Strategic Architecture of an Integrated Earth and Space-Based Observation Network for Earth Science

by

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Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

This thesis examines the strategic architecture of an integrated Earth and space-based observation network for Earth science. It examines the changing policy and technical environment for these observations. The thesis analyzes the current goals of the NASA Earth Science Enterprise, as well as larger National and International policy issues, and develops a goal statement for the Enterprise for use in this thesis.

The thesis focuses on the Earth- and space-based observation system. Based on state-of-the-art knowledge and the physical constraints of Earth- and space-based observation, the thesis identifies the essential functions delivered by individual missions and uses these to formulate functional goals for the multi-mission system.

With the functional goals as a framework the thesis examines the concepts behind current and proposed mission approaches in order to gain insight into future architecture options. Specific areas examined include:

- Concepts for coordinating measurements, both nationally and internationally.
- Options and classification of multi-mission observing configurations.
- Communication approaches, including likely cumulative data rates and the implications for use of radio or optical communications.
- Mission development processes, tools, facilities, and practices.

Building on the goals and concepts, the thesis analyzes options for the system form. Current examples and future options are discussed. This includes:

- Analysis of spacecraft orbits using three key aspects of value. This analysis identifies a potentially valuable eccentric orbit with an apogee that remains aligned with local noon.
- Categorization of different configurations and topologies for interconnected sensorwebs. Analysis indicates no clear preference; with options highly dependent upon the specifics of orbit configuration, data rate, latency requirements, spectrum crowding, and other drivers.

The author has a deeper understanding of the system as a result of this effort. Three main areas of uncertainty remain. They are:

- The various "Sensorweb" related concepts and the approaches for multi-mission interaction.
- The potential for changes in the underlying architectural drivers and the ability of the Earth Science Enterprise to recognize and adapt to these changes.
- The many stakeholder relationships and the potential influence they will have on the future of the Earth- and space-based observation network.

Thesis Supervisor: Edward F. Crawley
Title: Professor of Aeronautics and Astronautics, Margaret MacVicar Faculty Fellow, Head of the Department

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Many visionaries wish for humanity to explore space and expand the human presence beyond the Earth. The sustained exploration of space depends upon the sustainable development of the Earth. I hope that my work in Earth science will give to my children and my children's children a firm footing on Earth, from which they can reach for the stars.

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Executive Summary

The goal of this thesis is to develop guidance and recommendations for the NASA Earth Science Enterprise by assessing and refining strategic architecture options for an integrated Earth and space-based observation network for Earth science, evaluating upstream and downstream trends and influences that may affect the architecture and the Enterprise. In doing so the author intends to develop a deeper understanding of these issues for use in future policy and implementation discussions.

Chapter 2 examines the current goals of NASA and the Earth Science Enterprise. This chapter also examines the larger policy context as represented by commercial space interests, US National Space Policy, National Security space trends, and International Space Law. Documents reviewed include:

- The 2000 NASA Strategic Plan.
- The 2001 NASA Earth Science Enterprise Plan.
- The Space Act, as Amended.
- Current and Historical National Space Policy documents.
- The Report of The Commission to Assess United States National Security Space Management and Organization, Hon. Donald H. Rumsfeld, Chair.
- Congressional testimony and legislation concerning National Security Space activities.
- Summaries of International Space Law.

Based on this analysis, the thesis develops a goal statement for the NASA Earth Science Enterprise. This goals statement interprets and reflects the larger context influences. This is a working goal for this thesis, and is not endorsed by NASA.

Earth Science Enterprise Working Goal for this Thesis

The goal of the Earth Science Enterprise is to characterize the Earth system, understand how it is changing, and predict the consequences for life on Earth, by observing, analyzing, and modeling the Earth using Earth- and space-based observation systems, global information systems, and global modeling systems.

In pursuing this goal, the Earth Science Enterprise will broadly involve the International science community, demonstrate the application of its results for societal and economic benefit, produce and employ innovative technologies, encourage US commercial capabilities, and develop a cadre of US space professionals in government, academia, and industry.

This thesis focuses specifically on the architecture of the Earth- and space-based observation systems, and does not specifically address the global information systems or global modeling systems.

Chapter 3 develops functional goals for the Integrated Earth- and Space-based Observation System. After defining four levels of decomposition (levels 0 through 3), the approach is to skip or "zoom" to the individual mission level (Level 3). At this level the thesis examines the processes and intents for generic Earth- and space-based observation missions. It then uses state-of-the-art knowledge and the physical constraints of Earth- and space-based remote sensing missions to develop Level 3 functional goals. These level 3 goals are used to develop and check for completeness the level 2 functional goals for the integrated multi-mission system. The following table lists the level 2 functional goals developed in this chapter.

Table 1: Level 2 Functional Goals for the Integrated Earth- and Space-based Observation System

Intent	Process	Operand/Modifiers
To Enhance the Synergistic Benefits of Multiple Measurement Capabilities	By Coordinating Nationally and Internationally	The Identification, Selection, and Development of New Missions
	By Enabling	The Operational Coordination of Mission Observations
To Maintain and Upgrade the Multi-Mission Measurement System	By Developing	New Observation Techniques, Instruments, and Components
	By Developing	New Mission Platform Technologies for: • Guidance (Position Control) • Attitude (Orientation) Determination and Control • Observation Physical Support (Power, Heating/Cooling, etc.)
	By Improving	The Mission Development Process
	By Developing	Servicing/Repair or Partial Replacement of Mission Capabilities
	By Safely Disposing of	Mission Assets at Their End of Life
To Leverage Multi-Mission Economies of Scale	By Ensuring	The Availability of Multi-Mission Infrastructures for: • Conveying Observation Results • Communicating Command and Engineering Data • Launching and Deploying Missions • Navigating Missions • Operating Missions • Mission Development and Manufacture

Chapter 4 uses the level 2 functional intent statements from the previous chapter to organize descriptions of current and proposed multi-mission system concepts. These concepts may be methods, tools, policies, or mission implementation approaches to meet the intent statements in the functional goals. The concepts range from policy mechanisms for National and International coordination to the current multi-mission systems to guide and navigate missions. The author used these concepts to gain insight into future architecture options. These concepts helped refine the functional goals developed in the previous chapter and the decomposition of form developed in the next chapter.

For example, this chapter develops a structure (see table) for categorizing distributed observation systems by considering the spatial distribution of the measurements, the nature of the measurements, and the degree of real-time coordination required for the measurement.

Table 2: Three-Attribute Classification of Multiple Satellite Observation Concepts with Proposed Concept Names and Examples

Proposed Concept Name	Classification Factors			Examples
	Location/ Vantage	Observation Type	Coordination	
Stand-Alone Missions	Distributed	Complementary	Ground	UARS, TRMM, etc.
Satellite Train	Aligned	Complementary	Ground	Aqua/Aura Train
Precision Satellite Train	Precise	Complementary	Ground	
Global Constellation	Distributed	Similar	Ground	GPM, Iridium
Multi-View Formation	Aligned	Similar	Ground	“Parasitic” Cartwheel
Precision Formation	Precise	Similar	Ground	GRACE
Multi-Measurement Sensorweb	Distributed	Complementary	Autonomous	ESE Vision Sensorweb
Virtual Platform	Aligned	Complementary	Autonomous	
Precision Virtual Platform	Precise	Complementary	Autonomous	
Super-Instrument Sensorweb	Distributed	Similar	Autonomous	JPL Sensorweb
Multi-View Virtual Truss	Aligned	Similar	Autonomous	
Precision Virtual Truss	Precise	Similar	Autonomous	Optical Interferometry

The concept chapter also examines International planning and mission coordinating mechanisms and communication and navigation approaches, including likely cumulative data rates and the implications for use of radio or optical communications.

This chapter highlights aspects of the multi-mission development system, both for maintaining and upgrading the multi-mission system and for leveraging economies of scale. The views for the next two chapters, multi-mission system form (chapter 5) and multi-mission timing and operation (chapter 6), also highlighted development aspects. For readability and consistency, the discussion of the multi-mission development system is consolidated in this chapter.

Chapter 5 builds upon the functions and concepts developed in previous two chapters. It decomposes the level 2 form of the Earth- and Space-based Observation System. As was done for functions in chapter 3, the approach is to zoom to the individual mission level and expand the level 3 decomposition of individual mission form. The level 3 form decomposition is derived from the state-of-the-art in spacecraft mission design. The thesis uses the level 3 form decomposition to develop and check completeness of a level 2 decomposition of multi-mission system form. The following figure lists the elements of the multi-mission form, indicating how they relate to the multi-mission functional intent. This mapping was one approach to check these decompositions for consistency and completeness. In some cases the physical or structural implications of the level 2 form illuminated new aspects and insights into the system as a whole.

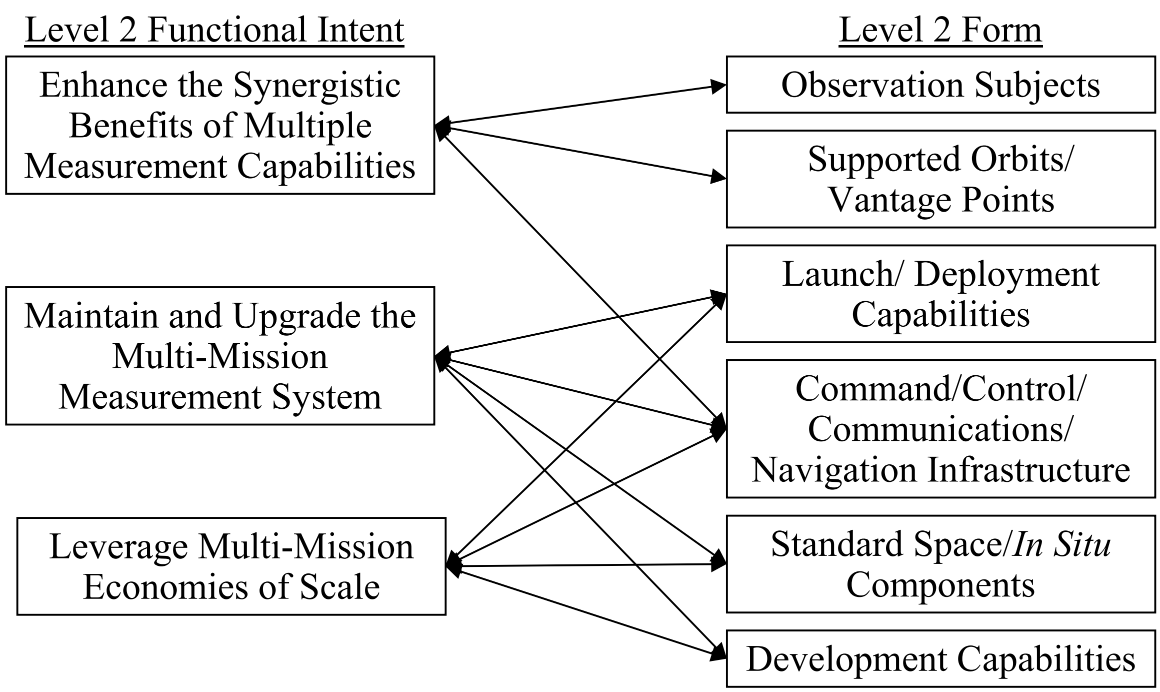

Figure 1: Mapping of Level 2 Functional Intent to Level 2 System Form

Current and potential future examples of these form elements are discussed. This decomposition of form leads to an examination of the types of measurements, spectral regions, and spatial scales of interest; the types of vantages and orbits of interest; implications of orbits on the design of the navigation system and the physical locations of ground stations and launch facilities; and the topology options for inter-linking multiple missions for real-time, autonomous observation strategies. The following table illustrates the classification and examination of orbit types.

Table 3: Orbit Value Trade Space

Range	Lighting/ TOD	Geo-Location	Corresponding Orbit Types
Close	Variable	Non-Repeat	Non-Repeating Non-Synchronous Orbits
Close	Variable	Repeating	Repeat Groundtrack Non-Synchronous Orbits
Close	Similar	Non-Repeat	Non-Repeating Sun-Synchronous (Retrograde Polar) Orbits
Close	Similar	Repeating	Repeat Groundtrack Sun-Synchronous Orbits
Distant	Variable	Non-Repeat	GEO Transfer Orbits, MEO, HEO, Earth-Moon Lagrange
Distant	Variable	Repeating	Geosynchronous Orbits, Molnoyia Orbits
Distant	Similar	Non-Repeat	Sun-Earth Lagrange Points, **Gap?**
Distant	Similar	Repeating	**Potential Gap: ESSE Orbits?**

Chapter 6 examines the level 2 Earth- and Space-based Observation System timing and operation to identify unique issues provided by this view that were not captured from other views of the system. The timing and operations of the individual missions is not discussed here, but was considered in earlier sections and reflected in the development of system function, concept, and form. For example:

- The major stakeholders and partners have differing timeframes of interest. Missions with short development times to allow flexibility to infuse the latest technology and adapt to emerging research results. Similarly, the timeframes of graduate students and career academics seeking to use space-based data indicate the desirability of mission development times on the order of two or three years.
- Operational agencies require assured capability. They often have considerable spare assets either in development or on orbit. There is almost always a long delay between when an operational agency agrees to take over a sustained, long-term measurement and when that agency actually launches the capability. Often NASA must develop an additional mission to "bridge" this coverage gap.
- Commercial communications satellites may have as little as six months between order and launch of a satellite. NASA has studied "quick-ride" flights of opportunity using excess capacity on these satellites that could support scientific research. Currently NASA has difficult matching this short cycle time.

These different timeframes suggested a further examination of strategies for increasing the flexibility of the mission development process. For conciseness and readability, the detailed discussion of concepts and improvements for the development system has been consolidated into chapter 4.

Other timing and operational constraints addressed include the time required to phase-in multi-mission measurement capabilities requiring multiple launch or deployments and orbital debris constraints and mitigation approaches for multi-satellite constellations.

Three main areas of uncertainty remain. They are:

- The various "Sensorweb" related concepts and the approaches to multi-mission interaction.
- The potential for changes in the underlying architectural drivers, including the ability of the Earth Science Enterprise to recognize and adapt to these changes.
- The many stakeholder relationships and the potential influence they will have on the future of the Earth- and space-based observation network.

Chapter 7 summarizes the major guidance concerning these three areas, as well as additional recommendations concerning the system.

Introduction

The goal of this thesis is to develop guidance and recommendations for the NASA Earth Science Enterprise by assessing and refining strategic architecture options for an integrated Earth and space-based observation network for Earth science, evaluating upstream and downstream trends and influences that may affect the architecture and the Enterprise. In doing so the author intends to develop a deeper understanding of these issues for use in future policy and implementation discussions.

The following provides background, explains terminology, and describes this thesis in general. Key terms are indicated in **bold**. Those that relate to the title of this thesis are also **underlined**.

The **Earth Science Enterprise** (ESE) is one of the five Strategic Enterprises of the National Aeronautics and Space Administration (**NASA**). The Earth Science Enterprise is dedicated to **scientific** research concerning the **Earth system**, which (for NASA and this thesis) is bounded by the top of the Earth's stratosphere. Missions observing regions above the stratosphere, such as the Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) Explorer, are the purview the **Space Science Enterprise**.*

Space-based observations of the Earth are by definition remote sensing observations obtained from the **vantage** of space. **Earth-based observations** may be remote or *in situ* observations, and are obtained from **vantages** within the Earth system, ranging from high altitude balloons and unmanned aerial vehicles to underground wells and ocean floor sensors. The text occasionally uses the term ***in situ*** to mean Earth-based when it seemed appropriate to emphasize that not all measurements are space-based.

Space-based global observation, navigation, and communications systems are useful for many purposes. Many organizations have or are developing these capabilities. By far the largest worldwide space segment is **commercial communications**, estimated at $68 B in 2000. Worldwide **commercial remote sensing** revenue is estimated at $4 B in 2000, with $2.6 B in aerial imaging, $1.2 B in value added services, an a nascent **space-based commercial remotes sensing** segment at less than $0.2 B.† The Rumsfeld Commission estimates that for the next decade the US will spend about $6 B per year upgrading or replacing its **National Security space** systems.‡ For comparison the annual budget for the NASA Earth Science Enterprise is

* NASA, "It's About Timed: NASA Spacecraft Will Use Lofty Perch to Study Gateway to Space," Press Release: 01-226, Nov. 19, 2001, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2001/01-226.txt

† U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

‡ Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

$1.6 B per year.* The number of **International** space programs is expanding, with countries from Argentina to the United Kingdom currently operating research, defense, operational, and commercial missions. Many of these missions involve **bilateral International agreements** with NASA. Nations share **operational** weather data through the World Meteorological Organization. Several nations including the US operate **navigation** systems used for space missions.

As a result the NASA Earth Science Enterprise and the Earth- and Space-based Observation System have many **stakeholders** who are interest in, influenced by, and can influence NASA's activities. NASA's observations are valuable to others, and NASA finds value in the observation, communication, and navigation capabilities of these stakeholders. This thesis uses the term **network** for the overlapping "system of systems" that simultaneously delivers different values to different stakeholders. Separate stakeholders develop the elements of the network. Influencing these to support NASA's needs requires a strategic approach to identify **collaborative** incentives and opportunities. This is a source of added complexity for the NASA Earth Science Enterprise.

