missions. They may lead to longer-term follow-on monitoring missions. Exploratory missions generally operate independently of other missions and utilize intensive ground operations. Mission response to geologic or other significant events are directed by the ground team after a substantial planning activity and time delay.

Collaboration between NASA and other U.S. Government and foreign space agencies as well as commercial ventures provides additional Earth science data. NASA leverages its partnerships by both acquiring and using data and by providing instruments for flight on the partners spacecraft. NOAA's GOES and POESS, and the Department of Defense Meteorological platforms augment NASA long-term monitoring capacity. Foreign partners, particularly from Europe and Japan, allow sharing of precious monetary and physical resources. Examples include ADEOS II, a NASDA mission flying NASA's SeaWinds instrument measuring ocean surface wind speeds globally, and Meteor 3M-1, a Russian spacecraft carrying NASA's SAGE III instrument providing data on atmospheric aerosols and chemical species. Commercial data buys such as SeaWiFS take advantage of emerging commercial markets and capabilities.

6.2 Earth science measurements in the 2002–2010 timeframe

Table 1 provides an analysis of existing Earth Science Enterprise plans and documents. The first section contains information from the ESE Strategic Plan. The left-most column lists the Earth science mission and science priorities. These translate into science areas reflected in both the ESE Technology Strategy, the Post-2002 Workshop results, and the ESE Vision. Requirements flow from the science questions, to research focus questions, goals and objectives, and science priorities. The Post-2002 measurement set has not at this time completed the transition into a reference architecture. A further description of the Post-2002 measurement set can be found in appendix D.

6.3 Earth science vision for the 2010–2025 timeframe

From table 1, we see the continuing flow of measurement requirements from the ESE Strategic Plan to the ESE Vision. The five science themes align well with the areas from the strategic plan. Table 2 traces the implementation of ESE measurements from the existing mission set through the Post-2002 era. Notional distributed spacecraft architectures, which are detailed in section 7, are

Table 1. Analysis of Earth Science Enterprise Plans

	From ESE Strategic Plan	
Content	**Research Questions**	**Science Priorities**
Earth Science Mission: To develop understanding of the total Earth system and the effects of natural and human-induced changes on the global environment.	How can we enable regionally useful forecasts of precipitation and temperature on seasonal-to-interannual time frames?	Seasonal-to-Interannual Climate Variability and Prediction
The Goal of Earth System Science: To obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales.	What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?	Long-Term Climate: Natural Variability and Change
The Challenge to Earth System Science: To develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity.	How and why are concentrations and distributions of atmospheric ozone changing?	Atmospheric Ozone Research
NASA Basic Question: How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, resource identification, and resource management models to help ensure sustainable development and improve the quality of life on Earth?	What are the nature and extent of land-cover and land-use change and the consequences for sustained productivity?	Land-Cover Change and Land-Use Change Research
NASA basic question: What cutting-edge technologies, processes, techniques, and engineering capabilities must we develop to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?	Can we learn to predict natural hazards and mitigate natural disasters?	Natural Hazards Research and Applications

From ESE Technology Strategy "Driving Vision	From Post 2000 Workshop	From ESE Vision	
Science Areas	**Six Panels**	**ESE Themes**	**What NASA Can Do**
Global Water and Energy Cycle	Global Water Cycle, Hydrology, and Mesoscale Weather	Global Water	Enable accurate two week weather prediction/ 12 -hour severe storm forecast
Climate Variability and Prediction	Atmosphere Climate Physics	Climate & Trends	Enable accurate climate prediction (monthly-seasonal-decadal)
Atmospheric Chemistry	Atmospheric Chemistry	Carbon Cycle & Biosphere	Enable prediction of biosphere and land process changes
Biology and Biochemistry of Ecosystems and the Globl Carbon Cycle	Ocean and Ice Land Cover, Land Use and Terrestrial Ecosystems	Atmospheric Ozone	Enable prediction of global air and water quality
Solid Earth Science	Geodynamics and Geology	Solid Earth	Enable prediction of natural hazards

introduced with the potential to enable or significantly enhance ESE science theme measurements in the 2010 to 2025 timeframe.

The goal of the ESE Vision for the 2010 to 2025 timeframe is proactive environmental prediction. Several advances, described in Table 3, are needed to achieve this goal including improved and interdisciplinary environmental models. These models will require more accurate, more frequent, and more flexible measurements. The result is an architectural vision with an extremely high data volume and autonomous reconfiguration in response to changing needs. The architecture would weave individual measurement architectures and leveraged existing and external resources into a higher order, coordinated structure. The first three notional architectures address individual measurements, which could be accomplished though distributed spacecraft technology. The fourth notional architecture specifically addresses technology needs imposed by the vision's architectural hierarchy.

7 Distributed Spacecraft Architectures

7.1 Notional distributed spacecraft architectures

Earth science encompasses a broad scope of measurement requirements. For the time period of this study, missions have not been formulated addressing these measurement requirements. However, reviews of Earth Science Enterprise plans, described in section 6, indicate that distributed spacecraft are likely to contribute to the Earth science post-2010 strategy and vision.

Four notional distributed spacecraft architectures are described in this section. It is likely that some variation on one or more of these generic architectures will serve as building blocks for post-2010 Earth science systems. These notional architectures stress key technological attributes and actual implementations will certainly differ. Each architecture is enabling and/or enhancing to some feature of the Earth science program beyond 2010. In general, the technologies build up from global constellations toward sensorwebs by adding complexity. The relationship among the architectures is illustrated in figure 1.

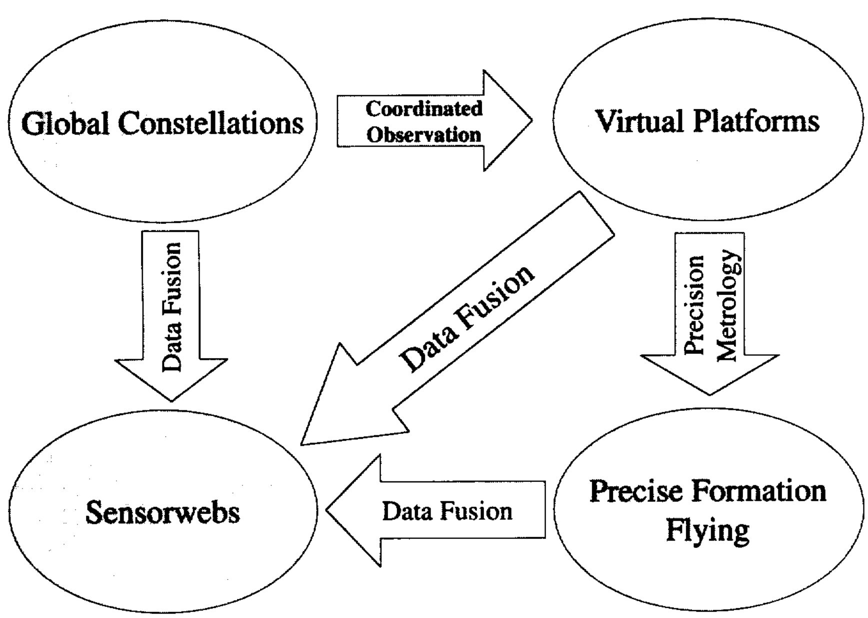


Figure 1. Architectural Transformations

Table 2. ESE Measurement Transition (Representative)

ESE Science Theme	Example Current Measurements & Implementation	Representative Post-2002 Measurements	2010–2025 Notional DST Architecture
Global Water	TRMM, JASON-1	EOS-9 (Global Precipitation), EX-4 (Soil Moisture)	Notional Architecture 1 (Constellations), Notional Architecture 2 (Large synthetic aperture virtual platform), Notional Architecture 4 (sensorwebs)
Climate & Trends	Aqua, Terra, ACRIMSAT, Picasso-CENA, SORCE	EOS-4 (Total Solar Irradiance Monitoring), OP-1 (Advanced Microwave Sounder), NPP, EOS-2 (Climate Variability and Trends), OP-3 (GPS Constellation for Atmospheric Sounding)	Notional Architecture 1 (Constellations), Notional Architecture 2 (Multi-angular viewing virtual platform, multi-instrument virtual platforms), Notional Architecture 4 (sensorwebs)
Atmospheric Ozone	CHEM, TOMS, SAGE	EOS-7 (Stratospheric Composition), OP-3 (GPS Constellation for Atmospheric Sounding), EX-2 (Aerosol Radiative Forcing Research)	Notional Architecture 1 (Constellations), Notional Architecture 2 (multi-instrument virtual platforms), Notional Architecture 4 (sensorwebs)
Carbon Cycle & Biosphere	Landsat 7, EO-1, Terra, VCL	EOS-1 (Land Use/Land Use Inventory), EOS-3 (Global Terrestrial and Ocean Productivity), NPOES Prep. Proj.,	Notional Architecture 1 (Constellations for Global Precipitation, High temporal resolution remote sensing), Notional Architecture 2 (multi-instrument virtual platforms), Notional Architecture 3 (high-resolution imaging interferometers), Notional Architecture 4 (sensorwebs)
Solid Earth	Landsat 7, EO-1, GRACE	EOS-1 (Land Use/Land Use Inventory), EX-5 (Time Varying Gravity Field Mapping)	Notional Architecture 1 (Constellations for Global Precipitation, High temporal resolution remote sensing), Notional Architecture 2 (multi-instrument virtual platforms), Notional Architecture 3 (Time varying gravity field), Notional Architecture 4 (sensorwebs)

Table 3. ESE Vision Initiative

From ESE Vision				
ESE Themes	**What NASA can do**	**Environmental Predictions and NASA ESE Themes**	**NASA's Goal**	**Advanced Sensors**
Global Water	Enable accurate two week weather prediction/ 12-hour severe storm forecast	Extended Weather	Develop the scientific understanding of the cause of environmental change with the goal of improving model predictability	Optical Detection
Climate & Trends	Enable accurate climate prediction (monthly-seasonal-decadal)	Climate	Lower sensor and launch costs, increase global and temporal coverage	Ultra-large Antennas & Telescopes
Atmospheric Ozone	Enable prediction of bio-sphere and land process changes	Biosphere Air Quality	Seamlessly infuse new technology into sensor systems	LIDARs
Carbon Cycle & Biosphere	Enable prediction of global air and water quality	Resource Management Water Quality	Lower information process-ing/storage costs to acceler-ate model development, data systems, assimilation of new data types	Hyperspectral Imaging
Solid Earth	Enable prediction of natural hazards	Natural/Hazards	Develop information systems capable of rapidly distributing data	µWave Sensing

7.2 Constellations

7.2.1 Characteristics

Constellations exploit relative position to add value to a measurement concept. For the purposes of this study, global constellations are defined as a system employing two or more spacecraft whose orbits, operations, and observations are coordinated to provide global coverage or to improve temporal resolution from an altitude below GEO. The constraint on altitude is driven by differences in operations and temporal coverage between LEO or MEO, and GEO spacecraft. Additionally, the topic of measurement acquired from different vantage points, including GEO, and coordination of these measurements will be addressed under sensorwebs, section 7.5.

Constellations provide increased temporal coverage by decreasing the revisit time to a given location, likewise, may be used to increase the spatial coverage at a given time. Constellations have recently been implemented for the commercial communications satellite industry. A number of others are in development and may include some commercial remote sensing ventures.

The simplest case for a constellation is probably two satellites in the same orbit with the right ascension of the ascending node (RAAN) phased apart. The principal design parameters are temporal density and area coverage. Constellations may also provide some vantage point diversity and opportunities for stereoscopic observations such as the European Space Agency's synthetic aperture radar campaigns afforded during the period in which ERS-1 and ERS-2 were both operational.

The New Millennium Program Space Technology 5 (ST5) mission is planning to validate constellation technology and concepts which may also be applicable to future ESE needs. These technologies include satellite cross-links, relative navigation, and ground systems constellation operations. ST5, which is planned for launch in 2003, will also investigate techniques for large quantity small spacecraft production to enable future constellations of 100 spacecraft or more.

7.2.2 Example constellation missions

Example constellation missions include:

Global Precipitation (EOS-9 and follow-on missions)—This proposed measurement approach would be comprised of nine satellites, a large active radar satellite, flying in a constellation with eight passive radar receivers.

Atmospheric chemistry/ozone (EX-2, OP-3, and follow-on missions)—Constellations provide the ability to conduct multi-point occultation and GPS soundings.

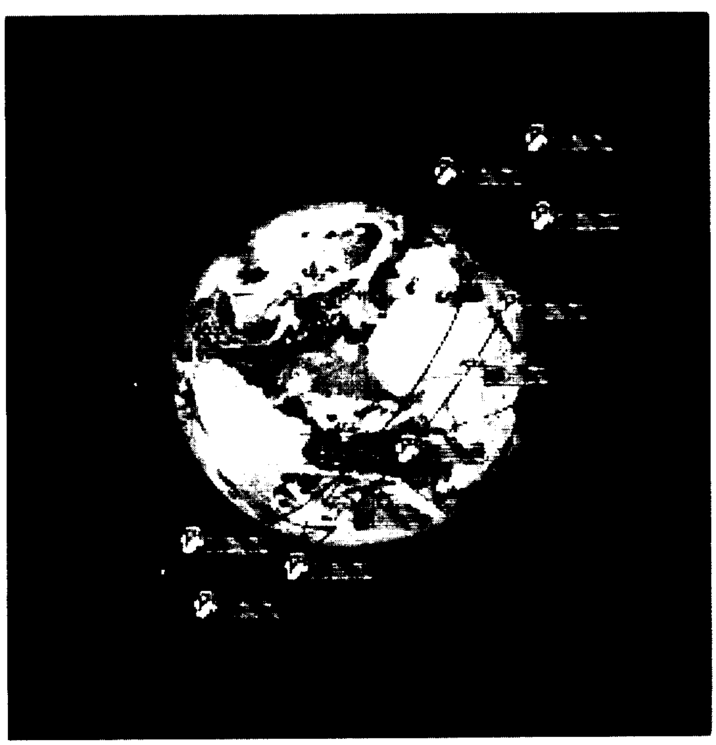
In situ magnetosphere and radiation measurement missions have been flown for the Office of Space Science under its Sun-Earth Connection (SEC) science theme. These missions monitor solar activity and the interaction with the Earth's environment. Future missions such as Magnetospheric Constellation will employ as many as 100 spacecraft to conduct simultaneous in situ multi-point observations.

7.2.3 Notional architecture for global constellations

The notional constellation architecture described here is meant to provide a stressing case to identify technology drivers and gaps. No system with these specific characteristics has been proposed. The architecture assumes all spacecraft are identical replicas of each other and carry a single moderate spatial resolution (about 500 m) instrument. The architecture would provide "instantaneous global" coverage (mean revisit time about one hour at the equator). The instrument is assumed to be nadir pointing push broom (no scanning). A 10% coverage overlap at the equator is also assumed. The architecture assumes a 705 km polar orbit typical of EOS missions. Using a Walker delta pattern (see appendix A, reference 7), 16 planes of 24 satellites each are required for a total constellation of 384 satellites. The architecture configuration is illustrated in figure 2.