This thesis defines a four level structure for organizing the analysis. **Level 0** is the level that considers the NASA Earth Science Enterprise as a single unit. At this level this thesis examines the current goals of the Earth Science Enterprise (Chapter 2). It also examines the larger policy context as represented by commercial space interests, US National Space Policy, National Security space interests, and International Space Law. Based on this analysis, the thesis develops a **goal statement for the NASA Earth Science Enterprise**. This level 0 goal is a **working goal** for this thesis, and is not endorsed by NASA.

Goal statements in this thesis follow a semantic structure developed by Professor Edward Crawley.† Goals include a statement of **intent** and the **process** to meet that intent. In most cases, the goals include the **operand** that the process operates on, possibly with some modifying text. The complete working goal statement for the Earth Science Enterprise also includes a statement of **form**, which is used for the **Level 1** decomposition of the system. However, **functional goals** are intended to be "solution neutral" and do not indicate form. Finally, a goal statement may contain additional statements that reflect **larger context goals** and **larger context constraints**.

For example, the working goal for the NASA Earth Science Enterprise developed for this thesis is structured as follows:

* NASA, "National Aeronautics and Space Administration, Fiscal Year 2003 Estimates," World Wide Web page, URL http://ifmp.nasa.gov/codeb/budget2003/03-Multi-Year_Budget.pdf

† Crawley, E., Lecture Slides, System Architecture, Massachusetts Institute of Technology, course number ESD.34j/16.882j, Fall 2001.

Table 4: Semantic Structure for the NASA Earth Science Enterprise Goal Developed as a Working Goal for this Thesis

Goal Element	Specific Instantiation
Intent (To)	Characterize the Earth System, Understand How It Is Changing, and Predict the Consequences for Life on Earth
Processes (By)	Observing, Analyzing, and Modeling
Operand	The Earth
System Form (Using)	Earth- and Space-based Observation Systems, Global Information Systems, and Global Modeling Systems
Larger Context Goals	• Broadly Involve the International Science Community • Demonstrate the Application of Results for Economic and Societal Benefit • Produce and Employ Innovative Technologies • Encourage US Commercial Capabilities • Develop a Cadre of US Space Professionals in Government, Academia, and Industry

Level 0 considers the NASA Earth Science Enterprise as a single unit. The statement of form in the working goal for the NASA Earth Science Enterprise suggests a natural grouping of the form into three **integrated** elements, the **Integrated Earth- and Space-based Observation System**, the **Integrated Global Information System**, and the **Integrated Global Modeling System**. This is the basis for the expansion or **decomposition** of the Level 0 structure into a 3-element **Level 1** structure. For readability, the term **integrated** is not always used when referring to these systems.

This thesis focuses on the Earth- and Space-based Observation System element of the Level 1 decomposition. It develops an **architecture** for the Earth and Space-Based Observation System, consisting of the **functions**, **concepts**, **form**, and **timing and operation** views of the system. This architecture is **strategic** in that it provides a framework for evaluating strategy options and pursuing collaborative efforts, rather than a detailed guide for immediate design. The following figure provides a conceptual roadmap to the thesis and the iterative architectural process followed. Chapter numbers are indicated in circles.

Integrated Earth and Space-Based Observation Network for Earth Science

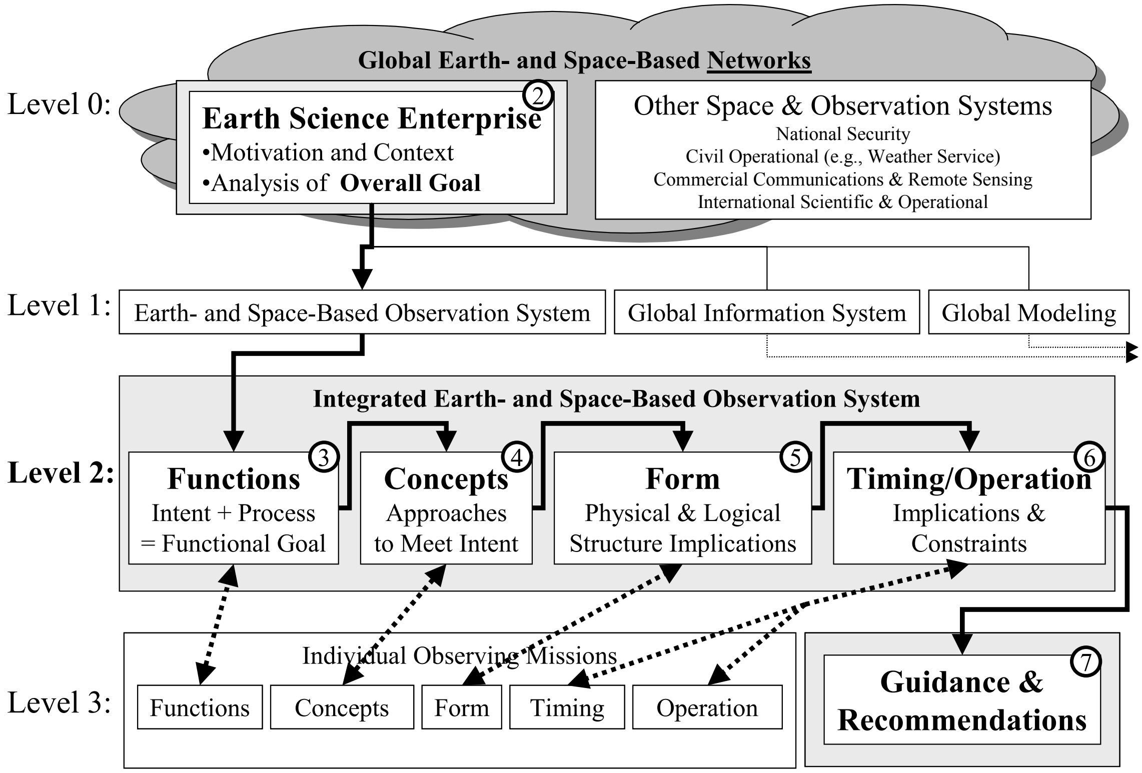

Figure 2: Conceptual Roadmap to this Thesis

The first **level 2** expansion (chapter 3) is a decomposition of **function**, resulting in a set of **Level 2 functional goals** (**intent** plus **process**). The approach is to skip or "**zoom**" to the next level (**Level 3**), examining the processes and corresponding intent of **individual Earth- and space-based observation missions** in order to develop generic **Level 3 functional goals** for individual missions. The thesis then uses these level 3 goals to develop and check for completeness the level 2 functional goals.

Chapter 4 uses the functional intent statements from the level 2 functional goals to organize descriptions of current and proposed approaches or **concepts** to meet these intents. These concepts range from policy mechanisms and communications approaches to facilitate National and International coordination to the current multi-mission capabilities to guide and navigate missions. The author used these concepts to refine the functional goals developed in the previous chapter. In some cases, the author found that the original statement of intent and process in the functional goal assumed an implementation approach. In this case the functional goal was broadened to eliminate the implied form. These concepts were also used as the foundation for the next chapter.

The second **level 2** expansion (chapter 5) is a decomposition of **form**. This decomposition builds upon the functions and concepts developed in previous chapters. The approach is to zoom to the individual mission level and expand a generic **level 3** decomposition of **individual mission form**, derived from the state-of-the-art in spacecraft mission design.* The author used this level 3 form to develop and check for completeness a **level 2 decomposition of form**. The level 2 form was mapped to the level 2 functional intent to screen for consistency and completeness. In some cases the elements of form closely aligned with the functions and concepts already discussed in earlier chapters. In other cases, the physical or structural implications of the level 2 form illuminated new aspects and insights into the system as a whole. For example, the decomposition of form led to an examination of the types of measurements, spectral regions, and spatial scales of interest, the types of vantages and orbits of interest, implications of orbits on the design of the navigation system and the physical locations of ground stations, and the topology options for inter-linking multiple missions for real-time, autonomous observation strategies.

Chapter 6 examines the level 2 Earth- and Space-based Observation System **timing and operation** to identify unique issues provided by this view that were not captured before. The thesis concludes with chapter 7, a summary of the **guidance and recommendations**.

As a general rule, **measurement** is used when discussing requirements or function, and **observation** or **mission** is used when discussing implementation or form. To streamline the text and avoid confusion with existing systems such as the NASA Earth Observing System (EOS) or the International Global Observing System (IGOS), the **level 2** Earth- and Space-based Observation System is often referred to as the **multi-measurement system** (when discussing function) or the **multi-mission system** (when discussing form), and elements at **level 2** are often described as **multi-measurement** or **multi-mission** elements. At **level 3**, both space-based and Earth-based measurement systems are referred to as **missions** (or **individual missions** to emphasize the distinction from the multi-mission system) that support **individual measurement** requirements. For brevity and readability the author occasionally uses the term **spacecraft** when referring specifically to the form of an individual space-based mission.

* As exemplified by Wertz, J., and Larson, W., "The Space Mission Analysis and Design Process," chapter 1 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

Chapter 1: Motivation and Context

1.1 Chapter Summary

The goal of this thesis is to develop guidance and recommendations for the NASA Earth Science Enterprise by assessing and refining strategic architecture options for an integrated Earth and space-based observation network for Earth science, evaluating upstream and downstream trends and influences that may affect the architecture and the Enterprise. In doing so the author intends to develop a deeper understanding of these issues for use in future policy and implementation discussions.

1.2 Leadership Role for NASA

NASA is a leader in the observation of the Earth from space. The new NASA vision and mission statement, reflecting the direction of the new NASA Administrator, emphasizes NASA's role "to improve life here" and "to understand and protect our home planet."*

Humans have observed the Earth from space for over 40 years, and have gained considerable experience in developing and operating individual missions. Taken together, these individual missions form an observation system whose architecture continues to evolve as space technology and the space industry matures. An emerging trend is the increased use of and reliance on observations from multiple simultaneous missions.

> NASA's Vision
> •To improve life here
> •To extend life to there
> •To find life beyond
> NASA's Mission
> •To understand and protect our home planet
> •To explore the universe and search for life
> •To inspire the next generation of explorers
> . . . as only NASA can

Earth observations from space are inherently global and international in scope. These observations have value for research, operations, defense and security, and commercial applications. Other entities are developing missions for a broad spectrum of uses. Commercial investments in space now exceed Government investments, driven by the space-based communications industry.†

* NASA, "Administrator Unveils Future NASA Vision and a Renewed Journey of Learning," Press Release: 02-66, April 12, 2002, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-066.txt

† Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL

NASA is a leader in the development of Earth observation missions for scientific research. In an era of constrained resources, NASA has the opportunity to use this leadership position to influence these emerging capabilities by establishing a collaborative strategic architecture that allows the scientific uses of these capabilities while respecting their proprietary, commercial, operational, and national security needs.

Leading the definition of the strategic architecture for this collaborative system is a major challenge faced by NASA. NASA needs to consider the implications of how NASA identifies future mission opportunities, establish voluntary collaborative standards for interaction (that add enough value that they will be adopted), develop technologies in preparation for these missions, solicit for scientific participation and mission implementation partners, negotiate commercial, interagency, and international implementation approaches, etc. This thesis will assist in this definition.

1.3 Reassessing NASA's Strategic Approach

Worldwide, both the number and the diversity of space system stakeholders are increasing for space applications in general and for Earth observations in particular. Driven mainly by the growth of space-based communications, access and use of Earth orbit is becoming more of a commodity. Launch services, standardized spacecraft busses, and mission operations capabilities are all now commercially available.

This growth is changing the value framework for NASA strategic approach from one in which the Government's interests are dominant to one in which multiple stakeholders share overlapping interests. As summarized in a June 2001 Department of Commerce report:

> First, the space industry is broader than most people realize. It is not only composed of satellites and their launches, but now encompasses many direct-to-consumer applications, Internet services, and entertainment applications. Second, the industry is rapidly evolving from an industry dominated by civil government and military activities to an industry experiencing dramatic growth in commercial arenas. The unprecedented demand for commercial telecommunications services and new commercial applications are the primary driving forces of the space industry today.*

This adds complexity for NASA, but creates the opportunity to collaborate, share investments and reduce costs, and has the potential to substantially increase the efficiency and effectiveness of NASA's Earth science research program.

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http://www.defenselink.mil/pubs/space20010111.html. From page 71: "In the United States, investments from commercial space activities now exceed those of the U.S. Government by a factor of two."

* U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, page 1-1, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

NASA's strategy is to find commercial and/or operational partners to take over sustained, long-term measurements. NASA's intent is to remain a research Agency, to focus its efforts on the cutting-edge, and to avoid obligations to obtain long-term data sets when these have proven their value to other entities. Currently, the principle operational partners are NOAA (for weather satellites) and the Department of Defense (for the future merged civil and military weather satellite system). However, operational satellites for other Government agencies (EPASat, FEMASat) are possible, as well as commercial partners. For example, NASA recently selected partners to evaluation the commercial continuation of the Landsat measurement set.[*]

1.3.1 U.S. National Stakeholders

The increasing numbers of National stakeholders include:

- Public/policy stakeholders who have concerns over issues such as climate change.
- Operational civil agency stakeholders who have responsibilities in weather, natural hazards, other emerging uses.
- Federal, state, local, and tribal governments who have needs and interests in decision support systems.
- National security stakeholders, whose major infrastructure investments in capabilities such as Global Positioning System (GPS) satellites and launch facilities have played a critical role, and who plan to invest $60 B over the next decade or so for the replacement of their satellite network.[†]

1.3.2 International Stakeholders

The number of International Earth observation participants is increasing. This includes countries with extensive Earth remote sensing space missions, such as Russia, China, India, Japan, Canada, and Europe. These countries actively engage in research, resource monitoring, weather monitoring, and intelligence gathering from space. In addition, there are many countries with fewer missions, such as Brazil, Argentina, Israel, Turkey, Korea, Malaysia, the Taiwanese authorities, and South Africa.[‡] NASA cooperates in space missions with most of these nations, and announcements of opportunity to participate in NASA Earth science missions are open to scientists from around the world.

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[*] NASA, "NASA Picks Landsat Data Proposals For Further Development," Press Release: 02-52, March 15, 2002, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-052.txt

[†] Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

[‡] U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

1.3.3 Commercial Stakeholders

The following figure, from a Satellite Industries Association and Futron survey, provides an overview of the major satellite service application sectors and summarizes the commercial space industry.*

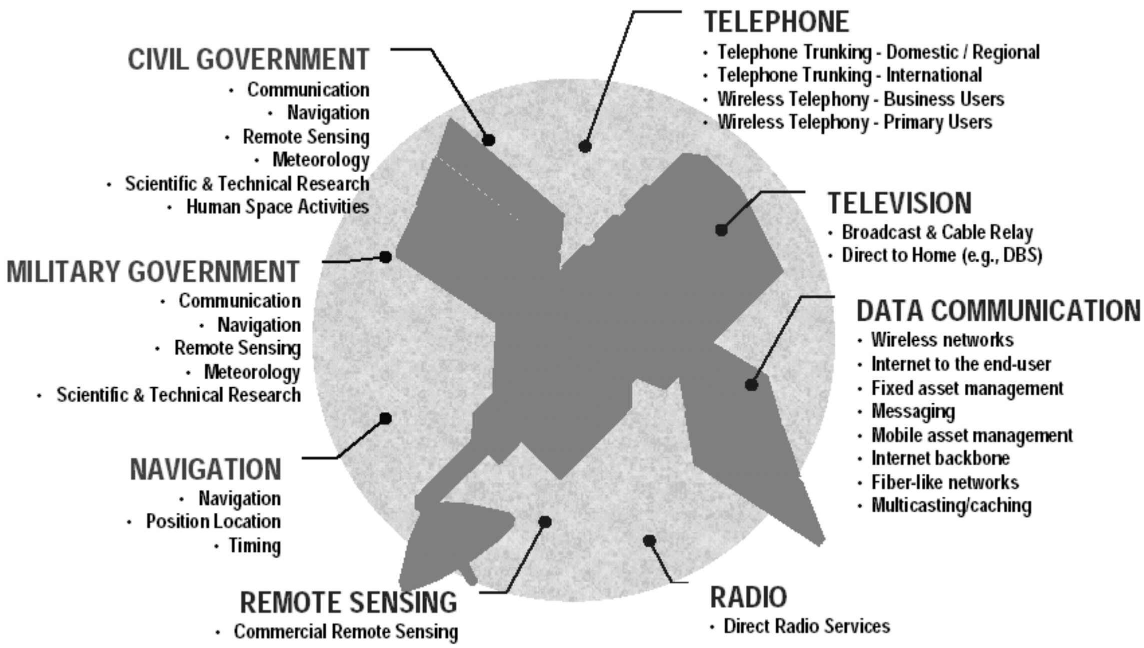

Figure 3: Overview of World Satellite Services (SIA/Futron)

This figure illustrates the increasing diversity of space applications. The next table, from a June 2001 U.S. Department of Commerce report, shows the past and projected growth in worldwide space industry segments.† This table does not include dedicated military or human space activities, but does reflect government purchases of commercial services. The values for 2001 and 2002 are projected.