Implementation Drivers for constellation missions include:

- Orbit knowledge
- Orbit Control
- Attitude knowledge
- Attitude control
- Bandwidth and communications
- Ground in loop to autonomous control
- Insertion and maintenance
- Launch and deployment
- Spacecraft and instrument production cost



Only single plane shown in figure

Figure 2. Notional Architecture 1—Global Constellations

7.3 Virtual Platforms

7.3.1 Characteristics of virtual platforms

Virtual platforms are defined as a system employing two or more spacecraft flying in formation and registered as if the observations were made and coordinated as a single spacecraft. All elements of a virtual platform must be within direct line-of-sight of each other at all times. These missions exploit coordinated position to enable or add value to the measurement concept. This architecture enables the creation of large synthetic apertures and permits simultaneous stereo or multi-angular views of the same ground track.

Virtual platforms may, for certain scientific observations, view the Earth through approximately the same column of atmosphere. In this way, single, large multi-instrument platforms such as Terra, Aqua, or Chemistry may, in the future, be dispersed among several co-flying elements without loss of geo-registration. This architecture provides risk reduction and graceful degradation. It permits replacement of the failed element while retaining the functioning assets. It would also allow for the introduction of new elements and technology into the orbiting virtual platform as measurement concepts and technology mature.

Another application of virtual platforms would be bandwidth splitting. In this scenario, elements of a large instrument are separated by spectral domains, and the elements are flown on different spacecraft within a virtual platform. This allows for the individual instrument and spacecraft to be optimized for the given wavelengths while retaining the ability to produce correlative observations.

A simple case of a virtual platform would consist of two spacecraft viewing the same ground track. EO-1 will demonstrate some of these attributes as it flies about one minute behind Landsat-7 providing comparative images along the same ground track. Atmospheric motion and its impact on the land imagery dictates the one-minute time scale. Different observations may impose differing time scales. For example, cloud cover may remain stable for as long as fifteen minutes while atmospheric disturbances on the order of a minute or less could affect high resolution land cover observations. EO-1 will also be followed by Terra, providing the basis for a three-element virtual platform.

Many of the attributes of a virtual platform would be demonstrated by the U.S. Air Force's proposed TechSat 21 mission. This mission would formation fly mutliple small spacecraft and demonstrate a distributed array radar application.

7.3.2 Example measurements and missions

Example measurements and missions enabled or enhanced by virtual platform technology include:

Multi-angular Viewing for radiative forcing: The proposed mission would extend beyond the measurement obtained by the Clouds and the Earth Radiant System (CERES) instrument on board Terra and Aqua. The concept would employ two large spacecraft in a central plane with approximately eight co-flying microsatellites.

Soil Moisture and Ocean Salinity Missions (EX-4 and follow-ons): Large synthetic apertures for soil moisture and ocean salinity (L-band measurement, 5 cm relative knowledge) where current approaches are constrained by packaging into the launch vehicle shroud.

Imagery Missions (Bandwidth Splitting): Distribute hyper-spectral measurements into overlapping regions obtained by co-orbiting platforms.

EOS Future Missions (Life cycle cost reduction over traditional larger, single platform): Costs can be reduced by graceful degradation, replacement of failed element, and technology refresh without reducing functionality of other virtual platform elements.

7.3.3 Notional architecture for a virtual platform

The notional architecture selected involves a larger "master" platform and four co-orbiting smaller platforms. The orbital configuration is similar to the Air Force TechSat 21 orbit. The spacecraft are in three orbital planes with the larger spacecraft occupying the central plane. Two of the smaller platforms are phased in each of the other two planes so that it appears as if they are orbiting the larger platform as the entire five spacecraft mission orbits the Earth. The altitude is about 800 km and the spacecraft are in a polar inclination.

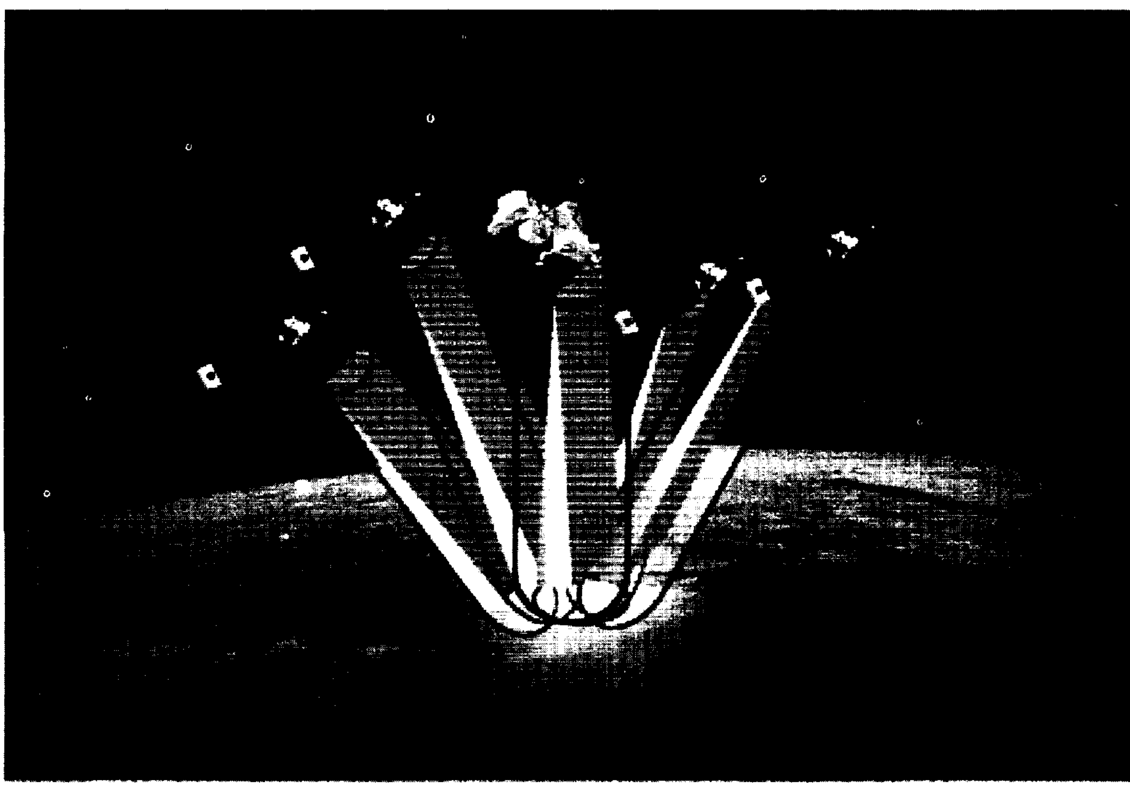


Figure 3. Notional Architecture 2—Virtual Platforms

Implementation drivers include:

- Relative range knowledge & control (soil moisture driver)
- Pointing knowledge, control & coordination (Earth radiation budget).
- Communications trade: Cost of multiple platforms versus cost of communication advances.
- Master controls virtual platform and handles data for down link through cross-links vs. independent spacecraft
- Co-calibration of instrument
- Ground truth validation

7.4 Precision Formation Flying

7.4.1 Precision formation flying characteristics

Precision formation flying exploits coordinated, precise, relative position knowledge and control to add value to a measurement concept. This category encompasses measurements, which require multiple platforms to fly in a very accurate formation where relative range knowledge and/or control becomes a major driver for the observation. Position knowledge and control requirements in this category often exceed the accuracy of GPS navigation by several orders of magnitude. Examples include time varying gravity field measurements and interferometric, very high-resolution imagery.

7.4.2 Example measurements and missions

Example measurements and missions include:

Time Varying Gravity Field Mapping (EX-5/Grace Follow-on): A gravity field mapping mission utilizing technology being developed for the Space Science Laser Interferometer Space Antenna (LISA). The mission would employ two spacecraft, each housing a disturbance isolated proof mass. Position is measured relative to this proof mass. Position knowledge requirements are on the order of 100 nanometers. Spacecraft control requirements are not stringent.

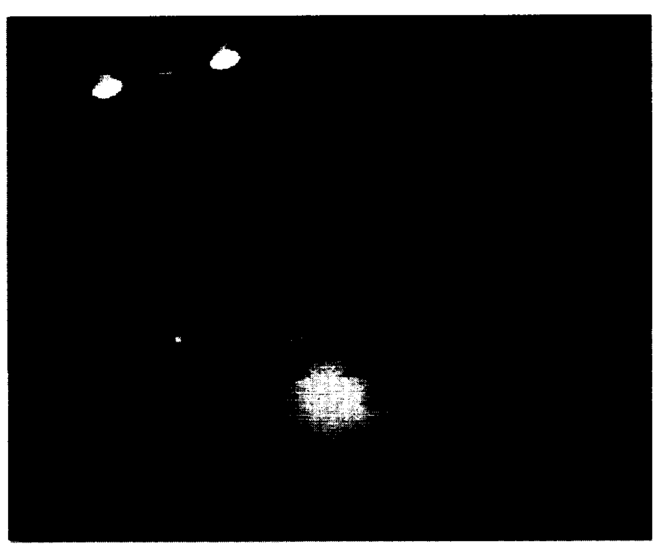


Figure 4. Notional Architecture 3–Precise Formation Flying

Very high-resolution imagery using interferometry: This capability would apply techniques being developed by the Space Science Enterprise for missions such as Terrestrial Planet Finder (TPF) and Separated Element Interferometer (SIM).

7.4.3 Notional Precision Formation Flying Architecture

The notional architecture envisions two spacecraft connected via an optical cross-link. Relative range knowledge and control requirements are 10^{-7} meters. The orbits are polar to obtain global coverage.

Implementation drivers include:

- Relative position and control
- Cross links
- Homogeneous instrumentation and data
- Synthetic aperture – phase retention
- Integer recovery (absolute separation)
- ACS Influences
- Flexible modes and vibration
- Control bandwidth and phase (latency driven)

7.5 Sensorwebs

7.5.1 Sensorweb characteristics

Sensorwebs have been proposed as the key architectural ingredient enabling the Earth Science Vision. For the purposes of this study, sensorwebs are defined as an architecture that utilizes multiple vantage points and a mixture of sensor types to achieve synergistic observations of the Earth. Such an architecture exploits information technology (processing power, modeling, and algorithms) to add value to a measurement concept. Data fusion and real-time measurement coordination and communication across platforms and systems create a leveraged system of systems.

The sensorweb envisions coordinating and obtaining measurements from various vantage points including LEO, GEO, and L1. New orbit types such as pole sitters are also envisioned. Enabled by new propulsion technologies like solar sail, these non-Keplarian orbits would provide continuous view of the Earth's polar regions. Data will also be provided from instruments carried on other platforms such as the International Space Station, U.S. and foreign government agency spacecraft, and commercial data providers. The Office of Earth Science will have to integrate these external systems into the vision's architecture plans.

The sensorweb concept will generate an enormous amount of data, but in addition, will require real-time space-based processing of data for rapid, autonomous measurement coordination. Coordination is made complex by the number of platforms and platform operators and the heterogeneous nature of the platforms and instruments.

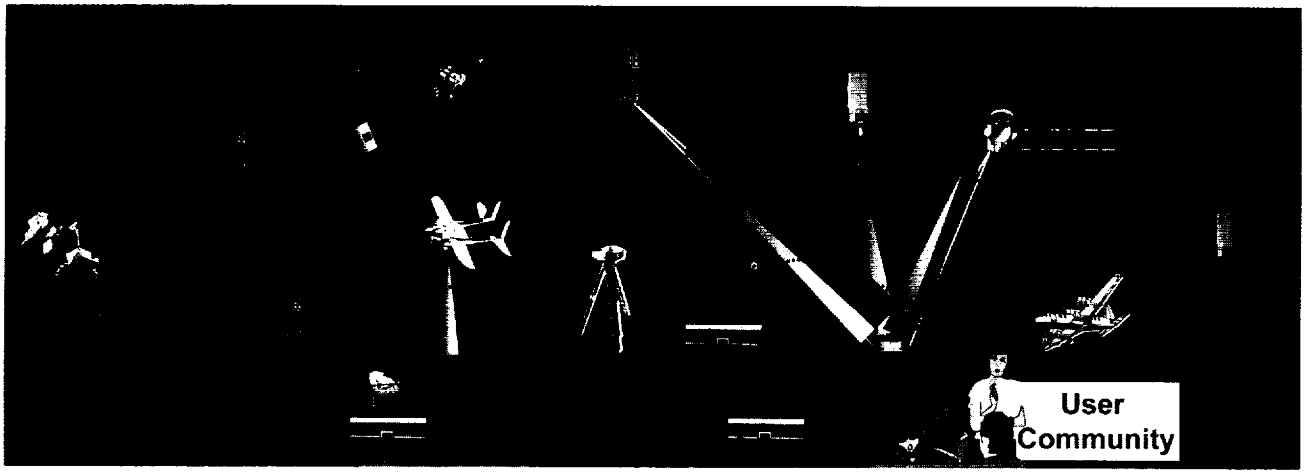


Figure 5. Notional Architecture 4–Sensorwebs

7.5.2 Notional sensorweb architecture

Mixed vantage points, platforms and measurements – L1 imager, GEO imager; four LEO spacecraft hyperspectral imager constellation, LEO virtual platform for multi-angle radiative forcing observations. Coordination among the elements is essential.

Implementation drivers include:

- Interdisciplinary Models
- Standards
- Geodesic coordinates
- Radiometric models
- Validation and Verification Sampling
- Model Interoperability
- Data fusion
- Command, Control and Communications
- Cross-platform calibration
- Integration of legacy systems

8 Distributed Spacecraft Technology Requirements Analysis

Development of enabling capabilities fall into one of five broad themes identified in this section.