* Satellite Industries Association and Futron, "SIA/Futron Satellite Industry Indicators Survey 2000/2001 Survey Results," Presentation by Richard DalBello, June 2001, URL http://www.sia.org/papers/satstats01.pdf

† U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

Table 5: World Revenue ($, B) for Space Industry Segments (Dept. of Commerce)

Space Segment	1996	1997	1998	1999	2000	2001	2002
Satellite Communications	35.33	45.46	56.10	60.52	67.57	77.74	88.69
Space Transportation	4.89	5.65	5.49	5.65	5.39	7.04	6.60
Global Positioning System	3.39	4.15	5.14	6.22	7.34	8.42	9.47
Remote Sensing	0.10	0.12	0.14	0.15	0.17	0.20	0.23
Total	43.71	55.38	66.87	72.54	80.47	93.40	104.99

1.3.4 Commercial Remote Sensing Stakeholders

Only a small portion of this worldwide commercial space activity relates directly to NASA's Earth science research programs. However, viable space-based commercial remote sensing companies are emerging. National and NASA policy require that NASA use these commercial capabilities, encourage the emergence of this industry, and refrain from activities that provide comparable data or detract from the markets for these companies.

The next table compares the revenues of pre-value added space-based commercial imagery from U.S. companies and the rest of the world.

Table 6: World Revenues ($, M) for Pre-Value Added Space-Based Commercial Imagery (Dept. of Commerce)

	1996	1997	1998	1999	2000	2001	2002
U.S. pre-value added commercial imagery revenues	28	32	38	43	50	63	83
Rest of world pre-value added commercial imagery revenues	74	88	101	111	123	134	148
Total	102	120	139	154	173	197	231

These tables only consider the pre-value added revenues for space-based commercial remote sensing. Acquiring the data is only a small part of the value chain. The next figure depicts the overall value chain, from space mission suppliers to delivery of usable information products to customers.*

* This figure adapted from Henderson, R., Lecture Slides, Special DLL Seminar in Management, Technology Strategy, Massachusetts Institute of Technology, course number 15.984, Spring 2001. Similar figures are in widespread use.

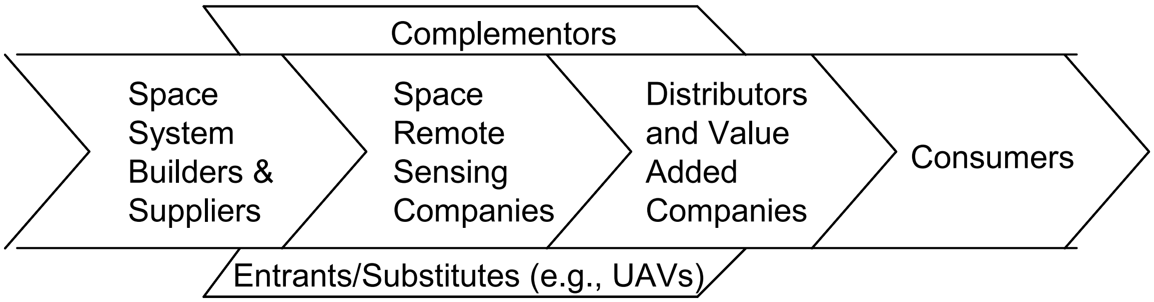

Figure 4: High Resolution Earth Remote Sensing Value Chain

Much of the value is captured by other elements of this chain. The companies that build the space assets for the commercial remote sensing companies capture considerable value from the effort. These companies own most of the equity in the corresponding three US companies actively in the space-based high resolution imaging business. The companies that add value and deliver the information to the customer capture much of the remaining value.

The next table, derived from information in the Department of Commerce report, shows that worldwide revenue from satellite imagery is small compared to airborne remote sensing and the value added data display and delivery systems, such as Geographical Information Systems. With the recent launches of the IKONOS satellite by Space Imaging and the QuickBird satellite by Digital Globe, space-based systems are just beginning to position themselves with high-resolution capabilities to address the market currently met by airborne remote sensing.

Table 7: World Revenue Shares of the Commercial Remote Sensing Segments

Commercial Remote Sensing Segment	1998	2000
Satellite Systems	$0.14 B	$0.17 B
Aerial Imaging	$2.1 B	$2.6 B
Value Added Products (e.g., GIS)	$1.0 B	$1.2 B
Total	$3.3 B	$4.0 B

1.3.5 Emerging Stakeholders

Finally, the above discussion and space segment revenues represent the established space industry segments. The Department of Commerce held a recent workshop on emerging segments, such as entertainment, space manufacturing, and space tourism.* While these are small and not included in the above summaries, they represent the potential for further growth and diversification of interest in space activities.

* U.S. Chamber of Commerce, "U.S. Chamber Calls Space Next Business Frontier," Press Release, November 7, 2001, URL http://www.uschamber.com/NR/exeres/4011CF75-2340-4E2B-8658-63F32842FCE0.htm

1.3.6 Implications of Diverse Stakeholder Interests

NASA's Earth Science Enterprise is small compared to the worldwide space activity, but large compared to the space-based remote sensing industry. Even within the narrower domain of space-based remote sensing of the Earth, the data have many diverse uses for multiple stakeholders. This diversity of interests and stakeholders adds complexity for the development of space remote sensing systems.

Christensen describes the concept of a firm's "value network," described as "a nested network of producers and markets through which the components at each level are made and sold to integrators at the next higher level."[*] For space systems, multiple stakeholders provide multiple assets and capabilities, seeking widely diverse aspects of value, such as scientific benefit, defense superiority, or commercial success. To effectively develop and leverage partnerships within these overlapping values, NASA will need to understand and consider not just the value chain of a particular observation capability, or even the value network of a particular segment, but the overlapping interests and capabilities of many segments that share suppliers, services, and technology investments.

1.4 Forecast of Influences

One approach for forecasting potential influences on the future evolution of a product, company, or system, is to develop scenarios.[†] The intent is to identify the major influences and a small number of corresponding scenarios that are likely to shape future Earth observation capabilities. Significant innovations in new measurement approaches and mission technologies are expected, and therefore not reflected in the scenario analysis. Major influences could include:

- The future health of the global and U.S. economy, which affects the willingness of governments to sponsor Earth science and applications research.
- The extent of consensus on the question of global climate change, which also affects the willingness of governments to sponsor Earth science and applications research.
- National security status, which could place priority on more immediate National needs.
- The influence of natural disasters, and the extent to which a consensus develops that space-based observations play a role in mitigating these risks, which could influence both the level of government investment and the need for rapid and reliable real-time coverage and response by the observation system.
- The evolution and maturation of the space-based commercial remote sensing industry, which directly effects NASA "make vs. buy" decisions.
- Other events within NASA, such as major failures, which could affect the overall investment and support for all NASA activities.

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[*] Christensen, C., *The Innovator's Dilemma*, Harvard Business School Press, 1997, page 32.

[†] Schwartz, P., *The Art of the Long View*, NY: Currency/Doubleday, 1991, chapter: "The Smith & Hawken Story: The Process of Scenario-Building," pp. 17-30.

These influences suggest the following scenarios:

- National willingness to invest in NASA increases in response to influences such as strong economic growth or clear consensus concerning climate change concerns.
- National willingness to invest in NASA decreases in response to influences such as weak economic growth or lack of consensus concerning climate change concerns.
- The priories for National investments in NASA shift towards more operational concerns, such as natural disaster warning or National security support. This could happen in response to increased concern over natural disasters, such as might be triggered if a major tragic event occurred, in response to increased National security concerns that could call upon the capabilities of NASA, or in response to a major restructuring of the Nation's space program.

The emergence of a strong commercial remote sensing industry would influence the degree to which commercial capabilities could support the research activities of NASA. This mainly influences the pace or degree of commercial collaboration and does not stand as a separate scenario. The above scenarios were considered in developing the remainder of this thesis.

1.5 Multiple Interacting Missions and the Sensorweb Concept

An emerging trend in both commercial and science satellite operations is the use of multiple satellites. The currently flying Iridium constellation of 66 communications satellites is an early commercial communication example of this trend. NASA currently selects and develops its Earth Observation missions individually, but has begun to operate them in small formations of spacecraft, such as the LandSat 7/NMP EO-1/SAC-C formation.

This trend will continue and increase in complexity. NASA's vision for the future includes "sensor webs," interacting constellations of small satellites. The following quote illustrates NASA's concept:

> "...the geospatial revolution will include networks of sensors, working in tandem to form intelligent, reconfigurable constellations that can respond to rapidly emerging events on Earth, or recover from failures on orbit. We will demonstrate this "sensorweb" concept in the EOS era by 'formation flying' several EOS satellites and processing the data as if the formation were a single "superinstrument."[*]

As the number of satellites increases, the current approach of individually commanding each one will become more difficult.

[*] NASA, "NASA Earth Science Enterprise Strategic Plan, 2001," page 27, URL http://www.earth.nasa.gov/visions/stratplan/ese_strategic_plan.pdf

1.6 Motivating Questions

The above trends, influences and scenarios, along with the author's experience in managing technology programs and Earth science mission evaluation efforts, lead to the following motivating questions.

- The current Earth Science Enterprise Strategic Plan includes a vision and concept for the future evolution of the system to observe the Earth. What is really meant by a "sensorweb"? Is this the right concept? Are there other concepts that are comparable or equally valid? What are the implications of these concepts for the entire system? What are the forces that caused NASA to move away from large, integrated Earth Observation Satellites to a more distributed approach. Are there innovations that might reverse these forces, making a return to large, integrated systems appropriate?

- What are the implementation options for a sensorweb? Assuming the "sensorweb" concept, what are the implementation options for command and control? Regarding each mission as an element in the sensorweb network, is it a network of peers (each mission independent, network decisions made by "egalitarian" rules such as majority or first come, first serve), a hierarchical network (an element belongs to a chain of command and only responds within this structure), a layered structure (each element responds to any element from the layer above, and has authority to command elements from the layer below), etc.? For example, the future sensorweb system may include the ability to monitor for tornados and volcanic eruptions. If a spacecraft sensor detects a volcanic eruption and needs to call upon additional sensors to observe the event, or to seek additional bandwidth to obtain and transmit the data, does it call only upon its own network of volcano-monitoring capabilities (described above as a hierarchical network), or can it call upon and perhaps interrupt the tornado monitoring system?

- Space assets tend to have long lifecycles. NASA is currently planning the satellites that will still be operating in 10 years. As an ongoing system that supports research, operational, National security, and commercial needs, the global collaborative system for Earth observation must be designed to accommodate innovation in the context of legacy systems. In particular:
    - Can NASA identify capabilities that NASA should add in the near term to satellites to make them (or at least increase the probability that they will be) compatible with these future "sensorwebs?"
    - NASA currently communicates with satellites directly from the ground. Yet NASA's vision includes a future of interactive sensor webs. Should NASA start adding to satellites the ability to communicate with each other directly? If so, how should NASA do this? The spectrum allocation for satellite-to-satellite links is different than that for satellite-to-ground (and commercial missions are

allocated different parts of the spectrum from government satellites). How much extra hardware would NASA have to add?
    - The "sensorweb" concept includes widely distributed, long-lived *in situ* assets, such as buoys, automated weather stations, balloon-born instruments, and unmanned aerial vehicles (UAVs). Current practice for airborne science is to record the data for analysis at the end of the flight. As the duration of missions increases, telemetry capability will become necessary. What are the implications in terms of interface planning and infrastructure investment to enable these options?
    - Would it make sense to make the investment now for technologies such as software radios, so that NASA has the option to reconfigure in the future, perhaps even dynamically adjusting the interface to adapt to a variety of satellites? What is the value of enabling this option?
    - Given how valuable spectrum allocation is, would NASA be able to make the case (and get funding) to move completely away from radio communications, investing in optical communications so that NASA can "give back" to the government valuable spectrum allocation for other uses? Is NASA likely to experience pressure to give up spectrum allocation in the future?
    - What are the advantages and disadvantages of these options? Are there other options?

- How does NASA go from selecting and operating individual missions to creating a collaborative sensorweb that includes both space missions and *in situ* platforms, unmanned aerial vehicles (UAVs), etc.?
    - How can NASA bring forward standards (which will have to be voluntary and collaborative) such that NASA can cooperate with satellites and incorporate observations from other agencies, International partners, and commercial systems?
    - Can NASA build its system in such a way that it can involve proprietary of national security assets, and if so, how can NASA do this without compromising these interests?
    - The government procurement process is designed to select the "best" of the missions proposed in response to a solicitation, effectively seeking the local optimum at the time of the solicitation. Is NASA assured that this process will lead to the global optimum? What changes should NASA make to the process for identifying, soliciting, and selecting future missions to increase the likelihood that NASA defines "best" in a way that allows these local optimum processes to lead to the global optimum?

- Is there a limit on the number of satellites that can share an orbit? Is there a danger of what is called the "cascade effect?" If a satellite is hit by a piece of space debris, it may break up and create its own "cloud" of debris. If enough satellites are sharing the same basic orbit altitude, any debris created may damage more satellites, creating more debris, leading to a chain reaction. Is there a "critical mass" of satellites above which a satellite constellation is unstable?

- Where will the next generation of scientists, engineers, and technical leaders come from? Are there mechanisms in place to train and sustain the human resources needed to meet the long-term goals of the Earth Science Enterprise and NASA? Will the culture be receptive to innovation? Is there evidence that the peer review process helps or hinders innovation, depended upon the cultural acceptance of innovation among the community of peers?

These are the questions that motivated this study. Not all are answered. This will be an on-going effort. This thesis provides a systematic framework for addressing these questions.

Chapter 2: Goals of the NASA Earth Science Enterprise

2.1 Chapter Summary

This chapter examines the current goals of NASA and the Earth Science Enterprise. This chapter also examines the larger policy context as represented by commercial space interests, US National Space Policy, National Security space trends, and International Space Law. Documents reviewed include:

- The 2000 NASA Strategic Plan.
- The 2001 NASA Earth Science Enterprise Plan.
- The Space Act, as Amended.
- Current and Historical National Space Policy documents.
- The Report of The Commission to Assess United States National Security Space Management and Organization, Hon. Donald H. Rumsfeld, Chair.
- Congressional testimony and legislation concerning National Security Space activities.
- Summaries of International Space Law.

Based on this analysis, the thesis develops a goal statement for the NASA Earth Science Enterprise. This goals statement interprets and reflects the larger context influences. This is a working goal for this thesis, and is not endorsed by NASA.

Earth Science Enterprise Working Goal for this Thesis

The goal of the Earth Science Enterprise is to characterize the Earth system, understand how it is changing, and predict the consequences for life on Earth, by observing, analyzing, and modeling the Earth using Earth- and space-based observation systems, global information systems, and global modeling systems.

In pursuing this goal, the Earth Science Enterprise will broadly involve the International science community, demonstrate the application of its results for societal and economic benefit, produce and employ innovative technologies, encourage US commercial capabilities, and develop a cadre of US space professionals in government, academia, and industry.

This thesis focuses specifically on the architecture of the Earth- and space-based observation systems, and does not specifically address the global information systems or global modeling systems.

2.2 Current Goals of the NASA Earth Science Enterprise

The current goals of the NASA Earth Science Enterprise represent the result of broad stakeholder review and debate over an extended period. They have evolved from earlier goal statements, and have been painstakingly reviewed both within the Administrative branch of the US government and by external advisory committees. The evaluation and update of these goals in this thesis is an academic exercise, and should not be taken as a criticism or recommendation that these goals should change. The author hopes that this effort will be useful in future discussions concerning the goals of the Enterprise. However, the author realizes and recommends that any actual goal revision or development involve extensive review and discussion with key stakeholders.

The current goals of the NASA Earth Science Enterprise, as stated in both the year 2000 NASA Strategic Plan[*] and the year 2001 Earth Science Enterprise Strategic Plan,[†] are shown in the insert box.

Current Goals of the NASA Earth Science Enterprise:

1. Observe, Understand, and Model the Earth System to Learn How It Is Changing, and the Consequences for Life on Earth
2. Expand and Accelerate the Realization of Economic and Societal Benefits From Earth Science, Information, and Technology
3. Develop and Adopt Advanced Technologies to Enable Mission Success and Serve National Priorities

NASA has developed an understanding and consensus on the scientific needs for Earth system science researchers through a multi-year process. To consider how the plans for future Earth observation missions should evolve to accommodate new scientific issues and emerging technologies, NASA conducted a Request for Information to solicit broad community input followed by a community workshop.[‡] NASA also solicited Advisory Committee and National

[*] NASA, "2000 NASA Strategic Plan," URL http://www.hq.nasa.gov/office/codez/plans/pl2000.pdf
[†] NASA, "NASA Earth Science Enterprise Strategic Plan, 2001," URL http://www.earth.nasa.gov/visions/stratplan/ese_strategic_plan.pdf
[‡] NASA, "Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions," March 3, 1999, URL http://www.earth.nasa.gov/visions/Easton/index.html

Academy Review, developed measurement concepts in order to estimate the budget requirements, and cleared the implied cumulative funding with the White House before publishing the collection of documents that make up the research strategy for the next ten years.*

This strategy leaves open the details of the individual mission implementations. NASA intends to use flexible mechanisms such as announcements of opportunity (AOs) to solicit innovative proposals from the broad community of researchers and mission developers.

The following figure shows the hierarchy of strategic planning documents within NASA and the Earth Science Enterprise. The Education and Commercial Strategy Plans have not been updated recently. These considerations are being incorporated into the higher level documents.

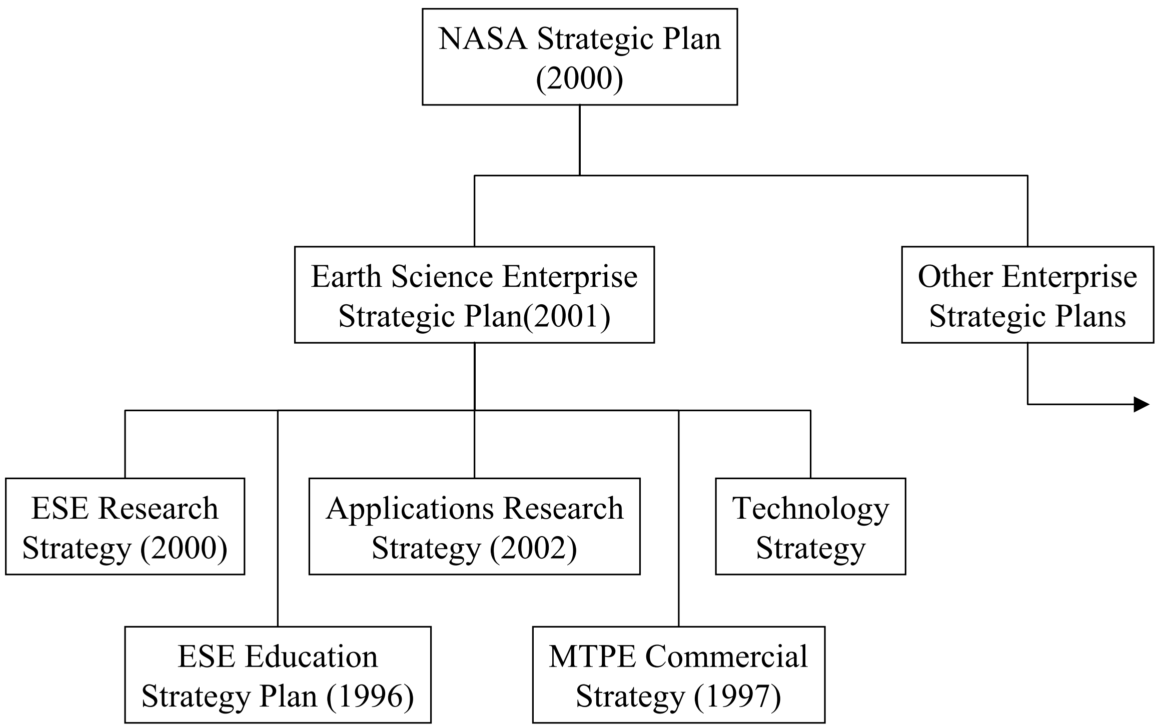


Figure 5: Hierarchy of Earth Science Enterprise Strategy Documents

* NASA, "Understanding Earth System Change NASA's Earth Science Enterprise Research Strategy for 2000 - 2010," December 2000, URL http://www.earth.nasa.gov/visions/researchstrat/Research_Strategy.htm

These NASA Earth Science Enterprise strategy documents identify the following overarching research question:

How is the Earth changing and what are the consequences for life on Earth?

The strategy documents expand upon this question to derive the following five questions that provide "a structure constituting the conceptual approach ESE is taking to improve our knowledge of the Earth system."*

- **Variability**: How Is the Global Earth System Changing?
- **Forcing**: What Are the Primary Forcings of the Earth System?
- **Response**: How Does the Earth System Respond to Natural and Human-induced Changes?
- **Consequence**: What Are the Consequences of Change in the Earth System for Human Civilization?
- **Prediction**: How Well Can We Predict Future Changes in the Earth System?

These research questions define a pathway of "variability, forcing, response, consequence, and prediction," corresponding to the Earth system conceptual model shown in the following figure. These questions are expanded further in the research strategy to develop a hierarchy of science questions.

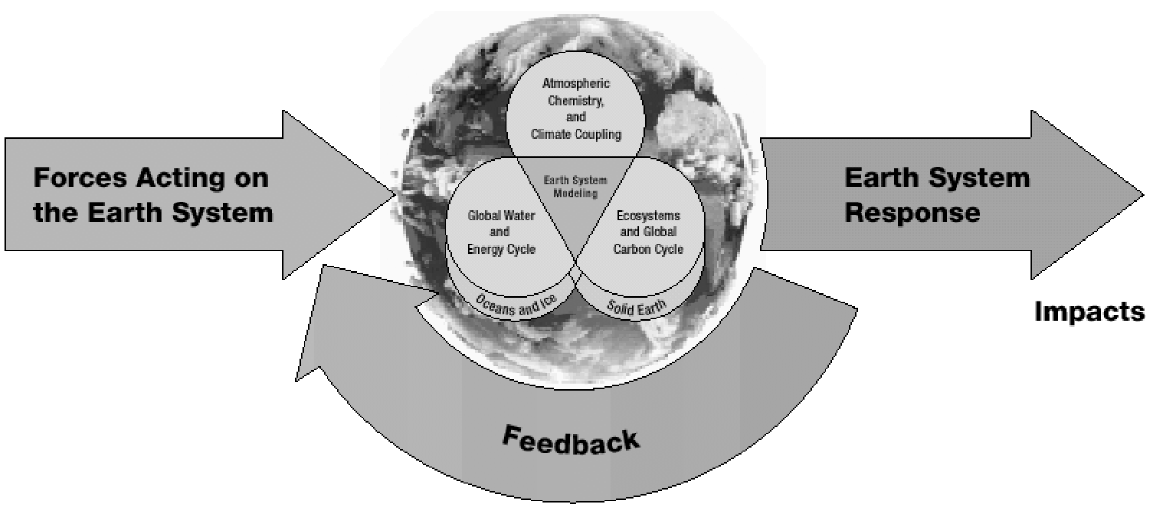


Figure 6: Earth System Conceptual Model (ESE 2001 Strategic Plan)

* NASA, "Understanding Earth System Change, NASA's Earth Science Enterprise Research Strategy for 2000-2010," December 2000, URL http://www.earth.nasa.gov/visions/researchstrat/Research_Strategy.htm

Complementing this research strategy, the applications strategy defines the following overarching goal for the Applications Program:*

> The overarching goal for the Applications Program is *to bridge the gap between Earth system science research results and the adoption of data and prediction capabilities for reliable and sustained use in decision support.* Related goals include the following:
>
> - Simplify and integrate the use of Earth system science data and prediction results for adoption in national applications that enable decision-making.
> - Enhance the availability, interoperability, and utility of ESE and U.S. private sector data sets, communications, computing and modeling capabilities as inputs to serve specific applications and research.
> - Produce prototypes, guidelines, assessments, and documentation of project results that are citizen-centered, results-oriented and market-driven.
> - Enable the project results to serve as benchmarks for policy and operational uses that benefit citizens through our Federal, state, local, and tribal partners.

2.3 Broader National and International Context

The study of the Earth system is inherently broad and international in scope. The NASA Earth Science Enterprise (ESE) operates in a broader network of multiple stakeholder investments, based on multiple needs and goals. To effectively leverage this broader investment, the Enterprise goals must be consistent with these stakeholder interests, identifying and seeking ways to mitigate conflicts within these interests. The intent of this section of this thesis is to assess the goals of the Earth Science Enterprise within this broader context.

2.3.1 United States Government Context

The following figure, from the 2001 "Report of The Commission to Assess United States National Security Space Management and Organization" (Rumsfeld Commission), depicts the many US organizations that are involved in space activities, with either operational, research, or regulatory roles.† Operational organizations include the Defense and Intelligence communities as well as the NOAA Civil weather service. Agencies with regulatory responsibilities include

* NASA, "Earth Science Enterprise Applications Strategy for 2002-2012," January 2002, URL http://www.earth.nasa.gov/visions/appstrat2002.pdf

† Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html, figure from page 3.

the Federal Communications Commission (FCC) for radio frequency spectrum allocation and the Department of Commerce for commercial remote sensing licensing.

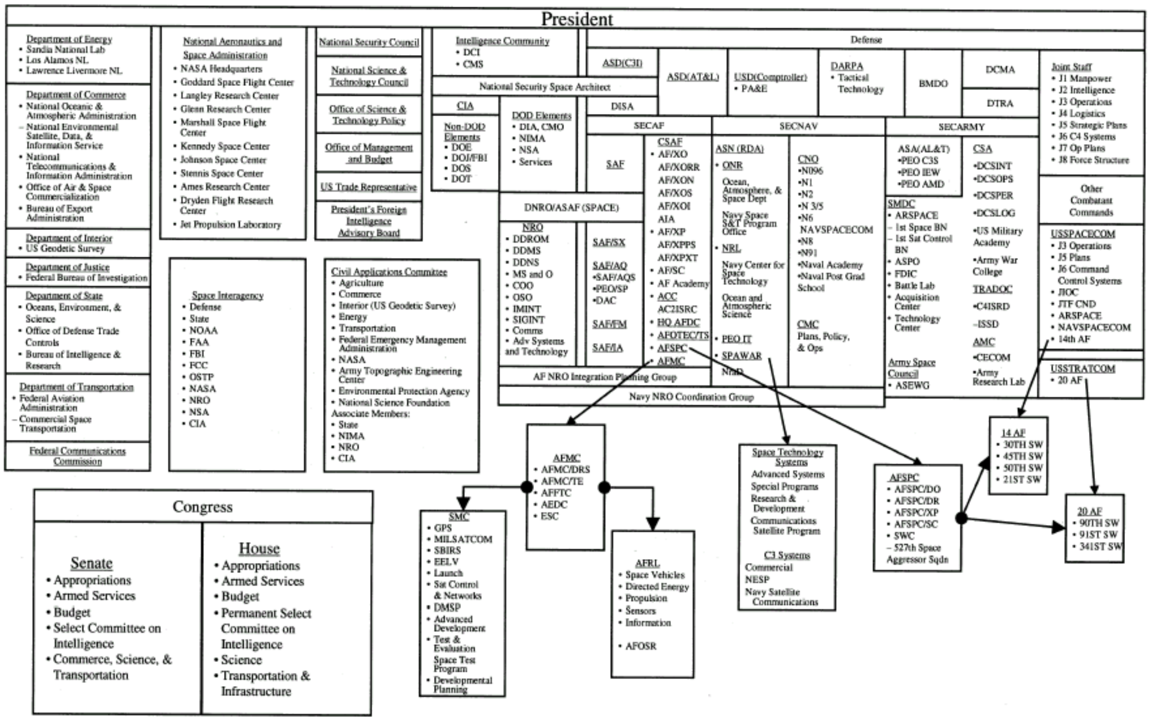


Figure 7: U.S. Government Organizations Currently Involved in Space Activities (Rumsfeld Commission)

NASA has the clear lead within the US government for space-based research observations of the Earth. In addition, NASA has considerable expertise and technical ability relating to *in situ* sensing. NASA is the US lead agency for the *in situ* sensing of every planet except the Earth.

United States Civil Government Context

NASA has operational responsibilities and relationships with both the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS). NASA develops the civil weather satellites for NOAA. NOAA takes over operation after the satellites are launched and complete on-orbit checkout.[*]

In addition, NASA is required by public law to ensure the continuity of Landsat-type data, a 30-year record of land cover and land use data. As stated in a recent press release, "NASA, together

[*] NASA, "NASA, NOAA Prepare to Launch Weather Satellite Designed to See Solar Storms," Press Release: 01-136, July 20, 2001, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2001/01-136.txt

with the United States Geological Survey, is working to guarantee that Landsat-type and -quality data are available to the science and applications communities well into the future, while ensuring and protecting commercial opportunities arising from the availability of those data." [*]

The climate change research efforts of the NASA Earth Science Enterprise are part of the larger, multi-agency United States Global Change Research Program (USGCRP), established in 1989.[†] The US Agencies involved in the USGCRP include:

- The Department of Agriculture
- The Department of Commerce, Natl. Oceanic & Atmospheric Admin.
- The Department of Defense
- The Department of Energy
- The Department of Health and Human Services, National Institutes of Health
- The Department of the Interior, US Geological Survey
- The Environmental Protection Agency
- The National Aeronautics and Space Administration
- The National Science Foundation
- The Smithsonian Institution

As described in the US Global Change Research Program reference above:

> The planning, coordination, and execution of USGCRP research activities are carried out in close association with and in support of the science priorities of the international research community; particularly those put forth by the World Climate Research Programme, International Geosphere-Biosphere Programme, and the International Human Dimensions Programme. These efforts underpin the United States' participation in and contribution to the international assessments related to aspects of global change.
>
> The USGCRP maintains an active interaction with the National Research Council through its Committee on Global Change Research and several other committees and panels that interface with many of the international scientific research programs.

[*] NASA, "NASA Picks Landsat Data Proposals For Further Development," Press Release: 02-52, March 15, 2002, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-052.txt

[†] USGCRP, "U. S. Global Change Research Program," World Wide Web page, URL http://www.usgcrp.gov/usgcrp/gcrproga.html

National Security Context

US National Security activities have a significant influence on the implementation of Earth Science Enterprise missions and activities. Many US National Security infrastructure investments are available for both security and civil use. For example:

- The investment in the Global Positioning System (GPS) has significantly changed the way space missions operate and navigate. Additional research applications of GPS continue to emerge. Current missions observe the rising and setting of GPS satellites through the atmosphere of the Earth to measure refraction, from which can be inferred atmospheric temperature, pressure, and water vapor content as a function of altitude. Researchers are investigating sensing the reflection of GPS signals off the surface of the ocean to obtain multiple, broadly distributed observations of sea surface height to complement the precise measurements of the TOPEX/Poseidon and Jason missions.

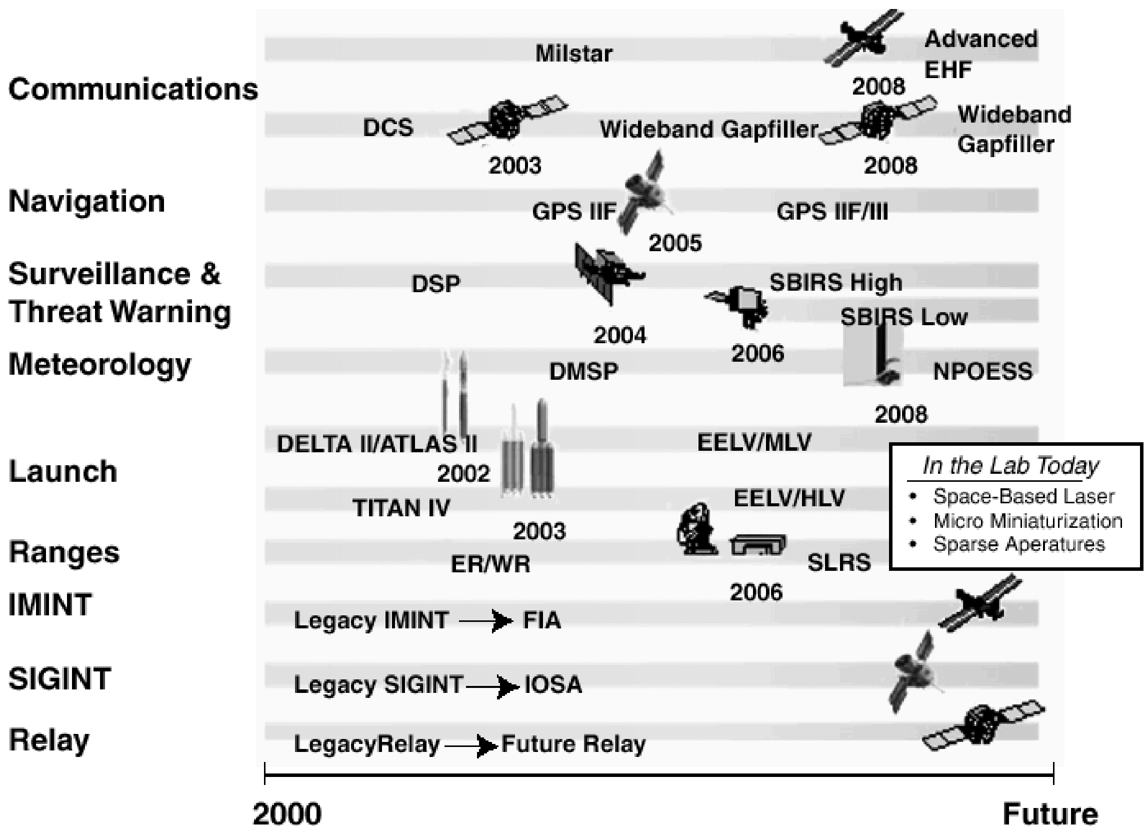
- NASA is a partner in the National Polar Orbiting Environmental Satellite System (NPOESS), the future polar satellite weather system. NPOESS merges the needs of the Civil and National Security operational weather services, which currently fly separate satellite systems. For NASA, this three-agency partnership represents an opportunity to transition long-term measurements to operational agencies.

Future National Security investments will likely present additional opportunities for cooperation and collaboration for space mission infrastructure developments. According to the 2001 "Report of The Commission to Assess United States National Security Space Management and Organization," the Defense and Security communities will be replacing virtually their entire inventory of satellites over the next decade or so, costing more than $60B.[*] These investments will include:

- New Intelligence Collection Systems
- Next Generation GPS for Military and Civilian Use
- Merged Weather Satellites (NPOESS) for Military and Civilian Use
- More Capable Military Communication Systems
- Deployment of the Space-based Infrared System (SBIRS)
- New Space Based Laser Program

The following figure, from this commission report, summarizes these planned investments.