8.1 Systems and architecture development tools

Systems and architecture development tools are needed for the design and development of heterogeneous space systems and hierarchical systems of systems. Concurrent engineering environments today use commercial as well as custom tools to design mission orbit, operations, communications, structural, navigation, attitude and other elements. As distributed spacecraft architectures become

Table 4. Systems and Architecture Development Tools

Notional Architecture	Technology Drivers & Trades	Current State of the Art	2010	2025
Global Constellations	Reliability Design for mass production	Highly dependent on all subsystems and instruments performing. Requires all components to be of high reliability. Spacecraft designed and implemented individually or as copies.	Graceful constellation degradation and recovery. Network architecture. Engineering for manufacture, production & test.	
Virtual Platforms	Mission design tools for cross-platform coordination. Recovery from failure.	Mission design tools perform multiple spacecraft orbit and ground track analyses of homogeneous or nearly homogeneous systems. Highly dependent on all subsystems and instruments performing. Requires all components to be of high reliability.	Concurrent engineering tools and simulation software assess interoperability of heterogeneous systems. Interoperability testing using internet from remote sites.	
Precision Formation Flying	Mission design tools for cross-platform coordination	Mission design tools perform multiple spacecraft orbit and ground track analyses of homogeneous or nearly homogeneous systems.	Concurrent engineering tools and simulation software assess interoperability of heterogeneous systems. Interoperability testing using internet from remote sites.	
Sensorwebs	Tools for formulation and development of systems of systems. Legacy system integration. Standards for interoperability of heterogeneous systems. Adaptive failure recovery.	Mission design tools perform multiple spacecraft orbit and ground track analyses of homogeneous or nearly homogeneous systems. Highly dependent on all subsystems and instruments performing. Requires all components to be of high reliability.	Concurrent engineering tools and simulation software assess interoperability of heterogeneous systems. Interoperability testing using internet from remote sites.	Visualization and multidisciplinary optimization software provides rapid convergence and evaluation of hierarchical systems design and implementation options. Systems support dynamic integration of new assets into sensorweb.

more complex and involve multiple heterogeneous systems, new tools will be needed to characterize and design these new systems. The tools would serve the needs of both engineering for interface, architecture and mission design, and data handling definition as well as science for selection and optimization of measurement parameters and instrumentation suites. The development of the tools is described in table 4.

8.2 Miniaturization, production, manufacture, test and calibration

This section addresses technology for miniaturization, production, manufacture, test and calibration to affordably develop and implement research quality systems composed of multiple space elements. Technology needs and development are described in table 5. Spacecraft buses have been getting smaller, lighter, and cheaper for some time. They can be commercially purchased off of an assembly line through a catalog and tailored to meet the needs of a particular mission. Much of these changes have been driven by commercial communications and remote sensing industries. A similar change in the development and acquisition of instruments has not occurred. In particular, advances in instrument technology is needed on two fronts: (1) reduction in the size and mass of the instruments and (2) mass production, test and calibration of research quality instruments and sensors.

Table 5. Miniaturization, Production, Test and Calibration

Notional Architecture	Technology Drivers and Trades	Current	2010	2025
Global Constellations	Ability to manufacture high quality spacecraft and science instruments in large numbers; smart self-calibrating instruments; cross-platform calibration. Mass and volume reduction.	Spacecraft mass >100kg (dry) Production of 10's of spacecraft. Instruments produced 1 at a time. Instrument miniaturization. Integration, test and calibration performed on individual instrument or spacecraft.	10-99 kg spacecraft buses. Production of 100's of spacecraft. Integration and test using robotic production line procedures. Instrument miniaturization and instrument production line of up to ~500. Smart self-calibrating instruments. Interoperability	Production lines of 3-axis stabilized nanosatellites (<10 kg) spacecraft
Virtual Platforms	Systems interoperability. Miniature propulsion for co-orbiting small platforms	Integration, test and calibration performed on individual instrument or spacecraft. (see Orbit Control, Planning and Operations)	Cross-platform calibration using standard procedures and benchmarks. (see Orbit Control, Planning and Operations)	Production lines of 3-axis stabilized nanosatellites (<10 kg) spacecraft
Precision Formation Flying				
Sensorwebs	Systems interoperability. Integration of legacy systems. Cross platform calibration.	Integration, test and calibration performed on individual instrument or spacecraft.	Cross-platform calibration using standard procedures and benchmarks. Smart self-calibrating instruments.	Systems support dynamic integration of new assets into sensorweb.

Moving to science missions composed of multiple homogeneous spacecraft poses several issues not accommodated within current technology. Currently we handcraft and individually fine-tune instruments to meet their science objectives. As we move to constellations of many spacecraft and instruments, techniques to affordably produce and test these instruments will be needed. The ability to produce quality detectors and instrument components with consistently high yield, and integrate these elements in a production line scenario, will contribute greatly toward the realization of large constellations. Additional efforts in manufacturing technology and concepts would further reduce recurring instrument costs.

EO-1 and its Advanced Land Imager (ALI) will formation fly approximately one minute behind Landsat-7 and the Enhanced Thermatic Mapper-Plus (ETM+). Calibration and image comparison will establish relative and absolute instrument performance characteristics allowing for future collaborative research. It is one thing to perform these cross-calibration and analyses on a single instrument pair, it is quite another to perform these exercises on 50, 100 or more instruments. Techniques and standards for production-line compatible instrument test and calibration are needed. Similarly the ability to perform cross-platform calibration and validation is a technology driver, particularly for a mixture of sensor types.

8.3 Data networks and information management

Data networks and information management technology to communicate, acquire, process and distribute science and status information required by ground and in-flight assets is addressed in this section and described in table 6. Hyperspectral imagers provide 30-m resolution with over 200 spectral bands and represent the state-of-the-art. Currently data rates are on the order of 10 megabits per second. Over time, spatial and temporal resolution will become increasingly important.

Hyperspatial instruments providing 1-m resolution and over 200 spectral bands are anticipated by 2010. Instrument data rates should increase by two orders of magnitude. By 2020, the requirement is expected to be global hyperspectral, hyperspatial imagery. Instrument data rates are expected to climb into the terabit per second range. The ability to handle this data is somewhat constrained by Moore's law which states that processing power available from the manufacturer at a given cost will double about every 18 months. Figure 6 provides an analysis of expected advances in data handling.

Current data recorder capacity is approximately 100 gigabits which is just sufficient to obtain one 90-minute orbit worth of hyperspectral data for burst transmission to the ground. Trades need to be made between store and forward systems and continuous data dumping perhaps with some on-board data processing and data compression.

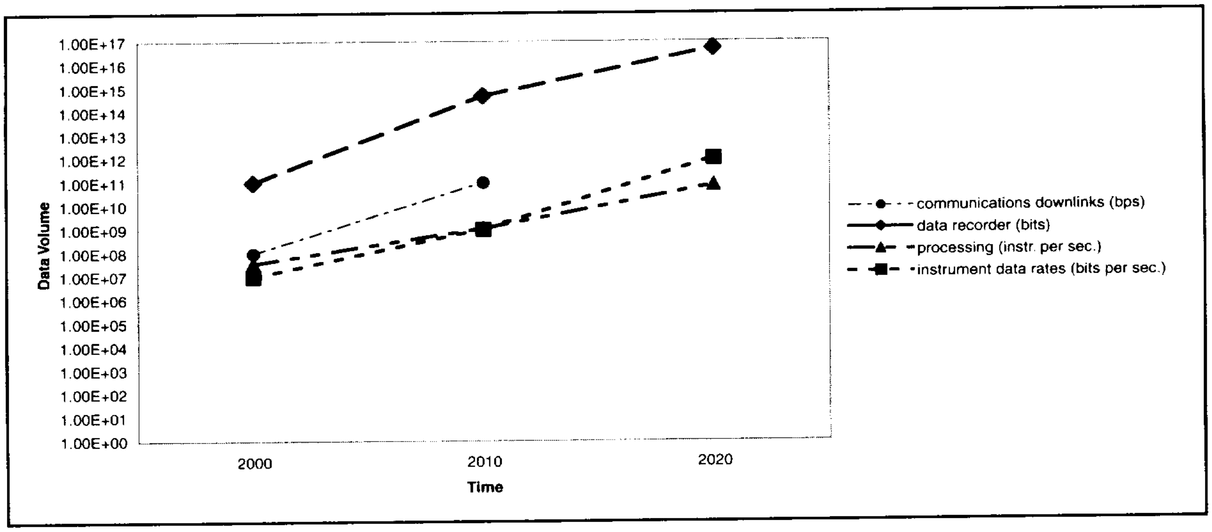


Figure 6. Advances in Data Handling

Currently, little or no science data processing is performed on board the spacecraft. By 2010, Level 2 data products (full resolution calibrated geophysical variables derived from instrument source data with spatial and temporal references) will be produced on-board the spacecraft. In the Earth science vision, these products are to be shared so as to produce a continuous distributed dynamic model.

Interoperable communications enabling systems of systems will be needed. Internet protocols and physical layer communications and ranging standards are needed for L, X, Ka and optical space to space links in the 2010 timeframe. Families of standards are needed to create the hierarchical space systems leading to the ESE vision in the 2020 time period. Analogous standards are also needed for the space-ground communications links. Multicast and mobile Internet protocol (IP) capabilities will be needed.

Current systems designs typically employ a low rate uplink for commanding. Ground-to-space and space-to-space data transfer does not generally approach the bandwidth used for science data transmission. As we move toward cooperative sensorwebs, science data would be transferred between spacecraft. Satellite space-to-space and ground-to-space communications receivers will need to approach the same data rates as the space to ground links. Data compression will need to evolve from today's lossless compression to context sensitive and model based compression. This capability is needed for space-based modeling and rapid event notification.

8.4 Orbit control, planning and operations

Advances in orbit control, planning and operations technologies are needed to affordably control, coordinate and operate constellations and sensorwebs. Specific technologies are listed in table 7.

Table 6. Data Networks and Information Management

Notional Architecture	Technology Drivers and Trades	Current	2010	2025
Global Constellations	Total aggregate data throughput limited by Moore's Law.	No onboard science processing Store and forward (100 Gb recorder, 100 Mbps space to ground.) Custom, non-interoperable space-to-space links. CCSDS space-to-ground non-interoperable (S,X bands). Lossless compressions. Labor intensive ground processing.	Level 2 data products onboard. Store and forward (540 Tb recorder, 100 Gbps space to ground) or continuous Gbps dump. Space to space IP and interoperability standards (L, X, Ka, optical). Multicast and mobile IP. Context sensitive compression.	Model based compression. Management and processing of enormous amounts of data, storage ~50 Petabits.
Virtual Platforms	Total aggregate data throughput limited by Moore's Law. Science processing onboard and data standards. Data fusion. Central communications verses distributed communications. Data standards for cross-links.	No onboard science processing Store and forward (100 Gb recorder, 100 Mbps space to ground.) Custom, non-interoperable space-to-space links. CCSDS space-to-ground non-interoperable (S,X bands). Lossless compressions. Asymmetric uplink.	Data fusion of homogeneous data. Level 2 data products onboard. Store and forward (540 Tb recorder, 100 Gbps space to ground) or continuous Gbps dump. Space to space IP and interoperability standards (L, X, Ka, optical). Multicast and mobile IP Context sensitive compression. Balanced uplink. Rapid event notification.	Data fusion of heterogeneous data. Families of space to space standards. Model based compression. Symmetric uplink. Management and processing of enormous amounts of data, storage ~50 Petabits.
Precision Formation Flying	Science processing onboard and data standards. Data fusion.	All science processing on ground. Data store and forward.	Level 2 data products onboard.	
Sensorwebs	Onboard science processing/pattern recognition. Standards for interoperability of heterogeneous systems (IP-like communication protocols, physical layer standards - RF/optical). Cross-links, multicasting, adressability, and timeliness. Legacy systems integration.	No onboard science processing Store and forward (100 Gb recorder, 100 Mbps space to ground.) Custom, non-interoperable space-to-space links. CCSDS space-to-ground non-interoperable (S,X bands). Lossless compressions. Asymmetric uplink.	Data fusion of homogeneous data. Level 2 data products onboard. Store and forward (540 Tb recorder, 100 Gbps space to ground) or continuous Gbps dump. Space to space IP and interoperability standards (L, X, Ka, optical). Multicast and mobile IP Context sensitive compression. Balanced uplink. Rapid event notification. Engineering trade between store and forward verses continuous dump operations concepts.	Data fusion of heterogeneous data. Families of space to space standards. Model based compression. Symmetric uplink. Management and processing of enormous amounts of data, storage ~50 Petabits.

This would include platform cross-links to share system topology and status information as well as perform any reconfiguration and orbital maneuvering. Specific needs for space-to-space links are described in section 8.3 above. Cross-link relative navigation for 5-10 spacecraft and coordinated attitude control is achievable by 2010. Fully decentralized swarm topology of hundreds of spacecraft would be needed by the 2020–2025 timeframe. The limit of GPS navigation is about cm-level position knowledge. Greater accuracy will require a different technical approach. Significantly greater relative ranging accuracy may be achieved by using RF or optical cross-link ranging. These technologies are being developed by the Space Science Enterprise for missions such as TPF and LISA. Autonomous operations for a distributed system will require cross platform closed loop control.

To accommodate the large number of spacecraft and rapid response needed by these systems, ground based planning and scheduling will have to migrate to the space. Autonomous coordination among space systems, facilitated by a hierarchical structure, and reactive on-board planning would permit dynamic resource allocation and control in response to observed events and data dissemination needs. Distributed systems reliability and fault tolerance will initially involve technologies to monitor data for cross-platform trends and for problem detection. Ultimately, some form of autonomous problem resolution will be needed.

New and scalable propulsion technologies will also be needed for formation flying missions and sensorwebs. Ion propulsion, which has been used for station keeping at Geo and demonstrated on New Millennium Deep Space 1 (DS1) for interplanetary applications, would be adapted for formation flying along with microscale propulsion. Micronewton thrusters, the most advanced of which are currently made in Europe, would be needed for precise formation flying. Table 8 provides an overview of propulsion technology development.