[*] Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html



Source: Headquarters Air Force and National Reconnaissance Office

Figure 8: Planned National Security Space Investments (Rumsfeld Commission)

2.3.2 Commercial Context

Commercial activities also have a significant impact on the goal and policy environment of the NASA Earth Science Enterprise. A number of these influences were discussed in the previous chapter as part of the motivation for this reassessment. The space-based commercial communications industry is thriving, although it may face some competition from land-based systems, particularly in established urban markets.*

Within the US, three high-resolution remote sensing companies are currently active, Space Imaging, Digital Globe, and OrbImage. Despite numerous launch failures, two of these three have currently operating satellites. Space Imaging's IKONOS satellite is providing imagery with

* Haller, L., and Sakazaki, M., "Commercial Space and United States National Security," Prepared for the Commission to Assess United States National Security Space Management and Organization, URL http://www.fas.org/spp/eprint/article06.html

resolution of 1 meter or slightly better, and Digital Globes' EarlyBird satellite is providing 0.6 meter imagery. In addition there is a very active value added industry, based upon both space-based and airborne remote sensing data. Internationally, ImageSat International is currently operating a satellite that provides 1.8 meter resolution data, and Sovinformsputnik is marketing access to Russian military satellite data with up to 1 meter resolution.

These are in addition to the worldwide capabilities to provide lower resolution data, from assets such as Landsat, SPOT, and IRS. The document "Trends in Space Commerce" from the US Department of Commerce provides a more complete discussion of commercially available satellite data.*

2.4 National and International Policy Context

The author conducted a systematic review of numerous policy documents. These include the 1958 Space Act that created NASA, past and present summaries of the National Space Policy from previous Presidential Administrations (an updated policy from the current Administration is not available yet), and space policy statements from the Rumsfeld Commission Report. These sources, both National and International, repeat consistent themes. The following table is a synthesis of these documents and sources, with representative traceability to key sources.

Table 8: Larger Context Goals, Traced to Representative Sources

Intent	Space Act/National Space Policy	International Space Law	Rumsfeld Commission/ National Security Space
Peaceful Purposes, Benefit of All Mankind	✓	✓	✓
International Scientific Cooperation	✓	✓	✓
Broad Scientific and Engineering Community Involvement	✓		
Wide Dissemination of Results	✓		
US Technological Preeminence	✓		✓
US Commercial Development	✓		✓
Cadre of Space Professionals			✓

The following summarizes these sources. Some are quoted directly while others are shortened and summarized. **Bold text** indicates elements that relate to and support the larger context goals indicated in the table above.

* U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

2.4.1 The Space Act

The National Aeronautics and Space Act of 1958 is the law that created NASA.[*] The following summarizes the National Space Policy, objectives, and functions of NASA from the Space Act.

The following bullets summarize US space policy as described in the Space Act (Title I, Section 102, and Title IV):

- **Peaceful Purposes for the Benefit of All Mankind**
- Responsibility of a Civilian Agency (NASA)
  - Except Weapons Systems, Military Operations, or the Defense of the United States
- **Seek and Encourage Commercial Use of Space**
- Specific Charter for Ozone Monitoring (Title IV)
- Also Includes "Clean Car" and Bioengineering Research

The following is a summary of NASA's objectives, from the Space Act (Title I, Section 102):

- The Expansion of Human Knowledge of the Earth and of Phenomena in the Atmosphere and Space
- The Improvement Aeronautical and Space Vehicles
- The Development and Operation of Space Vehicles
- Long-range Studies of Aeronautical and Space Activities
- **US Leadership in Aeronautical and Space Science and Technology**
- Coordination of Discoveries With US Military and Civilian Agencies
- **Cooperation With Other Nations and Groups of Nations**
- Effective Utilization of US Resources to Avoid Unnecessary Duplication of Effort, Facilities, and Equipment
- **US Preeminent Position in Aeronautics and Space Through Research and Technology Development** Related to Associated Manufacturing Processes

The following summarize NASA's functions, from the Space Act (Title I, Section 203):

- Plan, Direct, and Conduct Aeronautical and Space Activities
- Arrange for **Scientific Community Participation in Planning and Conducting Scientific Measurements and Observations**
- **Provide for the Widest Practicable and Appropriate Dissemination of Information** Concerning NASA Activities and Results
- **Seek and Encourage the Fullest Commercial Use of Space**
- **Encourage Federal Government Use of Commercially Provided Space Services and Hardware,** Consistent With Requirements

[*] U.S. Public Law, "The National Aeronautics and Space Act of 1958," Public Law number 85-568, as Amended, URL http://www.hq.nasa.gov/ogc/spaceact.html, from Title I, Sec. 102 & Title IV.

2.4.2 National Space Policy

The author reviewed current and past National Space Policy statements. These show considerable consistency. The following summarizes these Presidential policy statements from the last 20 years.

The following summarizes the National Space Policy goals from the early Regan Administration (1982):*

- Strengthen the Security of the United States
- Maintain **United States Space Leadership**
- **Obtain Economic** and Scientific **Benefits Through the Exploitation of Space**
- **Expand United States Private-sector Investment and Involvement in Civil Space and Space-related Activities**
- **Promote International Cooperative Activities** That Are in the National Interest
- **Cooperate With Other Nations** in Maintaining the Freedom of Space for All Activities That Enhance the Security and Welfare of Mankind

The following summarizes the National Space Policy goals from the late Regan Administration (1988):†

- To Strengthen and Security of the United States
- To Obtain **Scientific, Technological, and Economic Benefits** for the General Population and to Improve the Quality of Life on Earth Through Space-related Activities
- To Encourage Continuing **United States Private-sector Investment in Space and Related Activities**
- To **Promote International Cooperative Activities** Taking Into Account United States National Security, Foreign Policy, Scientific, and Economic Interests
- To **Cooperate With Other Nations** in Maintaining the Freedom of Space for All Activities That Enhance the Security and Welfare of Mankind; And, As a Long-range Goal
- To Expand Human Presence and Activity Beyond Earth Orbit Into the Solar System

* The White House, "National Security Decision Directive Number 42, National Space Policy," July 4, 1982.
† The White House, "Fact Sheet, Presidential Directive on National Space Policy," February 11, 1988, URL http://www.hq.nasa.gov/office/pao/History/policy88.html. The actual policy statement is classified, and only this fact sheet is publicly available.

The following summarizes the National Space Policy goals, still formally in effect, from the Clinton Administration (1996):*

- Enhance Knowledge of the Earth, the Solar System and the Universe Through Human and Robotic Explorations
- Strengthen and Maintain the National Security of the United States
- Enhance the **Economic Competitiveness, and Scientific and Technical Capabilities of the United States**
- Encourage State, Local and **Private Sector Investment In, and Use of Space Technologies**
- **Promote International Cooperation** to Further U.S. Domestic, National Security, and Foreign Policies

The Rumsfeld Commission has recommended an update to the National Space Policy. The recommendations are included under the Summary of National Security Space Policy below.

2.4.3 National Security Space Policy

Due to its classified nature, little information about National Security space activities is publicly available. Before his nomination for the position of Secretary of Defense in the current Bush Administration, the Honorable Donald Rumsfeld chaired the Commission to Assess United States National Security Space Management and Organization. Much of the information on National Security space activities in this thesis is drawn from this public report. The author also reviewed recent public Congressional testimony concerning National Security space activities. These sources were consistent with the Rumsfeld Commission report.

The following is a summary of National Security Space Policy, as represented by the Rumsfeld Commission report.† America's Interests in Space Are To:

- Promote the **Peaceful Use of Space**
- Use the Nation's Potential in Space to Support Its Domestic, **Economic, Diplomatic and National Security Objectives**
- Develop and Deploy the Means to Deter and Defend Against Hostile Acts Directed at U.S. Space Assets and Against the Uses of Space Hostile to U.S. Interests

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* The White House, National Science and Technology Council "Fact Sheet, National Space Policy," September 19, 1996, URL http://www.ostp.gov/NSTC/html/fs/fs-5.html. The actual policy statement is classified, and only this fact sheet is publicly available.

† Rumsfeld, D., chair, "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

Integrated Earth and Space-Based Observation Network for Earth Science

As mentioned above, the Rumsfeld Commission report recommends updating to the National Space Policy. The Commission recommends that this policy provide the following direction:

- Employ space systems to help speed the transformation of the U.S. military into a modern force able to deter and defend against evolving threats directed at the U.S. homeland, its forward deployed forces, allies and interests abroad and in space.
- Develop revolutionary methods of collecting intelligence from space to provide the President the information necessary for him to direct the nation's affairs, manage crises and resolve conflicts in a complex and changing international environment.
- Shape the domestic and international legal and regulatory environment for space in ways that ensure U.S. national security interests and enhance the **competitiveness of the commercial sector** and the effectiveness of the civil space sector.
- Promote **government and commercial investment in leading edge technologies** to assure that the U.S. has the means to master operations in space and compete in international markets.
- **Create and sustain within the government a trained cadre of military and civilian space professionals**

Indicating that the Rumsfeld Commission supports International Scientific Cooperation requires some interpretation. The actual recommendation wording is, "Use the nation's potential in space to support its domestic, economic, diplomatic and national security objectives." In addition, the report acknowledges, "Civil activity will involve more nations, international consortia and non-state actors." Later, in the body of the report (page 75) it states:

> Multinational alliances can increase U.S. space capabilities and reduce costs, as well as give the U.S. access to foreign investment, technology and expertise. Fostering these alliances can help maintain the U.S. position as a leader in the global space market. Civil multinational alliances provide opportunities for the United States to promote international cooperation and build support among other countries, especially emerging space-faring nations and developing countries, for U.S. positions on international policy or regulatory concerns.

International scientific cooperation is a longstanding part of national space policy. This, and the text from later in the document, indicates support for international scientific cooperation in civil space missions.

2.4.4 International Space Law

The following is a summary in bullet form of International Space Law, drawn mainly from the Law and Policy Considerations chapter of the book *Space Mission Analysis and Design*.*

- Outer Space Treaty of 1967
    - **International Cooperation** Is Essential and Encouraged
    - In the **Common Interest of All Mankind**
    - **Benefit All Peoples**
- Principles Relating to Remote Sensing of the Earth From Space (UN Resolution, 1986)
    - Applies to Sensing "for the Purpose of Improving Natural Resource Management, Land Use and Protection of the Environment"
    - "Open Skies" Policy
        - Do Not Need Permission of Observed Nation
        - Primary (Unenhanced) Data to Observed Nation at Reasonable Cost

2.5 Working Goal for the Purposes of this Thesis

In order to clarify and focus the work in this thesis, the author developed the following goal for the NASA Earth Science Enterprise. This goal reflects a synthesis of the current NASA Earth Science Enterprise goals as well as the larger policy context. This is a working goal for the purposes of this thesis only. This goal statement has been shared with but has not been endorsed by NASA senior management.

Earth Science Enterprise Working Goal for this Thesis

The goal of the Earth Science Enterprise is to characterize the Earth system, understand how it is changing, and predict the consequences for life on Earth, by observing, analyzing, and modeling the Earth using Earth- and space-based observation systems, global information systems, and global modeling systems.

In pursuing this goal, the Earth Science Enterprise will broadly involve the International science community, demonstrate the application of its results for societal and economic benefit, produce and employ innovative technologies, encourage US commercial capabilities, and develop a cadre of US space professionals in government, academia, and industry.

* Wirin, W., "Law and Policy Considerations," Section 21.1 of *Space Mission Analysis and Design*, 3rd Edition, 1999, Wertz, J., and Larson, W., editors.

This goal statement follows a particular semantic template for goal statements.* This structure is a valuable tool for checking goal statements for consistency and completeness. The following table indicates the specific elements of the goal statement.

Table 9: Goal Element Framework for Working Goal

Goal Element	Specific Instantiation
Intent (To)	Characterize the Earth System, Understand How It Is Changing, and Predict the Consequences for Life on Earth
Processes (By)	Observing, Analyzing, and Modeling
Operand	The Earth
System Form (Using)	Earth- and Space-based Observation Systems, Global Information Systems, and Global Modeling Systems
Larger Context Goals	• Broadly Involve the International Science Community • Demonstrate the Application of Results for Economic and Societal Benefit • Produce and Employ Innovative Technologies • Encourage US Commercial Capabilities • Develop a Cadre of US Space Professionals in Government, Academia, and Industry

The remainder of this thesis focuses specifically on the architecture of the Earth- and space-based observation systems. It does not specifically address the global information systems or global modeling systems.

The global information systems, the global modeling systems, and the larger context goals listed above could each be a thesis on their own. In parallel with this Master's thesis effort, Jen-Chow Duh is preparing a thesis focused on a systematic examination of the Earth Science Enterprise technology development effort. The other areas remain for future work.

For the purposes of this thesis, the boundary of the Earth system is defined as the top of the Stratosphere. This is consistent with the current division of responsibility between the Earth and Space Science Enterprises at NASA. This division ignores critical effects that tend to occur on much longer timescales, but that have shaped the Earth system. These include Sun-Earth system interactions, such as variation in the Solar "constant" and the top of the atmosphere chemistry and physics that are the boundary conditions for the Earth system. The NASA Space Science Enterprise "Living With a Star" Initiative is developing important insights in these areas. These also include catastrophic cosmic events, such as comet or asteroid impacts and near-by supernova or other energetic astronomical events.

* Crawley, E., Lecture Slides, System Architecture, Massachusetts Institute of Technology, course number ESD.34j/16.882j, Fall 2001.

Chapter 3: Functional Goals for the Integrated Earth- and Space-Based Observation System

3.1 Chapter Summary

This chapter develops functional goals for the Integrated Earth- and Space-based Observation System. After defining four levels of decomposition (levels 0 through 3), the approach is to skip or "zoom" to the individual mission level (Level 3). The thesis examines the processes and intents for generic Earth- and space-based observation missions. It then uses state-of-the-art knowledge and the physical constraints of Earth- and space-based observation missions to develop Level 3 functional goals. These level 3 goals are used to develop and check for completeness the level 2 functional goals for the integrated multi-mission system.

The following table lists the level 2 functional goals developed in this chapter. The three intent statements are used in chapter 4 to organize the discussion of Earth- and space-based observing system concepts.

Table 10: Level 2 Functional Goals for the Integrated Earth- and Space-based Observation System

Intent	Process	Operand/Modifiers
To Enhance the Synergistic Benefits of Multiple Measurement Capabilities	By Coordinating Nationally and Internationally	The Identification, Selection, and Development of New Missions
	By Enabling	The Operational Coordination of Mission Observations
To Maintain and Upgrade the Multi-Mission Measurement System	By Developing	New Observation Techniques, Instruments, and Components
	By Developing	New Mission Platform Technologies for: • Guidance (Position Control) • Attitude (Orientation) Determination and Control • Observation Physical Support (Power, Heating/Cooling, etc.)
	By Improving	The Mission Development Process
	By Developing	Servicing/Repair or Partial Replacement of Mission Capabilities
	By Safely Disposing of	Mission Assets at Their End of Life
(continued)		

Intent	Process	Operand/Modifiers
To Leverage Multi-Mission Economies of Scale	By Ensuring	The Availability of Multi-Mission Infrastructures for: • Conveying Observation Results • Communicating Command and Engineering Data • Launching and Deploying Missions • Navigating Missions • Operating Missions • Mission Development and Manufacture

3.2 System Decomposition Definition and Rationale

This thesis defines four levels of decomposition. The following figure depicts these levels.

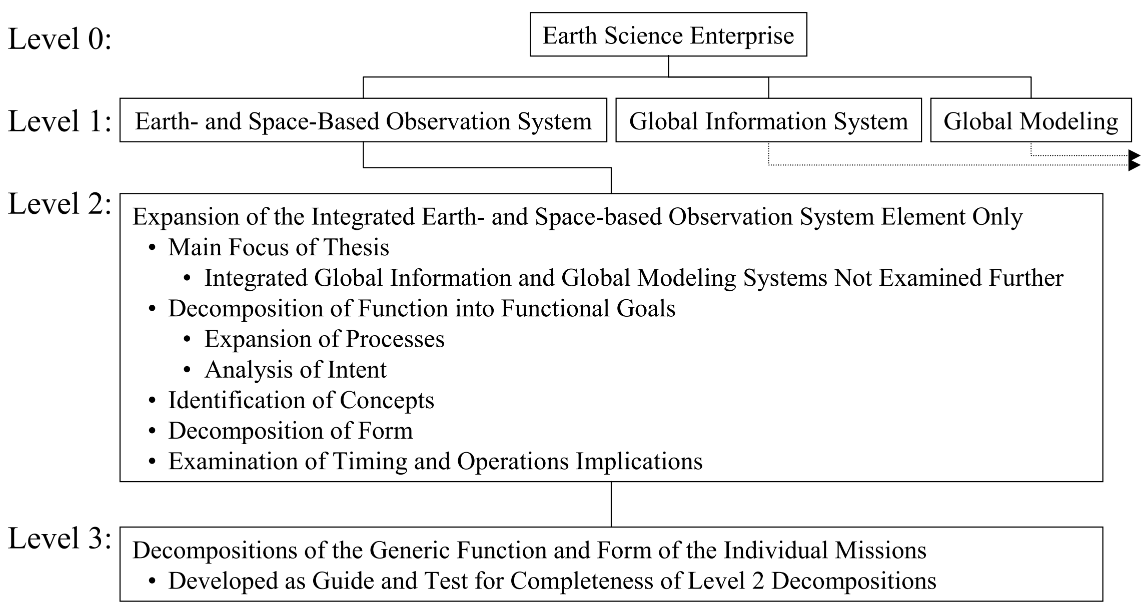

Figure 9: Levels of Decomposition Used in This Thesis

Level 0 treats the Earth Science Enterprise as a whole. Level 3 (the lowest level) treats the individual missions as the building blocks or modules for the system. This has significant advantages and allows the development of a generic description of the processes used by individual missions to perform their functions:

- The basic limits of physics and the state of technology development constrain the implementation of individual missions.

- Individual missions build upon worldwide experience and the state-of-the-art in space mission design. By comparison, the world does not have nearly the same experience building and operating multi-mission systems.
- Treating individual missions as modules creates a structure that allows mission innovation and provides a pathway for innovation into the multi-mission system.

A few practical and basic limits shape the design of any individual mission. Basic laws of physics restrict mission processes and form (for foreseeable future). This thesis uses the implications of these limits to define the basic processes and form of missions without specific insight into their internal implementation. This is treating the missions as "black box" modules with no visibility into the internal structure. As will be argued more extensively in the chapter on form, the extensive worldwide experience base and state-of-the-art practice in space mission design enables a generic view of both the processes and form of missions. This chapter focuses on these generic processes to develop level 3 and level 2 functional goals.

The act of sensing requires physical interaction with the sensed phenomena, which in turn requires the physical presence of hardware. Gravity, buoyancy, lift, drag, and momentum limit the sensing vantage options. Space missions are restricted to Keplerian (or near-Keplerian) orbits. Earth-based missions are constrained by the capabilities of balloons, unmanned aerial vehicles (UAVs), ocean buoys, etc. Missions are limited by the ability to develop, position, command, control, etc. The ability to return sensing results also places limits, and implies remote communications (radio or optical), although some missions physically return media or samples. Kramer also discusses these fundamental limits."[*]

Providing a pathway for infusing new technology is another reason for viewing the individual missions as the level 3 building blocks for the system. The larger Earth science community continues developing new and innovative observation approaches and mission technologies. The strategic architecture should allow innovative mission approaches and be robust to significant innovations in the technologies and techniques for Earth observation missions.

The structure used for this thesis does not assume any particular mission implementation approach. Christensen et al argue that the emergence of a dominant *architectural* design in a technology or industry is a key evolutionary step. They describe this dominant architectural design a the "concepts that define how the components within the product interact or related to one another"[†] A dominant architectural design provides a framework for innovation at the next level down, for the components of the architecture. Creating a level 2 architectural design that treats the individual missions (level 3) as the "components" of the larger Integrated Earth- and

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[*] Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002, section 1.2, "Fundamental Science Limits in Space Flight and Earth Observation."

[†] Christensen, C., Suarez, F., and Utterback, J., "Strategies for Survival in Fast-Changing Industries," Management Science, Vol. 44, No. 12, December 1998, pg. S208. "…concepts that define how the components within the product interact or related to one another (Henderson and Clark 1990)."

Space-based Observation System should create a pathway for infusing new technology and allow level 3 mission developers to focus their creative efforts.

3.3 Individual Mission and Multi-Mission Processes

This section examines the processes of individual Earth- and space-based observation missions in order to refine the intent and develop Level 3 functional goals for individual missions. The approach, suggested by the lecture notes of Professor Edward Crawley, is to progressively examine the primary processes that the mission delivers, the processes that support the primary processes, the processes involved in the deployment and operation of the system, and the processes involved in maintaining and upgrading the system.*

The following figure graphically represents this expansion of mission processes.

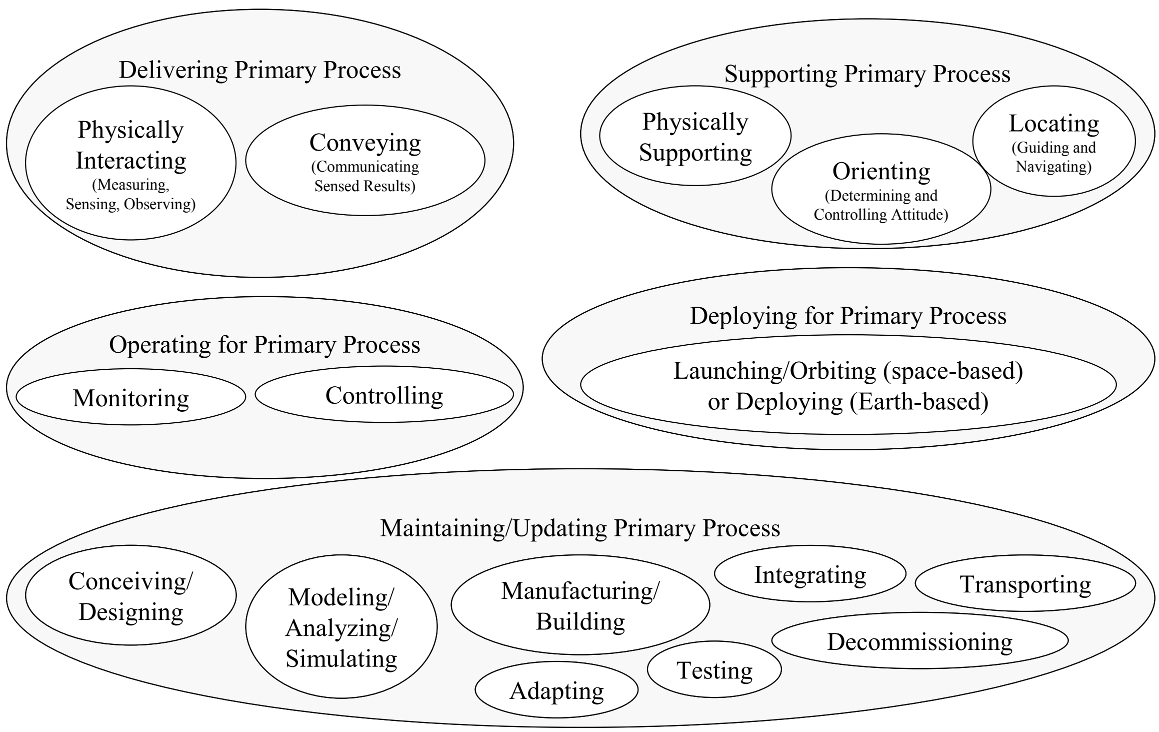

Figure 10: Expansion of Mission Level (Level 3) Processes and Mission Maintenance and Updating Processes

* Crawley, E., Lecture Slides, System Architecture, Massachusetts Institute of Technology, course number ESD.34j/16.882j, Fall 2001.

The use of the terms *navigation*, *guidance*, *attitude determination*, and *attitude control* follows that in the book *Space Mission Analysis and Design*.[*] Navigating and determining the attitude are passive measurement processes, while guiding and controlling the attitude are active control processes.

The individual-mission expansion (zooming) of the generic mission processes is provided in the following table.

Table 11: Individual Mission Decomposition (Zooming) of Generic Processes

Generic Processes	Mission Specific Processes	
Delivering the Primary Processes	Physically Interacting (Measuring, Sensing, or Observing)	
	Conveying (Communicating) the Results of Physical Interaction	
Supporting the Primary Processes	Navigating (Determining the Location) and Guiding (Controlling the Location)	
	Determining and Controlling the Attitude (Orientation)	
	Physically Supporting (Mechanically Supporting, Protecting, Powering, Heating/Cooling, etc.)	
Deploying for the Primary Processes	Launching (Space-based) or Deploying (Earth-based) Missions	
Operating the Primary Processes:	Monitoring and Controlling	
Maintaining/Upgrading the Primary Processes	Developing new, improved, and replacement missions	Conceiving/Designing
		Modeling/Analyzing/Simulating
		Manufacturing/Building
		Integrating
		Testing
		Adapting
		Transporting
	Decommissioning missions at end-of-life	

The author considered whether to include the processes of the development system (maintaining/upgrading the primary processes) as part of the missions at level 3 or as part of the multi-mission system at level 2. The current state-of-practice supports the multi-mission, level 2 view of individual mission development activities. However, individual missions must compatible with the larger design, development, and manufacturing lifecycle. These processes have a major influence on the system at level 3. For this reason, figures in this chapter and in the form chapter include the development process at level 3, separated and in some cases indicated by *italics*.

[*] Wertz, J., "Guidance and Navigation," Chapter 11.7 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

3.4 Individual Mission (Level 3) Functional Goals

Based upon the examination of these limitations and detailed processes, the author identified the individual mission level functional goals in the following table.

Table 12: Individual Mission Level (Level 3) Functional Goals

Intent	Process	Operand/Modifiers
To Obtain Measurements	By Physically Interacting with	The Earth System
To Provide Measurement Results	By Conveying	The Data to the Users, Operators and the Information and Modeling Systems, and for Use by the Level 2 System
To Position (Locate and Orient) the Measurement Capability as Necessary for the Physical Interaction	By Launching (Space-Based) or Deploying (Earth-based)	The Mission as Required
	By Guiding (Locating)	The Mission Observation System as Required
	By Controlling the Attitude of (Orienting)	
To Determine the Position from which the Measurement Physical Interaction was Obtained	By Navigating (Determining the Location)	The Mission Observation System as Required
	By Determining the Attitude (Orientation) of	
To Provide the Physical Conditions (Mechanical Support/Protection, Power, Heating/Cooling, etc.) Necessary for the Measurement Physical Interaction	By Supporting	The Mission Observation System as Required
To Coordinate, Correct, and Adapt Operation of the Mission and Measurement System	By Monitoring and Controlling	The Mission and Its Operation

3.5 Multi-Mission System (Level 2) Functional Goals

This level 3 or mission level decomposition of functional goals is then used to develop multi-mission observation system functional goals at the next higher level (level 2). These Level 2 functional goals are shown in the table at the opening of this Chapter, and are repeated here.

Table 13: Level 2 Functional Goals for the Integrated Earth- and Space-based Observation System

Intent	Process	Operand/Modifiers
To Enhance the Synergistic Benefits of Multiple Measurement Capabilities	By Coordinating Nationally and Internationally	The Identification, Selection, and Development of New Missions
	By Enabling	The Operational Coordination of Mission Observations
To Maintain and Upgrade the Multi-Mission Measurement System	By Developing	New Observation Techniques, Instruments, and Components
	By Developing	New Mission Platform Technologies for: • Guidance (Position Control) • Attitude (Orientation) Determination and Control • Observation Physical Support (Power, Heating/Cooling, etc.)
	By Improving	The Mission Development Process
	By Developing	Servicing/Repair or Partial Replacement of Mission Capabilities
	By Safely Disposing of	Mission Assets at Their End of Life
To Leverage Multi-Mission Economies of Scale	By Ensuring	The Availability of Multi-Mission Infrastructures for: • Conveying Observation Results • Communicating Command and Engineering Data • Launching and Deploying Missions • Navigating Missions • Operating Missions • Mission Development and Manufacture

Chapter 4: Concept Options for the Integrated Earth and Space-Based Observation System

4.1 Chapter Summary

This chapter uses the level 2 functional intent statements from the previous chapter to organize descriptions of current and proposed multi-mission system concepts. These include historical concepts, currently used concepts, and concepts that have been proposed in various publications. These concepts may be methods, tools, policies, or mission implementation approaches to meet the intent statements in the functional goals. Examples range from policy mechanisms for National and International coordination to the current multi-mission systems to guide and navigate missions. The author used these concepts to gain insight into future architecture options. These concepts helped refine the functional goals developed in the previous chapter and the decomposition of form developed in the next chapter.

For example, this chapter examines International planning and mission coordinating mechanisms. The chapter develops a structure for categorizing distributed observation systems by considering the spatial distribution of the measurements, the nature of the measurements, and the degree of real-time coordination required for the measurement. This chapter examines system communication and navigation approaches, including likely cumulative data rates and the implications for use of radio or optical communications.

Aspects of the multi-mission development system were highlighted in this chapter, both for maintaining and upgrading the multi-mission system and for leveraging economies of scale. The views for the next two chapters, multi-mission system form (chapter 5) and multi-mission timing and operation (chapter 6), also highlighted aspects of the development system. For readability and consistency, the discussion of the multi-mission development system is consolidated in this chapter. This consolidation includes current concepts and facilities (form) for the mission development system, as well as concepts to improve the development process and enable greater flexibility to match the timeframe of major stakeholders (timing and operations considerations).

4.2 Concepts to Enhance the Synergistic Benefits of Multiple Measurement Capabilities

4.2.1 Identification, Selection, and Development of New Missions

This section describes the concepts that the NASA Earth Science Enterprise uses to coordinate the planning of measurement missions. This includes developing clearly defined measurement requirements in a widely reviewed and vetted research strategy, establishing International agreements for mission implementations, and participating in the Integrated Global Observing Strategy (IGOS) and the Committee on Earth Observation Satellites (CEOS).

Science Research Strategy

One of the key concepts to coordinate the multi-mission measurement capability is to clearly identify measurement requirements in the Science Research Strategy.[*] This clear and public summary, with its validated scientific focus, has gone through extensive community and national academy input and review. It has also been validated for attainability. To scope the total system affordability, the NASA centers have developed specific mission implementation concepts and evaluated them for cost and feasibility. The NASA Earth Science Enterprise has used these to validate both the cost feasibility and overall technical feasibility of this research measurement set.

The Science Research Strategy identifies the following classes of research measurements:

Systematic Measurements: A select number of critical environmental parameters, mainly those that cannot be inferred from other parameters, require long-term and typically (but not always) continuous measurement. Systematic measurement missions are often replacing ongoing missions to assure continuity of long-term climate records. This adds to the complexity of these missions by adding compatibility and continuity constraints. Technology improvements for systematic measurements can improve capability, but must maintain “backward compatibility” with the legacy system.

Exploratory Measurements: These measurements yield new science breakthroughs by providing comprehensive information about a particular Earth system component or process. Exploratory measurement missions are typically one-time missions addressing a focused set of science questions. NASA seeks to allow the proposing community the maximum flexibility to establish specific mission goals that address subsets of the overarching measurement requirements.

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[*] NASA, “Understanding Earth System Change NASA's Earth Science Enterprise Research Strategy for 2000 - 2010,” December 2000, URL http://www.earth.nasa.gov/visions/researchstrat/Research_Strategy.htm

Operational Precursor and Technology Demonstration Missions: These missions demonstrate new instruments and related technologies. They either enable a transition to an operational system or demonstrate a new capability for research.

- **Operational Precursor Missions** develop measurements for future operational systems. These typically require partnership with or sponsorship from an operational agency. Operational agencies can take more than a decade from agreement to launch of a new capability. NASA will often work with the operational partner to build a "bridge mission" during this period.
- **Technology Demonstration Missions** demonstrate key technologies that require validation in space before they can be incorporated into mission from the above classes. Ensuring that the technologies needed to implement a mission are mature before the final commitment to implementation is part of NASA's approach to shorten the mission development time and cost.

The following table lists the twenty-three measurements identified in the Science Research Strategy.

Table 14: Measurement Requirements for NASA Earth Science Research Strategy

Variability	Forcing	Response	Consequence	Prediction
Precipitation, evaporation & cycling of water changing? (S&E)	Atmospheric constituents & solar radiation on climate? (S)	Clouds & surface hydrological processes on climate? (S&E)	Weather variation related to climate var-iation? (P/S/E)	Weather forecasting improvement? (P/S/E)
Global ocean circulation varying? (S)	Changes in land cover & land use? (S)	Ecosystem re-sponses & affects on global carbon cycle? (P/S/E)	Consequences in land cover & land use? (S)	Transient climate variations? (S&E)
Global ecosystems changing? (S)	Surface trans-formations? (E)	Changes in global ocean circulation? (S&E)	Costal region change? (P/S/E)	Trends in long-term climate? (M)
Stratospheric ozone changing? (S)		Stratospheric trace constituent responses? (S&E)		Future atmos-pheric chemical impacts? (M)
Ice cover mass changing? (S)		Sea level affected by climate change? (E)		Future concentrations of carbon dioxide and methane? (M)
Motions of Earth & interior processes? (E)		Pollution effects? (E)		

This table does not appear in the research strategy in this form, but is from a contemporaneous viewgraph summary. In this table, (S) indicates that the measurement requires systematic satellite observations, (E) indicates that the measurement requires exploratory satellite observations, (P/S/E) indicates that the measurement requires pre-operational and/or systematic/exploratory observations, and (M) indicates that the measurement can use available/new observations in better models.

The method used to translate subsets of the measurement requirements into mission-specific goals varies with the mission class. In general, NASA strives to specify high-level goals in a way that leaves open the broadest range of implementation options, effectively defining the external functional goals that are driven by science needs combined with constraints such as NASA and National policy requirements and budget limitations. Within these limitations, NASA strives to give the proposing community the widest possible flexibility to trade goals against form and function, proposing the specific mission goals to meet a subset of the overarching science needs while satisfying the high-level constraints.

In addition, the mission selection process is designed to help coordinate newly selected missions with existing and planned capabilities. This is an explicit evaluation consideration for the proposal evaluation science peer review panel. The selection official has the scientific and programmatic discretion to consider this factor when making final selection decisions.

International Coordination Mechanisms

There are also a number of International mechanisms to exchange information about observation plans that are intended to help coordinate measurement capabilities worldwide. Bilateral or government-to-government agreements are typically developed on a mission-by-mission basis. The partnership for the Integrated Global Observing Strategy (IGOS) involves both the Committee on Earth Observation Satellites (CEOS) and a number of United Nations organizations. Finally, professional society conferences and publications serve an important role in publicizing concepts, plans, and accomplishments.