Table 7. Orbit Control, Planning and Operations

Notional Architecture	Technology Drivers and Trades	Current	2010	2025
Global Constellations	Concept of operations trades between store & dump versus cross-link & down, master versus distributed communications, on-board versus ground processing; Non-toxic "green" chemical propellants for mass production and launch. Propulsion systems and components providing a wide range of capabilities including high Isp (>1000 sec) miniature, low mass/power/cost thrusters.	Ground planning teams. GPS based orbit maintenance (~5cm post processing, ~5cm real-time). Non-coordinated ACS.	Reactive ground based planning. GPS based orbit maintenance (<1 cm post processing, ~1 cm real-time). Space to space measurement coordination. Dynamic schedule optimization. Coordinated ACS. Families of propulsion systems suited to the individual mission need including miniature, high-impulse propulsers.	Autonomous reactive onboard planning. Autonomous spacecraft coordination. Fully decentralized swarm topology (100's of spacecraft). Spacecraft initiated ground communications and resource management. Goal driven commanding.
Virtual Platforms	Closed loop cross platform control. Station keeping to maintain formation. Event driven operations. Propulsion systems & components providing a wide range of capabilities including high Isp (>1000 sec), miniature, low mass/power/cost thrusters.	Labor intensive groundplanning teams. Orbit maintenance using GPS (~5 cm post processing ~5 cm real time), rendezvous radar, vision based systems. Can acquire a few spacecraft per ground contact. Relative navigation limited to 2 spacecraft/master-slave in LEO. Uncoordinated attitude control.	Space-space measurement coordination. Orbit maintenance using GPS (~1 cm post processing, ~1 cm real time). Cross link navigator relative navigation of 5-10 spacecraft. Attitude control coordination. Inter spacecraft measurement coordination. Dynamic schedule optimization. Reactive ground planning. Autonomous station scheduling and conflict resolution. Acquisition of multiple spacecraft per contact. Families of propulsion systems suited to the individual mission need including miniature, high-impulse propulsers.	Autonomous reactive onboard planning. Autonomous spacecraft coordination. Spacecraft initiated ground communications and resource management. Goal driven commanding.
Precision Formation Flying	Highly accurate ranging (~0.1 micron accuracy). Precision impulse bit, miniature, micro-Newton level thrusters.	GPS ranging limited to ~cm level accuracy.	Precision impulse bit miniature micro-newton thrusters (micro-PPT, FEEP, micro-coloidal, etc.)	
Sensorwebs	Standards for interoperability of heterogeneous systems (Goal driven cross platform commands, decision support), Intelligent C&DH (learning, decision-making, onboard command generation), Adaptive sensorweb recovery, Situational awareness, onboard adaptive scheduling. Hierarchical architecture. Trade onboard processing verses download and process. Propulsion systems & components providing a wide range of capabilities including high Isp (>1000 sec), miniature, low mass/power/cost thrusters.	Labor intensive groundplanning teams. Orbit maintenance using GPS (~5 cm post processing ~5 cm real time), rendezvous radar, vision based systems. Can acquire a few spacecraft per ground contact. Relative navigation limited to 2 spacecraft/master-slave in LEO. Uncoordinated attitude control.	Space-space measurement coordination. Orbit maintenance using GPS (~1 cm post processing, ~1 cm real time). Cross link navigator. Relative navigation of 5-10 spacecraft in distributed orbits (LEO, GEO, HEO, L1). Attitude control coordination. Inter spacecraft measurement coordination. Dynamic schedule optimization. Reactive ground planning. Autonomous station scheduling and conflict resolution. Acquisition of multiple spacecraft per contact. Families of propulsion systems suited to the individual mission need including miniature, high-impulse propulsers.	Space to space and space to ground sensorweb coordination. Autonomous reactive onboard planning. Autonomous spacecraft coordination. Fully decentralized swarm topology (100's of spacecraft). Spacecraft initiated ground communications and resource management. Goal driven commanding.

8.5 Launch and deployment

Launch and deployment include supporting technologies needed to reduce the cost of access to space for the large number of spacecraft comprising global constellations and sensorwebs. At today's rate of about $10,000 per kg, a 384 spacecraft constellation of 100 kg microsats would cost $384M in launch costs alone. Mass reduction (discussed more fully in section 8.2) combined with launch cost reductions are needed as financial enablers of large constellation missions. Table 9 provides an assessment of advances in launch and deployment.

Table 8. Propulsion Technology Developments

Thruster Type	Isp	Thrust uN [Ibit] uNsec	Developing Agency
H2O2 Monopropellant	160	1-1000	GSFC
Cold Gas	40-80	500-5000[0.5]	MIT, JPL, Aerospace Corp.
Digital Solid	200	[10-100000]	GRC, TRW, CNES
Turbopump Biprop	300	$15X10^6$	MIT, GRC
Digital Bipropellant	200	[3-50]	Princeton, Honeywell
Resistojet	45-100	[100-1000]	AFRL, USC, Aerospace Corp.
Vaporizing Liquid	75-125	1-100	JPL
FEEP	17000	10-200	SRI, Italy, MSU
Micro-colloidal	450-1350	20-100	Stanford, MIT
Micro-PPT	800-1000	[0.1-10]	UI, GSFC, EPLI, Primex, GRC
Ion Engine	1400-2000	0.1-10	Aerospace Corp., JPL

Table 9. Launch and Deployment

Notional Architecture	Technology Drivers and Trades	Current	2010	2025
Global Constellations	Need to reduce launch costs; Ability to increase launch frequency; constellation maintenance and refresh	$10,000/kg to LEO	$5,000 to $10,000/kg to LEO based on RLV	<$5,000/kg to orbit based on RLV and new propulsion technologies. Possible launch on demand.
Virtual Platforms	virtual platform maintenance and refresh	$10,000/kg to LEO	$5,000 to $10,000/kg to LEO based on RLV	<$5,000/kg to orbit based on RLV and new propulsion technologies. Possible launch on demand.
Formation Flying				
Sensorwebs	Need to reduce launch costs; Ability to increase launch frequency; maintenance and refresh	$10,000/kg to LEO	$5,000 to $10,000/kg to LEO based on RLV	<$5,000/kg to orbit based on RLV and new propulsion technologies. Possible launch on demand.

One of the benefits of constellations and virtual platforms is the ability to replace failed elements and introduce new, maturing measurements and technology into the formation. A launch on demand capability, that is the ability to launch space elements quickly after the need is identified, would enhance the robustness of distributed space architectures.

9 Conclusions and Recommendations

The Earth Science Enterprise measurement architecture beyond 2010 has not been developed at this time. However, ESE has identified a vision that would serve as a guide to establishing a long-range architecture. This vision's space-based measurement infrastructure rests heavily on distributed spacecraft technologies arranged as sensorwebs. The sensorwebs comprise a heterogeneous system of systems producing, processing, distributing and controlling an enormous volume of data. The complexities of the space architecture and the sheer volume of information will also stress associated ground-based systems.

It must be pointed out that this study assumed an extrapolation of current ESE measurement and themes into the ESE vision era. This time frame is two measurement architecture generations in the future. The next, intermediate generation, described in the Post-2002 scenario, is now in the process of being defined.

The vision's distributed spacecraft architecture will require a broad range of technologies. Distributed spacecraft technology funding cannot therefore be allocated toward a single enabling revolutionary advancement. Five technology areas with recommendations for possible investment are identified and described in table 10.

In summary:

- New tools are needed to develop and integrate the heterogeneous systems of systems contemplated by the Earth Science vision. Future systems development must also accommodate legacy spacecraft and instruments.

- Advances are required in techniques for mass production and cross-platform calibration of instruments.

- A number of new technologies are needed in the area of data networks and information management. These include both the protocols and standards necessary for interoperability, as well as hardware and software enabling the handling of higher data volumes.

- Operations will require advances in closed-loop cross-platform control, as well as interoperability standards and cross-platform commanding. Advances in onboard autonomy are also needed.

- Small impulse bit thrusters will be required for precision formation control with minimum platform perturbation.

- Launch cost must be reduced to achieve large constellations and sensorwebs.

Table 10. Key Areas for Distributed Spacecraft Technology Investment

Technology Area	Drivers	Recommended Technology Investment
Systems and architecture development tools	Formulation and development of systems of systems. Legacy systems integration. Interoperability. Design for mass production.	Concurrent engineering tools to assess interoperability of heterogeneous systems of systems. Engineering for manufacture, production, integration and test.
Miniaturization, production, test and calibration	Mass production of spacecraft and instruments. Mass and volume reduction. Instrument calibration en masse. Cross-platform calibration.	Instrument miniaturization and productionization. Cross-platform calibration procedures and benchmarks. Integration and testing using production-line procedures and the Internet.
Data networks and information management	High volume of data with constrained processing growth. Data fusion. Interoperability standards.	Model-based data compression. Symmetric uplinks (receivers, C&DH). Space-to-space communications protocols and standards. Interoperability standards.
Orbit control, planning and operations	Standards for interoperability of heterogeneous systems. Scalable and miniature, precision impulse bit propulsion. Cross-platform control.	Closed-loop cross-platform control. Autonomous onboard planning. Precision impulse bit miniature micro-newton thrusters. Interoperability standards, cross-platform goal-driven commanding.
Launch and deployment	Reduce launch costs. Increase launch frequency. Maintain and refresh orbiting assets.	Advances in this area are likely to be driven by the commercial sector. Continued development of RLV and new propulsion technologies.

Appendix A—Reference Documents

[1] 1999 EOS Reference Handbook

[2] Earth Science Enterprise Technology Strategy, June 1999

[3] Earth Science Mission Scenario for the Post-2002 Period, version 2.1, October 10, 1998.

[4] Earth Science Strategic Enterprise Plan 1998–2002

[5] Earth Science Vision Initiative, presentation of September 24, 1999

[6] http://www.vs.afrl.af.mil/vsd/techsat21/

[7] Larsen and Wertz, *Space Mission Analysis and Design*

[8] NASA Research Announcement NRA 99-OSS-05 Advanced Cross-Enterprise Technology Development for NASA Missions

[9] Ticker, Ronald L. and Douglas McLennan, "NASA's New Millennium Space Technology 5 (ST5) Project," 2000 IEEE Aerospace Conference, March 2000

Appendix B—Contacts

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Appendix C—Technology Formulation Team Task Statement

Technology Formulation Team (TFT) Task Statement for Earth Science Distributed Spacecraft Technology Study

Purpose

1) To identify Distributed Spacecraft Technology (DST) capabilities needed by the Earth Science Enterprise (ESE) in the 2010-2025 timeframe.
2) To provide a roadmap for DST technology infusion into ESE projects in the vision era.
3) To provide the foundation and serve as a prototype for a future Goddard institutional capability for technology program assessment and formulation as well as enhanced technology support of the IMDC.

Background

The Cross-Enterprise Technology Development Program DST Thrust Area Manager has commissioned Goddard to conduct a study of ESE future mission needs for DST. The study covers ESE needs in the 2010 timeframe and beyond. A two-prong approach is being used. The study is investigating DST fundamental principles as applied to Earth observation to determine break points for logical project categorization. Simultaneously, a survey is being conducted to identify ESE measurement driven concepts, which are likely candidates for DST infusion in the study timeframe. The results of the two activities will be integrated. Notional architectures for each of the project categories will be developed. These architectures will revolve around DST capabilities needed by ESE in the 2010-2025 period, but will remain non-measurement specific.

Discussions began with STAAC personal regarding use of the Integrated Mission Design Center (IMDC) to provide the needed architectural and technology infusion analyses. It became clear that a subset of IMDC capabilities augmented by a technology assessment and strategy development capability is needed for this study as well as for similar technology studies anticipated in the future. To provide the needed analytical capability for the ESE DST study, an ad hoc group comprised of IMDC, AETD, Earth Science and STAAC personal will form a TFT. Facility support may be provided by the IMDC, as needed. The TFT will also serve as a model for establishing an institutional architecture and technology infusion analysis capability at Goddard.

Scope

DST requirements typically stress, but may not be limited to, the following disciplines:

Guidance, Navigation and Control
Propulsion
Communications
Ground Data and Operations Systems
Command and Data Handling
Launch and deployment
Systems engineering and integration

Inputs

A summary of the interim study findings, including fundamental DST principles, project categorization, and survey of ESE needs, will be available prior to the TFT first session. A description of the notional architectures will be presented to the TFT.

TFT Products

For each notional architecture:
1) Determine feasibility and constraints.
2) Refine the notional architecture and iterate.
3) Identify technology drivers and long-poles as well as the technology trade space.
4) Develop technology development/infusion roadmaps from current state of the art to future ESE capabilities.

The TFT will focus on capabilities and not on specific approaches or implementations.

TFT products will be documented in a set of Power Point files. Technical data, such as STK analysis and Excel spreadsheets, will be provided and retained as part of the record. The Power Point files will be refined and provided to the TFT members for review within a few days after the last session.

Milestones

March 13	Interim Study Findings available
March 17	TFT Session #1
March 23	TFT Session #2
March 28	TFT results Power Point file available
March 31	Final TFT results documentation
April 3	Study Report draft #1
April 14	Final Study Report issued

Participants – Roles & Responsibilities

John Azzolini	GSFC 730	Systems Engineering/DST Study
Tom Bagg	GSFC/QSS	Documentation support
Richard Bolt	GSFC 302	Reliability and Safety
John Bristow	GSFC 572	GN&C/DST Technologist
Russell Carpenter	GSFC 572	GN&C
Marco Concha	GSFC 572	GN&C/IMDC
Bob Connerton	GSFC 581	Operations
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Dave Folta	GSFC 572	GN&C/Formation Flying
Shahid Habib	GSFC 900	Earth Science Technology
William Mackey	GSFC/CSC	Documentation support
John Martin	GSFC 581	Operations/IMDC
Gary Meyers	GSFC 581	Operations

Mike Rackley	GSFC 581	Operations
Carol Raymond	JPL	Earth Science/Vision
George Roach	GSFC	IMDC
Josephine San	GSFC	IMDC
Rick Schnurr	GSFC 560	Electrical Systems Technologist
Ron Ticker	GSFC 730	Systems Engineering/DST Study Lead
Clyde Woodall	GSFC 740	Access to Space/Launch Vehicles
Chuck Zakruzwski	GSFC 574	Propulsion

Process

TFT participants are expected to review the interim study findings prior to the first session. A facilitator/moderator will keep the session focused and moving smoothly. The customer/manager/systems lead will settle requirement disputes and provide general technical and programmatic guidance to the TFT. A contractor will provide documentation support with responsibility for note taking, data capture and retention, and developing the draft and final Power Point files. This documentation support will continue under the general study effort to assist in producing the study reports.

Resources

The respective directorates or IMDC will provide civil service labor and support. Funding for contractor support is available, as needed. Approximately $25K has been allocated to support this activity. Facilities and institutional support will be provided through the IMDC or STAAC, as appropriate.

Distributed Spacecraft Technology for the Earth Science Enterprise 2010-2025

Preliminary Agenda

Day 1 – March 17, 2000

Introduction
Charge to the Team
Fundamental DST principles/project categorization
Summary of ESE DST needs survey
Notional architecture 1 – Global Constellations
- Description
- Feasibility and constraints/iterated and refined architecture
- Identification of technology drivers, long-poles, and trade space

Notional architecture 2 – Virtual Platforms
- Description
- Feasibility and constraints/iterated and refined architecture
- Identification of technology drivers, long-poles, and trade space

Adjourn

Day 2 – March 23, 2000

Recap of Day 1 and intervening activities

Notional architecture 3 – Precision Metrology

- Description
- Feasibility and constraints/iterated and refined architecture
- Identification of technology drivers, long-poles, and trade space

Notional architecture 4 – Sensorwebs

- Description
- Feasibility and constraints/iterated and refined architecture
- Identification of technology drivers, long-poles, and trade space

Technology development/infusion roadmaps

Review and Summary

Action items/next steps

Adjourn

Appendix D Supporting Material

Context	Some Science Questions	ESE has identified five research questions as the focus of effort for the next several years	Goals	Expand scientific knowledge of the Earth system using NASA's unique capabilities from the vantage points of space, aircraft, and in situ platforms	Science Priorities
Earth Science Mission: To develop understanding of the total Earth system and the effects of natural and human-induced changes on the global environment.	Can climate variation be predicted a season or year in advance?	How can we enable regionally useful forecasts of precipitation and temperature on seasonal-to-interannual time frames?		Predict seasonal-to-interannual climate variations	Seasonal-to-Interannual Climate Variability and Prediction
The Goal of Earth System Science: To obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales.	Can long-term climate variation be detected and drivers identified?	What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?		Detect long-term climate change, causes, and impacts	Long-Term Climate: Natural Variability and Change
The Challenge to Earth System Science: To develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity.	What are the impacts of climate change on marine ecosystems?	How and why are concentrations and distributions of atmospheric ozone changing?	Objectives	Understand the causes of variation in atmospheric ozone concentration and distribution	Atmospheric Ozone Research
NASA Basic Question: How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, resource identification, and resource management models to help ensure sustainable development and improve the quality of life on Earth?	How do terrestrial ecosystems respond to land cover change?	What are the nature and extent of land-cover and land-use change and the consequences for sustained productivity?		Understand the causes and consequences of land-cover/land-use change	Land-Cover Change and Land-Use Change Research
NASA basic question: What cutting-edge technologies, processes, techniques, and engineering capabilities must we develop to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?	How do sudden solid Earth changes affect the land surface?	Can we learn to predict natural hazards and mitigate natural disasters?		Identify natural hazards, processes, and mitigation strategies	Natural Hazards Research and Applications

GOAL 1: Expand scientific knowledge of the Earth system using the unique vantage point of space

The near-term, mid-term, and long-term stages of progress on this goal are captured in the descriptions found in the Roadmap—namely to characterize changes, to understand changes, and to forecast and assess the state-of-the-Earth system. Near-term objectives and strategies are as follows.

Objective 1.1 To understand the consequences of land-cover and land-use changes as they impact ecological processes, and evaluate what human activities contribute to changes occurring in the landscape. To understand how changes in land-cover and land-use impact socioeconomic activity and human health. These involve developing the capability to perform repeated global inventories of land cover and land use from space, and to develop the scientific understanding and models necessary to evaluate the consequences of observed changes.

Characterize the forcing factors that drive changes in landscapes and the resultant impacts on biogeochemical and hydrological cycles and energy and gas fluxes. These forcing functions may be broadly separated into climatic and ecological factors, and socioeconomic factors.

Assess the responses to drivers of changes in land cover and land use, particularly in those parts of the world that are currently undergoing the most stress, where major changes are already taking place, and where the stresses from human activities are sure to increase the most rapidly. Assess and characterize how land-use and land-cover changes are manifested at multiple space and time scales using multispectral satellite remote sensing data.

Develop techniques to incorporate land-cover and land-use change observations and measurements into existing biogeochemical and biophysical models. This is important to develop, parameterize, and evaluate models that are able to couple the biogeochemical and biophysical dynamics of the land surface and its interactions with the atmosphere. Use will be made of global archives of high-resolution satellite data acquired over the last 20 years for addressing the extent, rapidity, and impacts of land-cover and land-use change at regional scales.

Develop well-documented regional case studies that couple land-use, land-cover, atmospheric and climate data sets and ecosystem modeling to evaluate the response of ecological systems to multiple stresses, as forced by land-use and land-cover changes.

Objective 1.2 To monitor, describe, and understand seasonal-to-interannual climate variability, with the aim of developing and improving capability to predict socioeconomically important climatic anomalies on these time scales.

Develop a capability to remotely sense variables that determine seasonal-to-interannual climate variability, using advanced instruments such as QuikSCAT, TOPEX/Poseidon, TRMM, SeaWiFS, and the suites on EOS-AM1 and -PM1. This capability will depend on the successful launch of all these and other instruments and will require continuity of observations over extended periods. It will also require appropriate calibration with in situ observations.

Document climate variability on seasonal-to-annual time scales based on space-based and in situ observations of atmospheric temperature, winds, water vapor and precipitation, aerosol and cloud properties, sea surface temperature and topography, ocean color and biota, sea ice, soil moisture, land vegetation, snow cover, and radiative fluxes.

Produce research quality climate data sets for seasonal-to-interannual applications by developing and improving methods for merging remotely sensed and in situ observational data using climate system models in assimilation mode.

Organize and coordinate experimental field campaigns to improve understanding of physical processes such as air-sea interaction, the hydrologic cycle, cloud-radiative feedback, and others that have key roles in causing or modulating seasonal-to-interannual climate variations.

Objective 1.3 To understand Earth processes that can lead to natural disasters, develop risk assessment capability for vulnerable regions, and coordinate with U.S. disaster managers and international space agencies.	Objective 1.4 To understand the causes and consequences of long-term (decades- to-centuries) climate variations on regional as well as global scales, both natural and human induced.	Objective 1.5 To develop understanding of processes affecting distributions of ozone and other constituents that most directly affect its concentrations in the global troposphere and stratosphere, as well as the distributions of oxidizing species in the global troposphere, to document their current evolution from ground-, aircraft-, balloon-, and space-based observations and predict future changes that affect biologically active radiation and predict future changes that affect radiative forcing and climate.
Continue to improve our ability to understand local tectonics and to relate these to seismic hazard vulnerability through advanced space geodetic techniques such as the dense Global Positioning System (GPS) arrays and Synthetic Aperture Radar (SAR) interferometry, focusing on the Los Angeles basin for GPS array demonstrations.	Assemble a multidecadal space-based and in situ record of primary global climate forcings (e.g., solar irradiance, atmospheric composition, aerosol burden) and responses (e.g., changes in the Earth's radiation budget), including systematic observations by the international constellation of operational polar orbiting and geostationary meteorological satellites (NOAA, GOES, GMS, Meteosat), current research satellite programs (ERBE, UARS), and planned global measurements, beginning in 1998, by the EOS-AM, -PM, and -CHEM missions.	Improve the understanding of processes affecting distributions of ozone and oxidizing species in the global troposphere and stratosphere through laboratory studies of reaction kinetics, molecular photochemistry, and spectroscopic research.
Develop understanding of regional disastrous consequences of shorter term climate events such as flooding, monsoon occurrence, storm frequency and severity, and drought.	Collect a multidecadal record of climate diagnostic parameters, including tropospheric and stratospheric temperature profiles, ocean and land surface temperatures, sea ice and ice sheet volume, snow cover, radiation budget at the top of the atmosphere, precipitation, ocean surface topography and wind, and ocean color and biota from the same observing systems as above.	Develop a long-term data base of changes in concentrations of ozone and trace constituents that affect its concentrations sufficient for providing for understanding of these changes, through application of ground-based in situ, ground-based remote sensing, and space-based instruments, including the Advanced Global Atmospheric Gases Experiment (AGAGE) network, the Network for Detection of Stratospheric Change (NDSC), and existing satellite projects such as TOMS, SAGE, SBUV/2, and UARS.
Improve the ability to forecast and assess risk of local and regional flooding using watershed models incorporating satellite-derived parameter topography, land cover, recent regional temporal rainfall history, soil moisture, snow cover (and water equivalent) and snow melting forecasts, and satellite land-cover time histories in regional drainages.	Promote Earth system model simulations to assess the role of atmospheric physical processes, ocean circulation dynamics, sea ice processes, and land ice mass balance, as well as changes in the carbon cycle, as factors of natural climate variability on decadal and longer time scales.	Improve the understanding of photochemical, dynamical, radiative, and microphysical processes that affect concentrations of ozone and other trace constituents in the stratosphere and upper troposphere, as well as of the relationship between the trace constituent and aerosol composition of the atmosphere with processes occurring at the Earth's surface, through model-based analysis of data obtained by past NASA measurement programs, including ground-based network observations, aircraft campaigns, balloon measurements, and satellite and shuttle programs.
Improve the ability to forecast and assess risk of local and regional flooding using watershed models incorporating satellite-derived parameter topography, land cover, recent regional temporal rainfall history, soil moisture, snow cover (and water equivalent) and snow melting forecasts, and satellite land-cover time histories in regional drainages.	Organize and coordinate experimental field campaigns to improve the representation of atmospheric radiative transfer, atmospheric chemistry, cloud physics, air-sea exchanges, sea ice, ground hydrology, and air-sea interaction in global climate models. Major emphasis in the near term will be on improved understanding of cloud-radiation interaction in the polar regions through the Surface Heat Energy Budget in the Arctic (SHEBA) program, organized by NSF, NASA, and DoE.	Conduct in situ and remote sensing aircraft campaigns to better characterize the distribution of trace constituents in the troposphere and stratosphere, the photochemical processes that interconvert them, the nature of the meteorological processes responsible for transporting constituents between different regions of the atmosphere, and the role of aerosols in influencing the chemical properties of these regions.

GOAL 2: Disseminate information about the Earth system	Objective 2.1 Implement data system architectures that are open, distributed, and responsive to user needs.	Objective 2.2 Increase public understanding of Earth System Science through education and outreach.
	Implement the currently defined EOSDIS with Government data centers (DAACs) to enable spacecraft operations and data management.	Support student enrichment and research opportunities to train the next generation of Earth system scientists.
	Conduct an evaluation of a "working prototype" federation of competitively selected Earth Science Information Partners (ESIPs), through cooperative agreements with organizations to produce selected Type 2 and 3 data products, who will participate in federation activities.	Emphasize nationwide preservice and inservice teacher enhancement programs that enable educators to incorporate Earth System Science concepts into their classrooms.
	Certify the existing DAACs and engage them in prototype federation activities.	Support the development of systemic change initiatives that incorporate Earth System Science into the State and local education system.
	Establish agreements with Federal mission agencies for long-term active archiving of key data sets.	Develop greater support by scientists for broad science communication and education efforts.
	Evaluate the operation working prototype federation and make a decision to proceed in time to issue cooperative agreement notices for EOS-CHEM1 data products.	Make information and assessments accessible to the broad continuum of ESE information customers, including the general public, media, publishers, and industry.

GOAL 3: Enable the productive use of Earth science and technology in the public and private sectors	Objective 3.1 Develop, infuse, and transfer advanced remote sensing technology and concepts.	Objective 3.2 Extend the use of NASA's research and technology beyond the traditional science community to be applied to the needs of national, State, and local users.
	Identify and periodically review the science vision and requirements through strong, formal links with the science research community, including the external advisory bodies.	Conduct applications research and development with the private sector, including value-added companies and private end-users.
	Identity and form cost and risk sharing Government partnerships in and outside of NASA that maximize the joint benefit of advanced technology developments.	Expand partnerships with other Federal agencies to sponsor joint applications projects of mutual interest with a U.S. regional focus.
	Prepare and implement an integrated technology development plan and funding profile for all recommended initiatives and activities. The plan should meet key budget assessment and commitment schedules.	Develop ESIPs designed to extend the use and applications of the EOSDIS and its extensive data holdings to a broader community.
	Assure the timely and effective infusion of advanced technologies and concepts into research and operational programs and projects.	Improve access to ESE science results and distribution of applications results through key transfer agents, such as associations of city, county, and State governments.
	Assure private sector understanding of Earth System Science requirements and technology development needs.	Develop advanced instruments, and develop and launch spacecraft for NOAA operational environmental satellite programs.
	Assure access to appropriate, unique Government facilities and capabilities that can enable the commercial development of remote sensing technologies and techniques that potentially can support future Earth System Science needs.	
	Assure the productive transfer of Government- developed engineering knowledge and technologies.	

Objective 3.3 Support the development and leverage commercial capabilities in remote sensing and information systems to cost-effectively meet Earth System Science objectives and to enhance the relevance of ESE scientific discovery.

Create opportunities for industry to define innovative, cost-effective ways to achieve program objectives by informing and consulting with them at the start of the ESE program planning process.

Seek technology development and practical applications partnerships that leverage commercial potential and support mission objectives.

Seek cost-effective science data purchase opportunities that meet ESE science requirements.

Objective 3.4 Make major scientific contributions to regional, national, and international environmental assessments.

Provide measurements, modeling, and analyses in support of the periodic assessments of such entities as the World Meteorological Organization (ozone assessment) and the Intergovernmental Panel on Climate Change.

Provide analyses of environmental effects of aircraft emissions in a joint program with the Aeronautics and Space Transportation Technology Enterprise.

Provide analyses of land-cover change in key regions to measure rates of deforestation, atmospheric impacts of biomass burning, and parameters for contribution to agricultural and other land-use assessments.

Objective 1.2 (Continued from page .)
To monitor, describe, and understand seasonal-to-interannual climate variability, with the aim of developing and improving capability to predict socioeconomically important climatic anomalies on these time scales.

Use observational and model-assimilated data sets and results from field campaigns to improve understanding of climate system processes and to develop or improve explicit or parameterized representations of these processes in climate system models.

Use model-assimilated data sets to develop, improve, and evaluate the performance of coupled ocean-sea, ice-atmosphere-land surface models that are capable of realistically representing the behavior of the Earth's climate system on seasonal-to-interannual time scales.

Use ESE observations, analyses, and coupled climate system models to characterize and predict seasonal-to-interannual variations, leading to an ability to reduce risks from floods, droughts, fires, and other natural hazards related to such climatic anomalies.

Objective 1.3 (Continued from page .)
To understand Earth processes that can lead to natural disasters, develop risk assessment capability for vulnerable regions, and coordinate with U.S. disaster managers and international space agencies.

Develop an approach to risk mitigation of the near-shore coastal environment where geologic, ecological, oceanographic, and meteorologic factors can lead to extreme storm surges, regional subsidence, flooding, erosion, and bathymetric changes. Characterize the utility of ocean color sensors in tracking the habitat of plankton-borne coastal disease vectors.

Develop airborne and satellite capabilities to detect changes in thermal anomalies and the ratio of different volcanic gases and centimeter-scale deformation of a volcano through radar interferometry and GPS-based techniques to monitor precursor activity to a volcanic eruption. Develop digital elevation models to predict the most likely paths of lava flows, lahars, and pyroclastic flows, thereby directing hazard mitigation toward populations at greater risk. Enhance remote sensing detection of eruption clouds in near real time for enhanced warnings.

Study the concept of a network of low-cost, student-run satellite ground receiver stations to serve as research and education tools but, during natural disasters, would be capable of providing real-time services to local and regional disaster officials. This includes the consideration of conversion or recruitment of existing facilities such as X-band receivers currently used for other research purposes.

Coordinate with international space agencies research, observations, and flight project development programs in natural disaster reduction under bilateral and multilateral conventions.

Objective 1.4 (Continued from page .)
To understand the causes and consequences of long-term (decades- to-centuries) climate variations on regional as well as global scales, both natural and human induced.

Develop improved remote sensing techniques and instruments to achieve the required degree of accuracy and calibration in measurements of key parameters to document and understand long-term climate variability and change.

Objective 1.5 (Continued from page .)
To develop understanding of processes affecting distributions of ozone and other constituents that most directly affect its concentrations in the global troposphere and stratosphere, as well as the distributions of oxidizing species in the global troposphere, to document their current evolution from ground-, aircraft-, balloon-, and space-based observations and predict future changes that affect biologically active radiation and predict future changes that affect radiative forcing and climate.