Integrated Global Observing Strategy (IGOS)

The Integrated Global Observing Strategy (IGOS) is an international partnership uniting the major worldwide Earth- and space-based systems for observing the Earth.* It covers all forms of data collection, including research, long-term monitoring, and operational observation systems. It links data producers and users to help identify observation gaps and resources to fill these gaps. It is intended as a framework that individual funding agencies will use for decisions and resource allocations that will help reduce unnecessary duplication of observations. The IGOS is

* UNESCO, "What is IGOS?" World Wide Web page, URL http://uic.unesco.org/igosparnters/igoswhat.htm

focused on major thrusts that include strengthening space-based and *in situ* linkages; encouraging the transition from research to operational observations; improving data policies and the archiving of data; and increasing calibration, validation, quality assurance, and what is called harmonization so that data may be used more effectively.

IGOS is a partnership involving the Committee on Earth Observation Satellites and a number of the United Nations organizations described below. The IGOS partners meet twice per year in association with the plenary sessions of the Committee on Earth Observation Satellites. The first IGOS Partners Meeting was held in June 1998.

Committee on Earth Observation Satellites (CEOS)

The Committee on Earth Observation Satellites (CEOS) was created in 1984 to coordinate International civil space-borne missions designed to observe and study the Earth.[*] This coordination includes ensuring coverage of critical scientific questions relating to Earth observation and global change, and avoiding unnecessarily overlap of satellite missions. CEOS involves 41 space agencies and organizations. Individual participating agencies make their best efforts to implement CEOS recommendations.

The Committee on Earth Observation Satellites has three primary objectives, quoted here from the CEOS Terms of Reference document:[†]

1. To optimize the benefits of spaceborne Earth observation through cooperation of its Members in mission planning and in the development of compatible data products, formats, services, applications and policies.

2. To aid both its Members and the international user community by inter alia, serving as the focal point for international coordination of space-related Earth observation activities, including those related to global change.

3. To exchange policy and technical information to encourage complementarity and compatibility among spaceborne Earth observation systems currently in service or development, and the data received from them; issues of common interest across the spectrum of Earth observation satellite missions will be addressed.

[*] CEOS, "CEOS Overview," World Wide Web page, URL http://www.ceos.org/pages/overview.html
[†] CEOS, "CEOS Terms of Reference," World Wide Web page, URL http://www.ceos.org/pages/ceos_terms.html

United Nations Organizations

In addition to CEOS, various United Nations agencies, programmes, and funds support observations of the Earth system. These fall under the United Nations Economic and Social Council. Specialized Agencies involved in Earth observation include the Food and Agriculture Organization of the United Nations (FAO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the World Meteorological Organization (WMO). Programmes and Funds involved in Earth observation include the United Nations Environment Programme (UNEP).

These organizations jointly support activities such as the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS).[*, †] The Global Climate Observing System (GCOS), for example, "stimulates, encourages, coordinates, and otherwise facilitates the taking of needed observations by national and international organizations."[‡] It is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP), and the International Council for Science (ICSU). Other activities include the World Climate Research Program, the International Geosphere/Biosphere Programme, and the Intergovernmental Panel on Climate Change.

International Professional Societies

Finally, this and other studies have benefited greatly from the open exchange of plans and concepts through professional societies and conferences. For example, this thesis has drawn heavily from the proceedings of the 2000 and 2001 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2000 and IGARSS 2001) as a source for future mission concepts and plans.

4.2.2 Operational Coordination of Mission Observations

This section evaluates concepts for coordinating observation missions once they are built and operating. It includes a discussion of the original Earth Observing System approach, which enabled the coordination of multiple observations by placing them on integrated platforms. It also includes a discussion of distributed satellite concepts with both non-real-time and real-time coordination. These latter concepts, distributed missions with real-time coordination, match

* WMO, "Global Climate Observing System," World Wide Web page, URL http://www.wmo.ch/web/gcos/whatisgcos.htm
† WMO, "World Meteorological Organization, Basic Facts about the WMO," World Wide Web page, URL http://www.wmo.ch/web-en/wmofact.html
‡ WMO, "What is GCOS," World Wide Web page, URL http://www.wmo.ch/web/gcos/whatisgcos.htm

several of the published “sensorweb” concepts. The thesis proposes an approach and uniform terminology for categorizing these concepts.

Large, Integrated Platform Concept

The original (mid-1980’s) concept for the Earth Observing System was for two very large (school bus-sized) platforms in polar orbit, EOS-A and EOS-B. Most of the individual instruments co-located on each platform had strong justifications for simultaneous (or near simultaneous) and coordinated observations. For example, instruments intended to observe the Earth’s surface benefited from the co-observations of atmospheric instruments to calibrate the “dirty blue filter” and allow adjustment for atmospheric effects.

The intent was to launch these platforms into Sun-synchronous polar orbits using the Space Shuttle. These two platforms were part of the Space Station program. They were designed for servicing by astronauts during periodic revisits. The instruments were modular to facilitate this servicing. However, the goal of long-term continuity in the measurement data led to an approach that would replace instruments with identical copies over the 15-year life of the platforms.

Several events led to gradual but radical change in direction from the original large platform approach to the current approach of smaller, more flexible individual missions. The lack of flexibility of the large platform approach to budget changes was a consistent driver across the entire development of the EOS program. Budget changes are a fact of life for any large, multi-decade government-sponsored program. The following is a summary of the changes in rough chronological order.

The first major event was tragic loss of the Challenger in 1987. As a result of the reassessment of the entire shuttle program, NASA abandoned plans to launch the Space Shuttle into polar orbit from the Western Test Range, eliminating the possibility of astronaut servicing of the EOS platforms. Despite this change, as late as November 1989, the basic approach still held; two large platforms with no new technologies for either the platforms or the instruments over the 15-year life still held.[*]

During this period major NASA programs would undergo a Non-Advocate Review (NAR) as part of the approval process for development and implementation. For a variety of reasons, EOS went through both a NAR and a follow-up review, called the Delta-NAR. At the time of the Delta-NAR, a white paper prepared in response to questions about the requirement to co-locate instruments on the same platform identified four timeframes of coordination between observations. The four time frames are for measurements requiring observations within a few days (most of the aspects of the Earth system), within an hour (vegetation drying), within a

[*] NASA, untitled viewgraph presentation of the results of the EOS Delta NAR, November 1989. The author of this thesis was a member of the follow-up Non-Advocate Review Panel (Delta-NAR) for the Earth Observing System (EOS).

minute (atmospheric changes), and instantaneously (for certain instruments that require precise knowledge of spacecraft location).[*]

By the start of the 1990's the realization was growing that the advent of space-based tracking and navigation capabilities, along with improvements in computer technologies, significantly decreased the time and effort required to guide and navigate Earth orbiting satellites. Many of the operational justifications for not considering distributed satellites flying in close formation were beginning to erode in light of these new capabilities.

By 1991, a major budget reduction led to a review of the EOS platform configuration and launch sequence. This engineering review found that intermediate and small satellites in formation could meet the simultaneity requirements, and that a variety of smaller launch vehicles would soon be available to launch these satellites.[†] Continued budget pressure led to the EOS reshape studies in 1995 and 1996, and the basic configurations of the current EOS missions (Terra, Aqua, Aura, etc.).[‡, §]

Multiple, Distributed Mission Concepts

This section begins with a summary of papers that describe future mission concepts. Based upon this review of the literature, this thesis identifies three attributes of the relationship between multiple missions that forms the basis of a multi-mission classification scheme. The author draws upon many concept names already proposed or in common use and proposes a complete set of concept names.

Discussion of Recent "Sensorweb" Papers

Current missions provide examples of many of the non-real-time coordination concepts. Current Earth remote sensing satellites and most Earth-based remote and *in situ* sensors operate independently by executing preprogrammed sequences that are periodically updated by ground-based operators and operations systems. Any coordination of observations between missions must be preprogrammed and rely upon absolute references, such as time, position, and/or pointing/geolocation. Responses to unexpected or unusual events typically require ground-in-the-loop adaptation by the mission operations system.

[*] Butler, D., "Eos Requirements in Platform Sizing: A White Paper," undated, circa November 1989.
[†] Frieman, E., chair, "Report of the Earth Observing System (EOS) Engineering Review Committee," September 1991.
[‡] Price, R., "EOS Program Reshape Presentation to Payload Panel," NASA viewgraph presentation, June 29, 1995.
[§] NASA, "Reshape Implementation Options Study Presentation to the Administrator," (no author or presenter indicated), February 12, 1996.

The real-time, autonomous coordination of observations is the focus of majority of current Earth science "sensorweb" concept work. The various "sensorweb" concepts that have been described in Earth Science Enterprise vision statements and IGARSS papers all share this attribute. In general, the Earth science oriented descriptions of sensorweb concepts tend to emphasize distributed, heterogeneous observations that are widely distributed in vantage (e.g., *in situ*, airborne, low Earth orbit, as well as high orbit and sentinel locations). These Earth science sensor web concepts interact autonomously in near real time to adapt observations strategies in response to rapidly evolving phenomena. On the other hand, the space science oriented descriptions of sensorweb concepts tend to emphasis homogeneous observations that are mostly *in situ*, such as might be deployed on the surface of Mars.

The following summarizes concepts from numerous reports and papers.

Ticker and Azzolini describe four of the types of distributed spacecraft architectures, global constellations, virtual platforms, precise formation flying, and sensorwebs.[*]

- They describe constellations as distributed in time and space, providing multiple similar observation spacecraft to increase (temporal and/or spatial) coverage.
- They describe virtual platforms as nearly co-located in time and space, providing multiple distinct observations of the same location (e.g., to increase spectral coverage).
- They describe precise formation flying as a special case requiring precise knowledge or control of position.
- Finally, they describe Sensorwebs as having multiple vantage points, multiple sensor types, and using data fusion for real-time, autonomous measurement coordination. Ticker and Azzolini define sensorwebs (for the purpose of their study) as both distributed in orbit/vantage and complementary in observation type, stating that sensorwebs are "an architecture that utilizes multiple vantage points and a mixture of sensor types to achieve synergistic observations of the Earth."

The following figure from Ticker and Azzolini depicts the relationships or transformations between these four architectures.

[*] Ticker, R., and Azzolini, J., "2000 Survey of Distributed Spacecraft Technologies and Architectures for NASA's Earth Science Enterprise in the 2010-2025 Timeframe," NASA/TM-200-209964, August 2000.

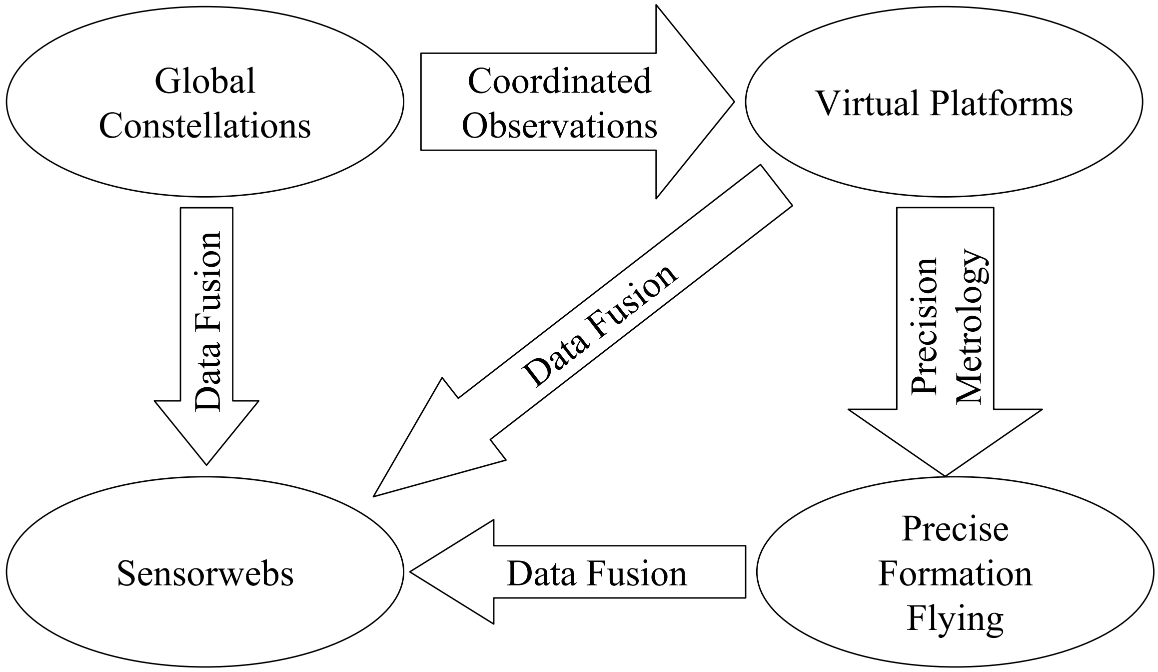

Figure 11: Notional Architecture Transformations (Ticker and Azzolini)

Ticker and Azzolini's classification of distributed spacecraft architectures views the distinction between Global Constellations and Virtual Platforms as the coordination of observations, the distinction between Virtual Platforms and Precise Formation Flying as the addition of precision metrology, and the unique attribute of Sensorwebs as the aspect of data fusion. In describing the characteristics of a Sensorweb, they state, "Data fusion and real-time measurement coordination and communication across platforms and systems create a leveraged system of systems." Similar heterogeneous and distributed sensorweb concept are discussed in numerous vision and strategic plan documents, as discussed earlier in this thesis.*

Kramer describes a number of multi-satellite observation concepts, particularly in section 1.3.3, "Cooperative Distributed Systems, Satellite Formations."† Kramer introduces the term "parasitic" in a discussion of multi-static sensing in which the passive receiving spacecraft use cartwheel orbits (originally proposed by CNES) and are "independent" of the transmitter function.

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* Asrar, G., "Earth Science Vision, Remarks of NASA Associate Administrator, Dr., Ghassem R. Asrar," International Geoscience and Remote Sensing Symposium, July 24, 2000, URL http://www.earth.nasa.gov/ebn/news00031.html

† Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002, section 1.3.3, "Cooperative Distributed Systems, Satellite Formations."

Several papers presented at the IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS 2001) provide further, and in some cases slightly contradictory discussions of the sensorweb concept.

Crisp et al describes an integrated web of surface, air, and in-space sensors that are coordinated by an advanced, semi-autonomous network.[*] This network would link the systems to each other, provide a seamless interface with data processing, and enable the system to rapidly assimilate, evaluate, and disseminate data and results. The sensorweb would include an enhanced space-based communications architecture to provide near real time access to data from all vantage points, continuously transmitting data at high communications bandwidth. This concept would require significant advances in spacecraft autonomy that enable the system to react autonomously in response to simple, goal-oriented commands. The paper describes the application of this sensorweb concept to a system to rapidly recognize, analyze, and disseminate information about natural hazards.

Peri, Hartley, and Duda describe a sensorweb approach that involves a large numbers of similar or identical frequency-agile instruments.[†] These hyperspectral remote sensing instruments would normally operate in lower resolution monitoring modes that would use techniques such as spectral band aggregation, spatial averaging, data selection, and compression to reduce the monitoring data rate. However, the system would be capable of autonomous event detection and real-time adaptive operation. When an event is detected, the system would adapt in real-time to higher resolution probing modes.

In a sense, this is a hybrid sensorweb concept, in which the hardware is capable of similar observations from distributed orbits and vantages, but might autonomously elect to obtain complementary subsets of observations in order to reduce data rates or user information overload.

Prescott, Smith, and Moe describe a sensorweb concept in which all instruments are independently controlled either directly by ground command (for example, giving an investigator direct command authority over an instrument), or autonomously by the integrated sensor-web system itself.[‡] The instruments would be networked into an organic measurement system, with each satellite able to act autonomously to significant events by making adjustments such as increasing precision and coverage where needed. This closely integrated constellation would

[*] Crisp, D., Delin, K., Chao, Y., Lemmerman, L., Torres, E., Paules, G., "Earth Science System of the Future: Observing, Processing, and Delivering Data Products Directly to Users," IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS 2001), July 9-13, 2001.

[†] Peri, F., Hartley, J., Duda, J., "The Future of Instrument Technology for Space-based Remote Sensing for NASA's Earth Science Enterprise," IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS 2001), July 9-13, 2001.

[‡] Prescott, G., Smith, S., Moe, K., "Information System Technology Challenges for NASA's Earth Science Enterprise," IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS 2001), July 9-13, 2001.

normally act autonomously in controlling instruments and spacecraft, but be able to respond immediately to the commands of the user. The real-time information systems would support on-board processing and intelligent sensor control, high data rate transmission and network control, intelligent platform control, and information production, distribution and storage.

The concept of the user having the ability to exercise real-time control over the system, while adding complexity, is comparable to the user input being the highest-level event trigger that alters the response of the system. Therefore the analysis in this thesis does not treat this as a unique driver.

Lemmerman, et al, describes a distributed, heterogeneous, adaptive, cooperating macro-instrument concept, coordinating efforts between multiple numbers and types of orbital and terrestrial sensing platforms, both fixed and mobile.* In this concept, information is shared and used across the system. Each element communicates within its local neighborhood, distributing information to the whole. The architecture would allow obsolete or damaged elements to be replaced with minimal impact. The web could be expanded over time as resources and budgets allow, using the same techniques as networks on Earth. The paper summarizes the major technical challenges in software (protocols, information security, and network reliability) and hardware (miniaturized and agile hardware elements). The space elements in the network face additional challenges unique to the space environment, including infrequent contacts, asymmetric links, high time delays, and increased bit error rates. The sub-space (or Earth-based) portion of the sensor web could leverage existing and evolving terrestrial Internet protocols, such as mobile ad hoc networking.