Expand the data base for global measurements of the trace constituent distributions in the stratosphere and troposphere using space-based remote sensing techniques, including measurements to be made as part of the EOS project (especially the MOPITT, TES, HIRDLS, MLS, ODUS, and SAGE III instruments), as well as other programs.

Develop a suite of modeling tools that represent the chemical, dynamical, and microphysical processes that affect the composition of ozone, aerosols, and other trace constituents in the stratosphere and troposphere, and also the multi-dimensional atmospheric models that can be used both retrospectively and prognostically to support the WMO/UNEP and NASA Atmospheric Effects of Aviation Project assessments for the stratosphere.

Provide validation data and correlative measurement information for U.S. and foreign instruments on aircraft and satellite platforms using NASA satellite, aircraft, balloon, and ground-based instrumentation, as well as appropriate preflight calibration comparisons and postflight algorithm intercomparisons.

Improve understanding of the effects of human activity, including the use of industrially produced compounds (chlorofluorocarbons and their replacements, halogens, methyl bromide) and subsonic and supersonic aviation and rocket exhaust, on the ozone, as well as water vapor and particle distribution in the atmosphere, through laboratory studies, field measurements, and models.

Develop new sensor and instrument technology to ensure the continued evolution of remote and in situ measurement capability, as well as explore the applicability of new classes of platforms (uncrewed aerial vehicles, long-term balloons, and microsatellites) to atmospheric ozone research.

SYSTEMATIC MEASUREMENT (EOS FOLLOW-ON MISSIONS)

Earth system science is dealing with a very complex dynamical system, governed by non-linear relations that can spontaneously generate variations of many time and space scales, from turbulent eddies to long-term changes in global ocean circulation. In addition, the system is subjected to a number of external forcing factors or changing boundary conditions. For lack of a capability to model and predict such external parameters (that may be controlled by inadequately known processes like solar activity, or changed by human actions), the only possible scientific strategy is the systematic observation of forcing and response, with the ultimate objective of linking one to the other. This is the fundamental reason why systematic observation and "climatological" data records play such an important role in this field of natural sciences. The following represents a nominal mission plan for systematic measurement of atmospheric, oceanic and land variables to which Step 1 reviewers gave highest scientific priority from an earth system science perspective. The sequence of missions is ordered according to expected launch dates.

EOS-1: Land Cover/ Land Use Inventory Program

The Land Cover and Terrestrial Ecosystem research program calls for systematic measurement of changes in global land surface cover and land use, and estimation of their impact on the global carbon cycle, to be provided by a series of land imaging missions following Landsat-7. The same information is also essential for a wide range of value-added applications, such as forest and range management or agriculture. Each mission would carry one main instrument: multi-spectral (visible/near IR) imaging radiometer providing global coverage with sufficient spatial resolution (~10-20m) to unambiguously identify the extent of different type of vegetation or other land cover, and sufficient frequency (revisit time of the order of 15 days) to determine seasonal & long-term changes in terrestrial biomass. The instrument concept could be based on the Advanced Land Imager design being tested on the New Millennium EO-1 demonstration mission, with the addition of appropriate coarse-resolution spectral channels for atmospheric corrections. Progress in detector array technology, especially performance at non-cryogenic temperature, and high data-rate on-board processing are the main technology drivers for further optimization. Implementation of the first mission in the series would begin in FY'01 for launch in year 2005, six year after the launch of Landsat-7. NASA intends to carefully examine private sector initiatives in this domain as a means for acquiring the relevant scientific data sets through data purchase instead of building a dedicated mission.

EOS-2: Climate Variability and Trend Mission

Most of what we currently know (or can infer) about the general circulation of the atmosphere and the global energy and water cycles is inferred from observation of basic meteorological variables, atmospheric pressure, temperature, moisture and wind. This information is obtained from a multiplicity of sources, in situ measurements by balloon-borne radiosondes at some 800 stations around the world and global remote sensing by atmospheric sounders on meteorological satellites. Currently, temperature and moisture profile data obtained from operational sounders suffer from significant weaknesses that make them less than ideally useful for atmospheric circulation analysis and forecasting (a large fraction of operational satellite sounder data is actually rejected by the more advanced data assimilation models). A decisive breakthrough is expected with the Advanced Infra-Red Sounder (AIRS), which is the first satellite sensor that can emulate the temperature and moisture measurement accuracy of radiosondes. It is expected that AIRS data will be available for the expected six-year lifetime of the PM-1 mission. NASA is working closely with the NPOESS Integrated Program Office to enable similar temperature and moisture profile accuracy with the next-generation operational atmospheric sounder system that will be deployed on future operational environmental satellites. The objective of the Climate Variability and Trend Mission, given high priority by atmospheric climate research, is to continue research-quality temperature and water vapor measurements during the interim period between the termination of PM-1 and the first NPOESS flight. A single bridging mission is needed to fill the gap between EOS PM-1 and the first NPOESS satellite. In order to ensure measurement continuity, the mission would need to be launched no later than 2006, i. e. about six years after the launch of PM-1. NASA has selected several R. an D. projects under its Instrument Incubator Program (IIP) to develop the advanced technologies that can be applied to this mission.

EOS-4: Total Solar Irradiance Monitoring Program

The source of the energy that drives all climate processes is radiation from the Sun, known as the "solar constant" or, since we know now that the Sun is a (mildly) variable star, Total Solar Irradiance. NASA and other space agencies have maintained an essentially continuous record of total solar irradiance variations since 1979. NASA has undertaken the development of the next-generation total solar irradiance monitor (TSIM), to be flown in 2001 on a scientific satellite mission of opportunity built by Canada (SciSat). The plan is to eventually rely on measurements planned by the NPOESS program, beginning at the end of the decade. NASA made sure that the specifications of TSIM meet NPOESS requirements for solar irradiance monitoring. In order to maintain the integrity of the total solar irradiance record, it is essential that successive TSIM missions provide sufficient overlap, since the stability (relative accuracy) of individual spaceborne radiometers is at least one order of magnitude better that their absolute calibration, and systematic differences between one instrument and the next can be as large as or larger than the signal. It is expected that one solar irradiance monitoring mission will be needed to ensure measurement continuity in the second half of the next decade (launch in 2005). The mission could be implemented on a small free-flying platform or as an instrument on space flights of opportunity. In addition, NASA is planning an intercomparison program of flight instruments with a laboratory-calibrated reference radiometer embarked on the Space Shuttle.

EOS-5: Ocean Surface Wind Measurement Program

The acquisition of surface wind data, interrupted in 1997 as a result of the premature shut-down of the NASDA/ADEOS satellite, will be resumed in late 1998 with the launching of the "QuickSCAT" recovery mission (using the first flight model of the new-generation Seawinds sensor developed by NASA), to be followed by the ADEOS-2 mission carrying the same Seawinds instrument in the year 2000 time frame. The nominal NASA strategy for surface wind data acquisition in the long term is to rely on global measurements provided by two operational observing systems: _ Passive dual-polarization microwave radiometer on the NPOESS satellite series during the next decade of the next century. _ ASCAT active microwave scatterometer on the European METOP satellite series under development by EUMETSAT, with first launch planned in 2003. The Workshop highlighted the importance of ocean surface (vector) wind data and insisted on the importance of full global coverage (which cannot be provided by a single ASCAT system) in order to capture fast weather developments and intense storms which contribute a disproportionate amount to mean oceanic forcing. NASA agreed to study the impact of data gaps in the coverage by a single scatterometer system. In addition to Europe's operational meteorological satellite program, the private sector also expressed interest in developing a constellation of small satellites equipped with scatterometers to provide global vector wind data. NASA plans to examine both operational agencies (NPOESS and EUMETSAT) and private sector plans prior to deciding on the development of a dedicated mission beyond Seawinds-1 on the Japan's ADEOS-2 mission. NASA also received informal indication of Japan's interest in flying a Seawinds-class instrument on the ADEOS-3 mission.

EOS-7: Stratospheric Composition Measurement Program

The foremost scientific problem in the field of atmospheric chemistry remains the stabilization and eventual recovery of the stratospheric ozone layer. (Is the Montreal Protocol working as expected? Could other factors not yet recognized impair the recovery?). Considering that stratospheric chemistry is a relatively mature field, first priority for the discipline is given to monitoring the ozone distribution as a function of halogen concentration, trace gases and aerosols in the stratosphere. The measurement strategy assumes that future operational systems, in particular NPOESS, will provide research-quality total ozone data similar to Total Ozone Mapping Spectrometer (TOMS) observations. NASA will consider, with national and international partners, the means to ensure the continuity of global total ozone measurements in the interim period between the end of the EOS-CHEM mission and the first flight of the NPOESS series. On this basis, the long-term systematic stratospheric composition measurement program could focus on accurate (essentially self-calibrating) observation of a relatively limited selection of precursor and reservoir species, at the minimum sampling rate that allows reliable detection of trends. Measurement methods of choice are occultation radiometry or spectrometry, and atmospheric limb emission radiometry. In order to achieve adequate geographic coverage, the mission requires a 2-spacecraft constellation, one in sun-synchronous orbit and the other on an inclined (50-60°) orbit. Implementation of the sun-synchronous component could begin in FY'04 for launch of the first spacecraft of the series in late 2008, six year after EOS-CHEM. The nominal option for implementation of the inclined-orbit component is a succession of attached payloads on the International Space Station (ISS). Fabrication of instruments for the attached payloads could be completed in a 2-3 year period beginning in FY'02 or 03.

EOS-9: Global Precipitation Mission

The scientific focus of global water cycle research and hydrologic sciences is understanding and predicting the impact of climate change on weather events, river flow and water resources. The discipline recognized that global rainfall distribution is the foremost measurement required to progress toward quantitative knowledge of the water cycle and arguably the most accessible hydrologic quantity for satellite remote sensing. Among several possible techniques, passive and active (radar) microwave measurements from low earth orbit is the most mature and reliable approach. Precipitation is associated with mesoscale weather systems that display considerable spatial and temporal variability. For this reason, high sampling frequency is essential: a sampling interval of three hours or less is required to estimate total rainfall reliably. Measuring rainfall from space would requires a constellation of at least 4 spacecraft in staged polar orbits. The nominal concept is to fly only one "master" rainfall-measuring satellite carrying both active (Precipitation Radar) and passive (Microwave Radiometer/Imager) sensors, and a number of "drone" satellites carrying only the passive microwave sensor. Considering that two DMSP spacecraft equipped with the SSM/I microwave radiometer are expected to be in operation, two drones would be sufficient to complete the constellation. The master satellite mission could be implemented on a dedicated platform, while the drones would be smaller free-flying spacecraft. The nominal plan was to begin implementation in FY'04, aiming for launch in year 2007 four years after the TRMM follow-on mission under consideration by NASDA. The Workshop agreed that implementing the original objective of EOS to measure global precipitation had very high scientific value for the progress of earth system science. The Workshop further noted that the Japanese space agency's plan for a TRMM follow-on mission were not firm and recommended that the implementation of a global rainfall measuring mission be advanced to the 2003 time-frame. NASA agreed to carefully examine opportunities for an earlier implementation and explore possible international partnerships.

EOS-10: Polar Altimetry Mission

The central question of polar climate science is the detection of changes in ice sheet dynamics and mass balance. For this purpose, systematic precision measurements of Greenland and Antarctic ice sheet topography are needed at appropriate intervals. The first measurement will be provided by the Icesat mission (launch date: 2001) as part of the first EOS series. The nominal plan included a repeat mission around 2010, using either one of two possible techniques that may (precision lidar and synthetic-aperture radar altimeter). The Workshop highlighted the importance of precision altimetry as the centerpiece of a systematic measurement strategy for ice-sheet dynamics and ice mass balance studies, and expressed concern about the expected discontinuity between the first Icesat mission and a repeat mission launched near the end of the next decade. NASA agreed to assess the scientific impact of a discrete (discontinuous) sampling strategy for the study of ice sheet dynamics.

EXPLORATORY AND PROCESS RESEARCH-ORIENTED MISSIONS

Progress toward more a fundamental understanding of the earth system, based on first physical, chemical or biological principles, will primarily result from process-oriented research or discovery missions. Such missions will need to collect adequate but not necessarily complete global data sets that sample the full global range seasonal and geographic conditions for periods of (typically) 3 to 5 years. Such research missions can be taken as the discovery component of the ESE flight program. They respond to the recommendation of the National Academy of Science/National Research Council to promote an innovative program of focused research satellite projects addressing sharply defined science questions. Exploratory missions may entail high scientific and technical risks, as investigators try to break into new fields of investigation, and attack unsolved scientific questions with the resources of the latest technology. It would be unwise at any time to define a ten-year program of experimental missions that would ignore future prospects for new scientific ideas, new technological advances and unforeseen science breakthroughs. In this regard, it is best to select each new experimental mission through a solicitation process open to a range of competing projects as late as possible in the implementation process, following a practice pioneered in the Earth System Science Pathfinder program. On the other hand, it is essential to correctly gauge the scope of the exploratory mission program that would optimally balance the systematic measurement component in the overall research strategy for the Enterprise. For this purpose, NASA applied the same scientific evaluation, technical feasibility and cost assessment procedures to both systematic measurement and discovery mission concepts. The candidate mission concepts described below are those that emerged as particularly promising in the Step 1 review. This set should be considered as illustrative of the discovery missions that might be implemented in response to scientific priorities that will emerge in the next ten years, and does not suggest a particular implementation order. Several among these mission concepts have already been considered by partner agencies abroad and would therefore be good candidates for joint cooperative projects. Each of candidate experimental mission listed below has been highlighted by Step 1 reviewers as essential for the advancement of their respective scientific disciplines and is representative of the state of the art. However, this set of mission concepts by no means represents the variety of meritorious ideas that were presented in the RFI process, nor the diversity of new proposals that may emerge in the future from regular Announcements of Opportunity or the next program-wide RFI. The ordering of the candidate missions does not reflect a judgment of scientific priority, and the actual Earth Probe mission program of the Enterprise remains to be determined by successive solicitations and a competitive selection process.

EX-1: Tropospheric Chemistry Research Mission(s)

Observation of chemical/dynamical processes in the troposphere faces two challenges: the need for sufficient vertical resolution to identify the layered structure of constituents transported by the atmospheric circulation and the need for adequate temporal resolution to resolve possible diurnal variations and fast emission events. The latter requirement would be ideally fulfilled by observation from geostationary orbit, except for the fact that feasible measurement are generally lacking in vertical resolution within the troposphere. Differential absorption lidar and other active sounding systems operating from low earth orbit can ideally meet the requirement for vertical resolution, but only provides relatively sparse sampling. The Step 1 review panel for Atmospheric Chemistry concluded that, given a choice between vertical resolution and high sampling frequency, the former had the highest potential for discovery. This scientific judgment is reflected by the scientific priority given to a number of promising measurement concepts in low earth orbit. The scientific discovery potential of global tropospheric chemistry justifies at least one and ideally two experimental missions during the period of reference. Each would a one-time mission, carrying a payload limited to a small number of sensors (to be determined by the assessment of competing research mission proposals). The instrument payload could include passive and active sensors (such as tunable differential absorption lidars) to observe ozone, CO and precursor species, or pollutant emitted by surface sources (SO2, hydrocarbons, etc.).

EX-2: Aerosol Radiative Forcing Research Mission

A high visibility issue in climate change research is the impact of natural and anthropogenic aerosols on the radiative balance of the planet. One possible strategy for investigating this problem is based on monitoring trends in the global distribution of stratospheric and tropospheric aerosols. Two candidate systematic observation missions listed in Appendix 1 address this objective (measurements of solar occultation by stratospheric aerosol and solar radiation backscatter by tropospheric aerosol). Nevertheless, the diversity of aerosol origin, composition and optical properties, and the complexity of radiation scattering and absorption by aerosol and ice/water particles are so overwhelming that conclusive findings can only be expected from considerably more sophisticated and penetrating observations. It is essential, in particular, to resolve the vertical layering of aerosol distribution in order to backtrack tropospheric transport and identify the source of the material. The instrument payload that could provide this information would be organized around a backscatter lidar with a range of smaller complementary sensors (polarimeter, multi-directional radiometer, etc.) that could contribute to characterizing the size, shape and optical properties of aerosol and (optically thin) cloud particles.

EX-3: Cloud-Radiation Feedback Research Mission

A high visibility issue in climate change research is the impact of natural and anthropogenic aerosols on the radiative balance of the planet. One possible strategy for investigating this problem is based on monitoring trends in the global distribution of stratospheric and tropospheric aerosols. Two candidate systematic observation missions listed in Appendix 1 address this objective (measurements of solar occultation by stratospheric aerosol and solar radiation backscatter by tropospheric aerosol). Nevertheless, the diversity of aerosol origin, composition and optical properties, and the complexity of radiation scattering and absorption by aerosol and ice/water particles are so overwhelming that conclusive findings can only be expected from considerably more sophisticated and penetrating observations. It is essential, in particular, to resolve the vertical layering of aerosol distribution in order to backtrack tropospheric transport and identify the source of the material. The instrument payload that could provide this information would be organized around a backscatter lidar with a range of smaller complementary sensors (polarimeter, multi-directional radiometer, etc.) that could contribute to characterizing the size, shape and optical properties of aerosol and (optically thin) cloud particles.

EX-4: Soil Moisture and Ocean Salinity Observing Mission

Soil moisture, a component of ground water storage, is the state variable that represents the terrestrial hydrologic system on time scales relevant to flooding, evapotranspiration and impacts on vegetation (water stress). Soil moisture integrates precipitation and evaporation over periods of days to weeks and introduces a significant element of memory in the atmosphere/land system. There is strong climatological and modeling evidence that the fast recycling of water through evapotranspiration and precipitation is the primary factor in the persistence of dry or wet anomalies over large continental regions during summer. On this account, soil moisture is the most significant boundary condition that controls summer precipitation over the central US and other large mid-latitude continental regions, and essential initial information for seasonal predictions. Precise in situ measurements of soil moisture are available but each value is only representative of a small area. Remote sensing, if achievable with sufficient accuracy and reliability, would provide truly meaningful wide-area soil wetness or soil moisture data for macroscale hydrological studies and precipitation anomaly prediction over large continental regions. The most mature technique, low-frequency passive microwave radiometry, would also allow the determination of Sea Surface Salinity (SSS). Global surface salinity measurement would provide invaluable information to close the planetary water budget over the oceans and understand the pre-conditioning of surface waters that controls deep water formation in the north Atlantic. The SSS measurement places a challenging requirement on the sensitivity (signal/noise ratio) of spaceborne passive microwave radiometers. The measurement of soil moisture (and ocean salinity) must still be considered experimental and, for this reason only, was ranked as the second priority of the Hydrology and Global Water Cycle discipline. Developing an effective soil moisture remote sensing system based on passive radiometry requires the deployment of very large antennas (or realization of a correspondingly large synthetic aperture) in order to achieve meaningful spatial resolution (of order ~ 10 km or less) at the relatively low microwave frequencies that can penetrate moderately dense vegetation. The objective of an experimental soil moisture/ocean surface salinity measurement mission would be a 3 to 5 year demonstration of an advanced low-frequency dual-polarization passive microwave radiometer or combined active/passive system in low earth orbit (to be determined by selection of competing mission proposals).

EX-5: Time-Dependent Gravity Field Mapping Mission

Measuring the time-varying component of the gravity field is a totally new "remote sensing" approach that provides a unique insight in mass redistribution within the earth system, including climate effects such as ground or surface water storage, and changes in oceanic circulation, as well as tectonic motions and post-glacial rebound. The concept of measuring temporal variations in the gravity field to monitor mass redistribution has already been demonstrated, using various time series of geodetic and gravimetric data. The Earth System Science Pathfinder GRACE mission will extend this proven capability to harmonics above 100. There are strong expectations from both the solid earth science community and global oceanography community that the GRACE mission (to be launched in 2001) will be a pathfinder for a powerful new method to investigate geophysical and geodynamic phenomena. If this breakthrough is achieved, further technological advances are clearly in sight that will allow at least one order of magnitude improvement in the sensitivity of the method, thus expanding the range of scientific applications. Knowledge of the geoid is a limit to the scientific utility of sea-surface topography data for dynamic oceanography at shorter length scales. Advanced satellite-to-satellite tracking in low Earth orbit would allow significant refinements of the shape of the geoid down to 50-100 km scales, comparable to the scale of ocean eddies and the exploitation of altimetric observations closer to continental margins to characterize coastal currents). In addition, directly detecting changes in total water column mass would allows computing the mean geostrophic flow or Sverdrup circulation. In view of the fundamental importance of earth gravity data, the oceanic, polar and geodynamic disciplines would place this measurement in their top two or three scientific priorities for long-term systematic observation of fluid and solid earth. On the other hand, the required technology (satellite-to-satellite laser interferometry) is definitely a technical challenge, so that the concept must still be considered experimental. An experimental mission would involve launching two essentially identical spacecraft on the same orbit with a single launch vehicle. Operational life time should be a minimum of five years. In view of a broad international interest in space geodesy, this mission would be also a likely candidate for an international cooperative project.

EX-6: Vegetation Recovery Mission

Understanding the carbon cycle is essential to assess future changes in the atmospheric concentration and greenhouse effect of carbon dioxide. A major component of this cycle is net ecosystem productivity in terrestrial temperate and boreal ecosystems, which integrates the regrowth of previously disturbed landscapes, carbon dioxide fertilization, and the result of nitrogen deposition. Quantifying the first of these effects is critical to understanding the response of the carbon cycle to human perturbations. For this reason, the land cover and terrestrial ecosystems discipline places high priority on a disturbance recovery mission, that could be flown in the late 2000's time frame. The main instrument would be a steerable lidar altimeter system, based on technological evolution of the ESSP Vegetation Canopy Lidar mission (to be launched in year 2000). The purpose of the mission would be to sample the evolution of specific terrestrial biosphere targets that have been subject to major disturbances, like clear-cutting or fires. The scientific objective is to characterize the recovery of above-ground biomass in those areas. A complementary visible-near IR imager could document the recovery of grasslands and semi-arid ecosystems. Altogether this experimental mission could be implemented on a small spacecraft and aim for a 3-5 year life time.

EX-7: Cold Land Processes Research Mission

Over large regions (e. g. the interior of North America and Eurasia) and high altitude mountainous areas, much of the annual precipitation contributing to streamflow occurs in the form of snow during the winter months. Snow accumulation is a major storage term that strongly impacts the seasonal cycle of runoff. The freeze-thaw status of the soil surface determines the partitioning of precipitation or snowmelt between runoff and infiltration. The high albedo of snow-covered terrain results in large contrasts in net radiation during the thaw period. Important science questions that come to mind are: How does the extent of snow and frozen ground affect atmospheric climate? Can snow water equivalent be quantified from remote sensing data with sufficient accuracy to improve hydrologic forecast? Could these factors be measured accurately enough to identify meaningful climatic trends? Snow water equivalent and the extent of frozen ground have not been adequately measured from space, due to limitations in spatial resolution of passive microwave instruments and the poor sampling frequency achievable with existing spaceborne imaging radar systems. A promising, but technically challenging measurement concept is based on applying active SAR imaging techniques at relatively coarse spatial resolution (of order ~ 1 km) to detect freezing conditions on the ground, the extent & amount of snow, and probably various vegetation properties. Coarse resolution could allow a wider swath and short repeat cycle (~ 3 days). This experimental mission could be implemented on a dedicated platform in low altitude sun-synchronous orbit. The primary payload would be a 2-polarization, coarse resolution SAR system at L-band or lower frequency. The technical challenge is measuring the intensity of the backscatter signal with much higher accuracy than currently envisaged in high-resolution imaging radar systems. NASA intends to carefully examine and take advantage of potential commercial and international initiatives in this domain of global SAR observation with high revisit frequency and relatively coarse spatial resolution.

PROTOTYPE OPERATIONAL INSTRUMENT DEVELOPMENT

The Step 1 review highlighted several projects to develop and demonstrate new sensors intended for operational applications as particularly meaningful for scientific research. It has been long recognized that earth system science relies heavily on information and climatological records acquired and archived by operational environmental agencies (for a variety of applications). This is especially true in the field of climatology, as most of what is currently known about the earth climate is derived from the study of weather observation records. Thus, improving the capabilities of operational observing systems (especially polar satellites that provide global coverage) is also essential for the progress of earth system science. On the other hand, there is currently no established process for identifying joint scientific and application priorities for operational sensor developments, nor for transition from scientific developments to the procurement and accommodation of new operational instruments on operational satellite systems. The development and flight demonstration of specific prototype operational instruments is not explicitly included in the nominal mission plan but could be accommodated by re-ordering flight priorities in the Enterprise's EOS follow-on, Earth Probe and New Millennium programs. NASA is seeking active participation of cognizant user agencies in the definition, development and transition to operational use of new advanced instruments that would meet ESE long-term science objectives as well as operational application requirements. The following is a list (no priority order implied) of instrument concepts that were discussed in the RFI process or otherwise brought to the attention of the Enterprise: The Workshop generally agreed with this new NASA approach to contributing to the development of new or improved operational observing capabilities. Although no discipline had ranked high-frequency observation from geostationary orbit as their highest scientific priority, there was general recognition of the value of developing a new geostationary sensors for a diversity of research and application objectives. NASA has focused the forthcoming announcement of opportunity for the next New Millennium Program technology demonstration mission precisely to address this objective. NASA is also holding consultations with NOAA/NESDIS on priorities for the development of improved sensors for operational GOES satellites.

OP-1: Advanced Microwave Sounder

The current operational microwave sounder suite, including AMSU-A and MHS, has a total mass of 160 kg. The utilization of new microwave circuit technology would permit substantial weight reduction for the same functionality and the addition or substitution of new microwave channels that would better support the retrieval of precision temperature/moisture soundings in combination with a companion IR sounder. NASA had studied the feasibility of upgrading existing microwave sounders, as part of the Integrated Multispectral Atmospheric Sounder (IMAS) project. Significant progress had been made in the development of microwave technology at the relevant (very high) frequencies and NASA plans to apply these technique to the development of an advanced operational microwave sounder for NPOESS.

OP-2: Tropospheric Wind Sounder

Global measurement of tropospheric wind has been widely heralded as potentially the most significant contribution of satellite remote sensing to existing global meteorological observations (World Weather Watch). Direct measurement of horizontal wind vectors in clear air has been demonstrated using lidar from the ground and from aircraft, based on determination of the wind-induced Doppler shift in the backscatter signal. Two competing techniques are envisaged: _ Coherent detection Doppler lidar system, which is the most sensitive and potentially most accurate technique, but works only in atmospheric layers where sufficient density of scattering particles exists (aerosols). The technique requires development of a unique laser transmitter technology. _ Incoherent detection Doppler lidar system, which is less sensitive but operates uniformly in clear air (works with both Mie scattering from aerosol particles and Rayleigh scattering from air molecules). The technique can utilize a widely used type of laser transmitter. NASA is preparing a demonstration of the first technique (coherent detection) on a Space Shuttle flight in 2001 (SPARCLE project). There is also private sector interest in developing alternate measurement techniques which could offer the prospect of the availability of tropospheric wind data from a commercial provider.

OP-3: GPS Constellation for Atmospheric Sounding

Measurement of the phase-delay occurring in the propagation of GPS signals near the limb of the atmosphere allows inferring dry air density, temperature and pressure as a function of geopotential height in the region where the concentration of water molecules remains negligible. Below this level, the same technique allows estimating water vapor concentration, provided reasonably accurate temperature information can be obtained from other sources. Altogether, the technique is a completely different approach to atmospheric sounding and would, in principle, provide practically drift-free temperature information throughout the upper troposphere and lower stratosphere, as well as unmatched vertical resolution. Further refinements are also conceivable to extend the domain of application of this and related microwave limb sounding methods. NASA has made substantial investments in the development of relevant spaceborne GPS receiver technology, as well as software for flight equipment operation and data processing. NASA has also begun to constitute an experimental GPS constellation by furnishing GPS equipment to scientific satellite missions of opportunity developed by international partners. It is expected that this international system will deliver a sufficient number of GPS soundings per day to carry out a meaningful test of the impact of this type of data on the quality of global weather forecast (although only in a delayed or "hindcast" mode). A further initiative, co-sponsored by UCAR and the Taiwan Academy of Sciences would launch a constellation of 8 dedicated micro-satellites, allowing real-time collection of GPS measurements and delivery of temperature/moisture profile data to weather forecasting centers in time for insertion into the operational analysis and prediction system. NASA is considering possible means to demonstrate this new observing technique.

OP-4: Advanced Geostationary Sounder

One of the two principal sensor on NOAA Geostationary Operational Environmental Satellites (GOES) is an IR atmospheric sounder of relatively conservative design and technology. The sensor allows repeated soundings at very short time intervals over specific regions of interest (where rapid weather development is being observed). However the lack of vertical resolution in the lower and mid-troposphere, where rapid weather development actually occurs, reduces the usefulness of frequent soundings for the purpose of numerical weather prediction. This deficiency could be overcome by a new sounder instrument using state-of-the-art technology (in particular, advanced IR detector arrays and mechanical cryogenic cooling systems). Dynamical meteorology supports the expectation that AIRS-grade temperature and moisture soundings at high spatial and temporal resolution would bring a significant improvement in the ability to forecast mesoscale weather systems and, in general, assist with severe storm warning.

OP-5: Volcanic Ash and Gas Emission Mapping Mission and Advanced Geostationary Earth Imager

The visible and IR imaging radiometer on the current GOES series is a new instrument design that delivers images of the earth disc with unprecedented spatial and temporal resolution. Nevertheless, several improvements are envisaged, such as augmenting the number of spectral channels and further increasing spatial resolution. These upgrades would be justified by a multiplicity of operational applications of geostationary imager data, from tornado warning to fire detection to tracking ash clouds from volcanic eruptions.

OP-6: Special Event Imager

The "Special Event Imager" concept (SEI) is a steerable high-resolution imager that could be pointed to stare at occasional or predictable regional events that vary within a time span of hours rather that days. The SEI is being promoted by the biological oceanography community as well as operational users as a desirable addition to the standard payload of GOES satellites. In addition to numerous applications from wildfire assessments to algal bloom monitoring, the SEI could provide invaluable ocean color change information to capture coastal phenomena that are dependent upon tidal effects.

OP-7: Geostationary Lightning Mapper

Electrical charges that cause lightning strikes are created by rapid ascending air flow associated with strong convective storms. There is evidence that instantaneous mapping of lightning strikes over the disc of the earth from geostationary orbit would enhance the ability to judge the strength of developing storm cells and forecast the likelihood of tornadoes and severe downdraft. The strike rate can also be related in a semi-quantitative manner to convective precipitation. Altogether, a geostationary lightning mapper holds considerable attraction for weather forecasters, but the scientific significance of such observations from one or two geostationary satellites does not match the scientific interest of global lightning distribution data obtained by the NASA-provided lightning detection sensor on TRMM.

Goal 1: Expand Scientific Knowledge*

Assumptions:

An Assessment of the External Environment A number of key assumptions underlie this Earth Science Strategic Enterprise Plan. These assumptions should remain valid for the planning horizon for this document (1998–2002). Changes in these fundamental assumptions could have significant effect on the objectives and strategies that follow.

— NASA will continue to have an important statutory role, via the Space Act, the Global Change Research Act of 1990, the Land Remote Sensing Policy Act of 1992, and others, in Earth scientific research and to play a significant role in the policy framework for national efforts to understand global change. The Federal Government will continue to support research needed to address many environmental issues. NASA uses the unique vantage point of space to provide the scientific basis for informed policymaking, and the research to support the operational missions of other U.S. Government organizations.

— The Earth Science Enterprise will have to operate within a level or declining NASA budget.

Competition for national and international financial re sources will increasingly compel NASA and ESE to find new ways to achieve goals more efficiently. It follows that even in a constrained budget, ESE must make re sources available to support the development and infusion of new technologies to enable an improved rate of science return on the national investment.

OBJECTIVE

UNDERSTAND LAND-COVER/ LAND-USE CHANGE

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
Landsat 7/ETM+	Global and regional land-cover maps	More efficient forestry practices	Forestry and farming
MODIS	Fluvial transport	Better pollution management	Ecosystem science community
ASTER	Nutrient budgets	Better Ecosystem Management	Stewards of coastal and other fragile ecosystems
MISR	Rates of land-cover/-use change	More efficient urban planning	City managers and transportation planners
Field campaigns and regional studies	Consequences of land-cover change	Better World crop estimates	Fishing industry
Modeling		High-precision agriculture	Recreation industry
			U.S. and foreign agricultural agencies

Assumptions:

OBJECTIVE

Goal 1: Expand Scientific Knowledge*

UNDERSTAND SEASONAL-TO- INTERANNUAL CLIMATEVARIABILITY

— Clear links exist between ESE and areas of high public concern. It will be essential to maintain clear communications with the public on these issues to enable informed decisions on the program.

It is critical that ESE foster a shared vision of science priorities within the scientific community and highlight areas of mutual interest with the industrial community. ESE scientists and engineers are active participants in this process and lead the way through state-of-the-art research and participation in scientific and technical forums; they must also be encouraged to share their knowledge in forums with broader public access. ESE will continue the practice of conducting workshops and other forums to seek out the needs of the public and commercial communities for Earth System Science data and technology, and work with these communities to meet their needs.

— ESE will be implemented within an international framework.

The United States is providing roughly half of the world investment in space-based remote sensing of the Earth for environmental research through 2000. ESE incorporates extensive international collaboration in both mission development and scientific research, with agreements in place covering $3.75 billion in foreign investments and data sharing agreements covering almost $5 billion more. As the new century unfolds, ESE intends to shape and be shaped by the development of an international, integrated global observing strategy.

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
TRMM	Coupled model simulations of the upper ocean/ atmosphere/ land climate system	Improved weather forecasts and climate prediction	Climate science community
TOPEX/Poseidon	New lidar and radar technologies	Planting strategies for farming	Farming and forestry
Modeling and analysis	Maps of ocean biomasss and productivity and regional precipitation	More efficient fisheries	Commercial fishing industry
AIRS	Prediction of seasonal and inter-annual climate events (El Ni o, etc.)	Improved management of heating and cooling energy resources	Disaster relief agencies
AMSU	Influence of volcanoes on climate	Better flood and drought mitigation strategies	Water resources management
CERES	Global water vapor maps	Better crop estimates	U.S. and foreign agricultural agencies

Assumptions:

OBJECTIVE

Goal 1: Expand Scientific Knowledge*

UNDERSTAND SEASONAL-TO- INTERANNUAL CLIMATEVARIABILITY

— ESE-generated data and technology have clear, recognized value beyond science, for example, in the commercial, educa tional, and environmental monitoring areas.

ESE recognizes these leverage points and will amplify them in order to achieve stronger re t u rns to the American taxpayers for their investment in space. ESE capabilities and research results are used to analyze crop and forest maturity, assess the impacts of floods, and fight large-scale fires in forest and brushlands. Examples of these uses are shown in the ESE Applications Fact Book (see Appendix 2). At the same time, these leverage are a s p rovide opportunities for closer international and inter-agency collaboration (as with NOAA), greater involvement of the private sector in collaborative relationships with ESE, and long-term ties to the national educational community. ESE capabilities have strong potential for application to public health problems, such as vector-borne diseases, which are strongly influenced by environmental and climatological variables. Section VI provides a view of the value of ESE products in these broad communities.

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
MODIS	Analysis of weather and flood variability	Economic savings from more accurate planning	Insurance industry
MHS	Risk assessment studies	Better forecast of world rice production	Energy industries
Passive Microwave	Monsoon onset analyses	Improved sea-ice forecasts	Defense agencies
SAGE	Variability in sea-ice cover	Improved weather forecasts	Travel and tourism industry
SeaWIFS MODIS			International food supplies
QuikSCAT			High latitude fisheries, shipping, and oil drilling
Field cam-paigns, modeling, and data assimilation			
SSM/I			
INSAT			
SAR			

Goal 1: Expand Scientific Knowledge*

OBJECTIVE	PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
UNDERSTAND DISTRIBUTION OF ATMOSPHERIC OZONE	HALOE	Continued monitoring of stratospheric ozone	Evaluation of effective-ness of international agreements on the photochemical recovery of stratospheric ozone	Atmospheric science community
	MLS	Initial monitoring of tropospheric ozone and the precursors that lead to its formation	Identification of distribution and sources of tropo-spheric ozone	National and international environmental and health
	TES	Assessment of effects of aircraft emissions	Effects on marine life and terrestrial ecosystems	U.S.manufacturing
	MLS	UV light levels	Assessment of effects of aircraft emissions	U.S. aircraft industry
	HIRDLS	Delineation of the roles of chemical and transport processes on the global distribution of ozone in the stratosphere and troposphere		Recreation industries
	MOPITT	Characterization of natural and anthropogenic forcings on ozone abundance and distribu- tion and the attendant effects on climate and UV radiation on the ground		International regulatory authorities
	ODUS			NOAA operational ozone monitors
	TOMS, SAGE III, ADEOS			
	STRAT, POLARIS VOTE/TOTE, PEM-Tropics			
	Modeling and analysis			

Assumptions:

OBJECTIVE

Goal 1: Expand Scientific Knowledge*

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— The Earth Science Enterprise will have to operate within a level or declining NASA budget.

Competition for national and international financial re sources will increasingly compel NASA and ESE to find new ways to achieve goals more efficiently. It follows that even in a constrained budget, ESE must make resources available to support the development and infusion of new technologies to enable an improved rate of science return on the national investment.

IMPROVE DISASTER CHARACTERIZATION AND RISK REDUCTION

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
GPS array technology	Characterize of pre-, syn-, and postseismic regional surface deformation and seismic activity	Transfer to technology for location and characterization of hazards to Federal and some state agencies	Solid Earth science community
Remotely sensed SAR interferometry time series	Multifaceted approach toward forecasting local and regional flooding, droughts, and land- s lide potential	Establish an interna-tional global sea-level change characteriza-tion program	Federal, State, and local governments and regional authorities
Airborne measurements	More frequent and accurate typhoon, hurricane, and flood observa-tions	Saving of lives and property due to evacuation and property protection	U.S. industry
Process studies and modeling	Location of toxic blooms	Risk assessment to human health of vector-borne disease outbreak	World Meteororological Organization
EOS Direct Broadcast for world warning			World Health Organization
MODIS			National Meteorological Agencies
SeaWIFS			PTTs

Assumptions:

OBJECTIVE

Goal 1: Expand Scientific Knowledge*

IMPROVE DISASTER CHARACTERIZATION AND RISK REDUCTION

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
ASTER			CNN
Landsat 7/ETM+			Regional warning centers
SRTM			Recreation industries
TOMS			U.S. and foreign health ministries
TOPEX/Poseidon			Sensors may contribute to multiple outputs, outcomes, and customers. There is not a one-to-one correspondence across columns
Jason-1			
GLAS			
SAR			

— Clear links exist between ESE and areas of high public concern. It will be essential to maintain clear communications with the public on these issues to enable informed decisions on the program.

It is critical that ESE foster a shared vision of science priorities within the scientific community and highlight areas of mutual interest with the industrial community. ESE scientists and engineers are active participants in this process and lead the way through state-of-the-art research and participation in scientific and technical forums; they must also be encouraged to share their knowledge in forums with broader public access. ESE will continue the practice of conducting workshops and other forums to seek out the needs of the public and commercial communities for Earth System Science data and technology, and work with these communities to meet their needs.

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Assumptions:

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OBJECTIVE

UNDERSTAND LONG-TERM CLIMATEVARIABILITY

Goal 1: Expand Scientific Knowledge*

PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
HALOE	Predictive estimates of future variation of the climate system	Risk management strategies for coastal zones	
MLS	Changes in marine ecosystem structure	Effects on fish stocks	Climate science community
AIRS/AMSU/MHS	Estimates of sea-level change	Informed industrial and governmental decisions on mitigation strategies	Federal, State, and local governments and regional authorities
SAGE III	Estimates of average surface temperature change	Estimates of effects on sustainable development strategies for food, water, energy, etc.	Fishery industries
GOALS	Long-term impacts of El Niños, tropical cyclones, etc.	Explain natural global temperature variation	Insurance industry
Process studies and modeling	Global moisture availability variation	Estimate future food production	Energy industries
Climate change assessments	Long-term stratospheric temperature trends	Estimate risk to future populations	Farming and forestry
SeaWiFS	Changes in volume of terrestrial ice and their causes	Understanding sea-level change and improved predictions	Water resources management
MODIS	Long-term trends in sea-ice cover	Improved climate models	Global community interactions sustainable development planners
POES/NPOES	Long-term measurements of total solar and UV irradiance		Coastal communities
MSU			Coastal wetlands
GLAS			Coastal pollution
ALT			Policymakers
SAR			
SSM/I			
MODIS			
AVHRR			
CERES			
ACRIM			
SOLSTICE			

Assumptions:

OBJECTIVE

Goal 2: Disseminate Information

IMPLEMENT DATA SYSTEM ARCHITECTURES THAT ARE OPEN, DISTRIBUTED, AND RESPONSIVE TO USER NEEDS

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PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
Establish a working "prototype" federation	New partners and data products for both nonglobal change science and nonscientific users	A broader, more user-driven community of environmental data product providers	Worldwide Earth system science community
Certify the existing DAAC's	Experience for long-term Federation implementation	A more flexible, cost-effective data product distribution system	Value-added remote sensing processing industry
Establish agreements with other agencies for long-term active archival			Assessors of population growth impacts
Decide on federation in time for Chem-1 data products			Sustainable development managers
			Application users

Assumptions:

OBJECTIVE

Goal 2: Disseminate Information

FOSTER THE DEVELOPMENT OF AN INFORMED AND ENVIRONMENTALLY AWARE PUBLIC

— The Earth Science Enterprise will have to operate within a level or declining NASA budget.

Competition for national and international financial re sources will increasingly compel NASA and ESE to find new ways to achieve goals more efficiently. It follows that even in a constrained budget, ESE must make resources available to support the development and infusion of new technologies to enable an improved rate of science return on the national investment.

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PRINCIPAL ACTIVITIES	OUTPUTS	OUTCOMES	CUSTOMERS AND BENEFICIARIES
Student enrichment and research opportunities	Research fellowships	Improved scientific and technical literacy in the U.S. general public	College and graduate students
Nationwide inservice and preservice teacher enhancement programs	Young investigator programs	U.S. leadership in science in the next generation	Inservice and preservice teachers and their students
Systemic change initiatives	Public workshops/ meetings	More adequate supply of skilled and informed workers for U.S. industry	Libraries, museums, and planetariums
Scientist involvement in public communication	Media awareness/ coverage		Media organizations
Expand accessibility of ESE information to broad community, including the general public			Publishers of teaching materials
			General public

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13. ABSTRACT (Maximum 200 words)
The study investigates NASA's Earth Science Enterprise needs for Distributed Spacecraft Technologies in the 2010–2025 timeframe. In particular, the study focused on the Earth Science Vision Initiative and extrapolation of the measurement architecture from the 2002–2010 time period. Earth Science Enterprise documents were reviewed. Interviews were conducted with a number of Earth scientists and technologists. Fundamental principles of formation flying were also explored. The results led to the development of four notional distributed spacecraft architectures. These four notional architectures (global constellations, virtual platforms, precision formation flying, and sensorwebs) are presented. They broadly and generically cover the distributed spacecraft architectures needed by Earth Science in the post-2010 era. These notional architectures are used to identify technology needs and drivers. Technology needs are subsequently grouped into five categories: Systems and architecture development tools; Miniaturization, production, manufacture, test and calibration; Data networks and information management; Orbit control, planning and operations; and Launch and deployment. The current state of the art and expected developments are explored. High-value technology areas are identified for possible future funding emphasis.

14. SUBJECT TERMS
Distributed spacecraft, space architecture, space technology, constellations, formation flying, sensorwebs.

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