In addition to these IGARSS papers, a number of other papers describe slightly different concepts of sensorwebs. In particular, Delin outlines "the potential of the Sensor Web concept" and describes, "How the Jet Propulsion Laboratory Sensor Webs Project ... uses a set of criteria in evaluating Sensor Web applications."† The observations used as examples in this paper tend to be similar but not always identical. An example is a distributed network of less accurate sensors to provide earlier detection with occasional high accuracy sensors to provide calibrated observations. The emphasis in this concept and definition of a sensor web is not on differentiation between sensor types, but on the sharing and use of data among "pods" in the sensor web, providing real-time interaction and adaptive sensing strategies.

Finally, a recent summary paper (submitted for IGARSS 2002) identifies the following unique architectural properties for these concepts.‡

* Lemmerman, L., Delin, K., Hadaegh, F., Lou, M., Bhasin, K., Bristow, J., Connerton, R., Pasciuto, M., "Earth Science Vision: Platform Technology Challenges," IEEE 2001 International Geoscience and Remote Sensing Symposium (IGARSS 2001), July 9-13, 2001.

† Delin, K., "The Sensor Web: A New Way to Monitor Environments," Jet Propulsion Laboratory undated white paper.

‡ Torres-Martinez, E., Schoeberl, M., and Kalb, M., "A Web of Sensors: Enabling the Earth Science Vision," submitted for the IEEE 2002 International Geoscience and Remote Sensing Symposium (IGARSS 2002).

- Autonomy: adapt and take advantage of opportunities under uncertain conditions.
- Heterogeneity: dynamically accommodate diverse combinations of hardware and software components.
- Scalability: dynamic addition and retirement of assets.
- Human-interface consistency: human understanding and control of emergent, collective sensorweb behavior.

As long as "heterogeneity" is not interpreted as requiring that the observation type be heterogeneous, but rather that the configurations are heterogeneous in that they can change rapidly due to orbital motion, this represents a concise but accurate and inclusive summary of the architectural issues concerning the sensorweb concepts.

With a few exceptions the conceptual papers do not really address how the nodes of the sensorweb will connect. This thesis will describe a number of network link topologies and discuss their implications in the next chapter, which discusses system form.

Classification of Multiple Satellite Observation Concepts

In examining and trying to reconcile these related but slightly different multi-mission observation concepts, the author identified three attributes that could be used as a basis for classification. The three attributes are:

1. *Position/Vantage*: Whether either the observed locations or the observation vantage points are:
   - *Distributed*: widely distributed in space, typically with global coverage.
   - *Aligned*: generally aligned, typically with the precision available through standard methods, as in the current Terra/Landsat-7/EO-1/SAC-C satellite train.
   - *Precise*: using precise control or knowledge beyond that generally available, requiring additional hardware or unusual operating procedures, as is needed to recover the gravity signal from the GRACE mission. Ticker and Azzolini use the term Precision Formation Flying, and make a distinction between Virtual Platforms and Precision Formation Flying.[*] This recognizes that some mission concepts require knowledge and/or control of the relative positioning of satellites to accuracies that exceed by several orders of magnitude what is possible with GPS and other standard techniques.
2. *Observation Type*: Whether the types of observations are:
   - *Complementary*: using different instrumentation, as in infrared observations that complement visible observations, or cloud contamination measurements to complement land surface observations.

[*] Ticker, R., and Azzolini, J., "2000 Survey of Distributed Spacecraft Technologies and Architectures for NASA's Earth Science Enterprise in the 2010-2025 Timeframe," NASA/TM-200-209964, August 2000.

- *Similar*: using the same or related instrumentation to obtain similar observations, as in global coverage with multiple copies of the same instrument, as in stereo imagery, or as are the microwave links in the GRACE mission.

3. *Coordination*: The degree to which the coordination of the observations is:
   - *Ground*: pre-scheduled with the ground-in-the-loop, as is the common practice today.
   - *Autonomous*: performed autonomously and in real-time, as in the descriptions of the sensorweb concepts.

The following table uses these attributes to classify multiple satellite observation concepts, cites examples, and proposes names for each type of concept, building upon concept names that are already in use.

Table 15: Three-Attribute Classification of Multiple Satellite Observation Concepts with Proposed Concept Names and Examples

Proposed Concept Name	Classification Factors			Examples
	Location/ Vantage	Observation Type	Coordination	
Stand-Alone Missions	Distributed	Complementary	Ground	UARS, TRMM, etc.
Satellite Train	Aligned	Complementary	Ground	Aqua/Aura Train
Precision Satellite Train	Precise	Complementary	Ground	
Global Constellation	Distributed	Similar	Ground	GPM, Iridium
Multi-View Formation	Aligned	Similar	Ground	"Parasitic" Cartwheel
Precision Formation	Precise	Similar	Ground	GRACE
Multi-Measurement Sensorweb	Distributed	Complementary	Autonomous	ESE Vision Sensorweb
Virtual Platform	Aligned	Complementary	Autonomous	
Precision Virtual Platform	Precise	Complementary	Autonomous	
Super-Instrument Sensorweb	Distributed	Similar	Autonomous	JPL Sensorweb
Multi-View Virtual Truss	Aligned	Similar	Autonomous	
Precision Virtual Truss	Precise	Similar	Autonomous	Optical Interferometry

The following text discusses these concepts, the rationale behind the proposed concept name, and provides some examples.

Stand-Alone Missions: Until recently, and with a few exceptions, most of the satellites in operation have unique sets of instruments and observation capabilities, and are in distinct orbits. This is what is referred to as the *Stand-Alone Missions* in the above table. The observations are *complementary* in that they provide distinctly different data about the Earth system, the positions or vantages are *distributed*, and any coordination between missions is performed on the *ground*.

Satellite Trains: In contrast, separated, multi-mission observations that are *aligned* or co-located in position or vantage can provide simultaneous or near-simultaneous observations of the same location, or provide simultaneous or near-simultaneous contiguous observations of adjacent areas. A recent trend in NASA Earth science missions is to fly missions with distinct but *complementary* observing capabilities in *Satellite Trains*. Current and planned near-term satellite trains include:

- The currently operating train containing Terra, LandSat-7, EO-1, and SAC-C.
- Jason-1 and Topex/Poseidon, flying 1 minute apart for cross-calibration.
- The planned "A-Train" (Aqua & Aura Train), with Aqua, CALIPSO, PARASOL, CloudSat, and Aura observing the same location in a span of about 6 minutes.

Distinct observations of the same location can extend spectral coverage by using sensors that cover different regions of the spectrum. This can provide overlapping observations for later data fusion by the information system. They can also support cross-calibration of methods for consistency, legacy, and continuity requirements, or cross-calibration of replacement measurements, including new approaches for system upgrades/new technology observations. To a certain extent, it is a matter of definition as to how similar or different a replacement has to be in order to be considered *similar* or *complementary*. For example, the New Millennium Program (NMP) First Earth Observing mission (EO-1) is flying innovative technologies for the next generation of land cover and land cover change instruments. EO-1 is currently flying in a *Satellite Train* with LandSat-7 in order to demonstrate compatibility between the old and new technologies and to address data continuity and legacy concerns.

Precision Satellite Trains: A *Precision Satellite Train* would be a set of multiple missions acquiring *complementary* observations with distinct instrument sets, requiring *precise* metrology, but only requiring *ground*-in-the-loop coordination between the spacecraft. The author is not aware of any mission concept that would call for such an arrangement.

Global Constellation: *Similar* observations using separated missions that are *distributed* in position or vantage can be used to provide greater spatial and temporal coverage. Multiple missions that are distributed in location and timing can reduce the time between satellite observations or cover wide areas with distributed *in situ* sensors. If they only require *ground*-in-the-loop coordination between satellites, these are referred to as *Global Constellations*. This is consistent with the sense in which the term *Constellation* is used in the book *Space Mission*

Analysis and Design.* If the similar observations are distributed, cross-calibrations may occur whenever coverage overlaps.

If we consider a constellation as two or more satellites obtaining similar measurements in different or distributed orbits, a very early example of a satellite constellation are the Polar Orbiting Environmental Satellites (POES), with one Sun-synchronous satellite in a morning orbit and one in an afternoon orbit. Similarly, the Geostationary Orbiting Environmental Satellites (GOES) qualify, with operational satellites at two longitudes, and International agreements to obtain comparable observations from International satellites at additional longitudes. Large constellations are currently in use to provide communications coverage, such as the Iridium constellation, with 66 active satellites and 7 on-orbit spares.

Multi-View Formation: This is a proposed term, not in the literature. *Multi-view Formations* would have *aligned* observations for viewing nearly the same location. They would involve *similar* or related instruments. Coordination would be preprogrammed from the *ground*.

One use of *Multi-view Formations* might be to observe the same areas for cross-calibration of sensors. Cross-calibration is often needed for consistency, legacy, and continuity requirements when replacing an observation capability with a replacement or an upgraded/new technology capability. Another use could be similar observations made from similar, but not the same orientation, such as stereo observations, phase-angle observations, polarization observations, and active bistatic or multistatic observations, such as interferometric synthetic aperture radar, that can be performed without direct satellite-to-satellite coordination.

Precision Formation: This is another proposed term that builds upon the concept of a formation. A *Precision Formation* would require *precise* metrology, although almost certainly only for after-the-fact determination, because there would only be *ground*-in-the-loop coordination between the satellites. The observation type would be *similar*.

For example, the currently flying Gravity Recovery and Climate Experiment (GRACE) mission requires extremely accurate knowledge after-the-fact of the separation between the spacecraft. However, the measurement does not depend upon controlling the spacecraft separation, which is allowed to drift within broad limits.

Multi-Measurement Sensorweb: To make a distinction between sensorwebs that have multiple, similar nodes from sensorwebs made up of many distinct observation capabilities, the term *Multi-Measurement Sensorweb* is proposed. These would be globally *distributed* missions carrying distinct and *complementary* instrument sets that are connected into a sensorweb through real-time links that allow the system to respond *autonomously* to events detected throughout the

* Wertz, J., and Larson, W., editors, *Space Mission Analysis and Design*, 3rd Ed., Microcosm Press and Kluwer Academic Publishers, 1999.

system. Multi-measurement sensorwebs might use sentinel and monitoring observations to trigger other observations, such as:

- A geostationary clouds monitor that notifies LEO land imaging instruments when areas of interest are clear.
- *In situ* volcano stations to trigger low Earth orbit satellites to change observation modes to better observe plume evolution.
- Geostationary total lightning monitors that trigger higher time-resolution modes in ground-based cloud-to-ground lightning observations when thunderstorms with tornado potential are detected.

Virtual Platforms: Ticker and Azzolini define virtual platforms 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." The registration would require that *Virtual Platforms* have *autonomous*, real-time coordination between the spacecraft. Generally speaking a real platform would carry distinct, *complementary* instruments that would be *aligned* on the platform, and this is carried over to the virtual platform concept.

For example, the satellites in the "A Train" (Aqua, CALIPSO, PARASOL, CloudSat, and Aura) do not have the ability to communicate with each other. Because each points to within a fairly loose dead-band based upon absolute coordinates, there will be times when the observations are not completely aligned. If they were able to communicate directly, the more agile spacecraft could control to the relative pointing of the least agile spacecraft, increasing the degree of alignment and co-coverage without significantly affecting the attitude control design.

Precision Virtual Platforms: The *Precision Virtual Platform* concept would build upon the platform as a carrier of diverse or *complementary* instruments, with *virtual* signifying autonomous coordination. The term *precision* implies the use of precise metrology. I am not aware of any measurements requiring this approach.

Super-Instrument Sensorweb: In a sense, the daily worldwide release of radiosondes to calibrate satellite weather observations represents a kind of *Super-Instrument Sensorweb*, without the network capability to make this information available across the observing system in real time. As mentioned above, much of the sensorweb work done in support of space science is based on *distributed* but *similar* observations with *autonomous* real-time coordination. The JPL Sensorweb Project has as a demonstration a small, distributed network of miniature weather stations that can be accessed over the Internet.

Multi-View Virtual Truss: The term truss is proposed for virtual structures that carry similar instruments, such as the boom or truss that held the second antenna for the Shuttle Radar Topography Mission (SRTM). A *Multi-View Virtual Truss* would potentially serve the same function as the real truss for SRTM. In the case of SRTM, the truss allowed the two receiving radar antennas to observe the same region at the same time, building an interferometric data set that provided topographic measurements. SRTM is an example of *similar* measurements that were *aligned*, and that required real-time, *autonomous* coordination using a real truss. Future interferometric synthetic aperture radar observations may rely upon separated spacecraft, connected as a virtual truss.

Precision Virtual Truss: This thesis proposes the term *Precision Virtual Truss* for *similar* observations that require *precise* and *autonomous* control of the spacecraft location. The examples cited by Ticker and Azzolini that fit this category are gravity field observations and optical interferometers. In the gravity observations the “signal” from variations in the gravity field is manifested in very small variations in the separation between co-orbiting spacecraft. While the current GRACE mission only requires after-the-fact knowledge, future missions concepts require active control. As another example, optical interferometers require position control to a fraction of the wavelength of the light being observed. Current concepts use this technique for outward-looking astronomy missions and not for Earth observation.

Hybrid Cases: There are clear examples of current or near-term assets that fit more than one of these categories. For example, the “A-Train” includes the Aqua, CALIPSO, PARASOL, CloudSat, and Aura missions. Because there is no real-time coordination between satellites, these are an example of a *Satellite Train*. However, the MODIS instrument will be flying on both Aqua and Terra. From the point of view of the measurements that use the MODIS instrument, Aqua and Terra are *Global Constellation* members. Similarly, there is an on-going effort to place GPS sounding instruments on flights of opportunity, and several instruments are currently operating. Even though each of the satellites hosting a GPS instrument is quite different, from the point of view of the GPS sounding measurement, these satellites form a GPS *Global Constellation*.

4.3 Concepts to Maintain and Upgrade the Multi-Mission Measurement System

4.3.1 New Observation Techniques, Instruments, and Components

The NASA Earth Science Enterprise encourages the creative development of mission concepts and proposals through an integrated strategy spanning the full range of concept development timelines, as depicted in the following figure.

Integrated Earth and Space-Based Observation Network for Earth Science

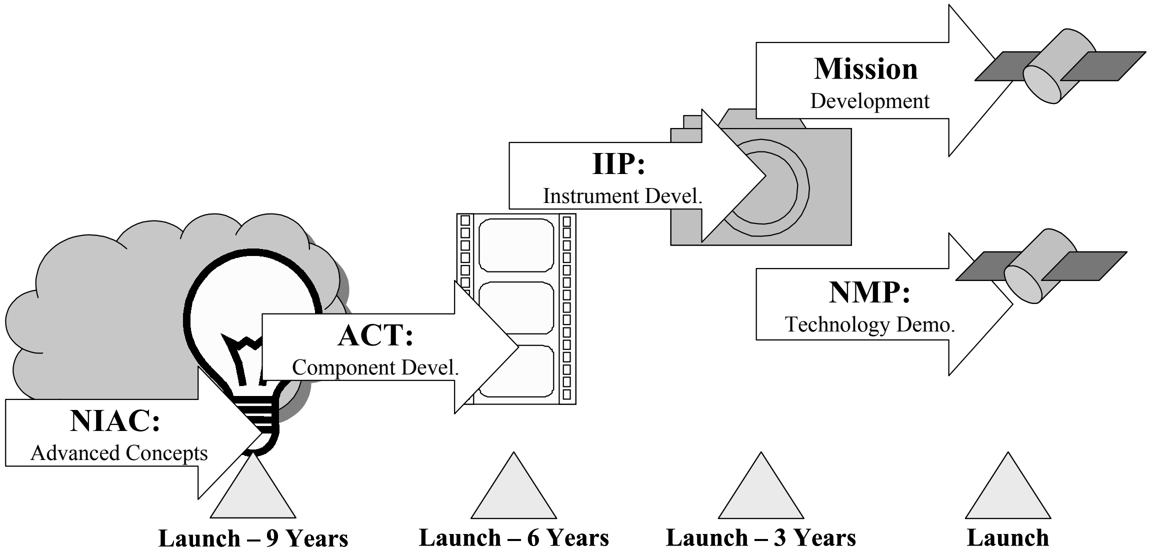

Figure 12: Notional New Measurement Concept Technology Development Roadmap

In practice, the concept development process takes longer that the figure and text illustrate. Technical innovations do not always occur on a predetermined schedule, and opportunities to compete only occur on one or two year cycles.

Mission Development: For near-term missions, the Earth Science Enterprise (ESE) encourages and rewards innovative mission approaches in our mission solicitations. ESE identifies key measurement requirements or poses key science questions as goals without specifying the implementation. ESE establishes minimal high-level constraints and uses flexible solicitation mechanisms. In general the missions must involve some space hardware (although it could be commercially developed such as Space Imaging's IKONOS satellite), must be technically mature enough to be completed in approximately three years (we hold regular competitions to encourage proposers to wait until ready), comply with National policy (which imposes certain restrictions of foreign participation, etc.), and fit within the available budget. These solicitations provide opportunities for mission concepts that require less than 3 years development.

NMP Technology Demonstration: If a concept depends upon a technology that requires space validation before the technology would be judged mature enough for selection, NASA provides opportunities to compete for the New Millennium Program.*

IIP Instrument Development: If a concept is not technically ready for full mission selection, it can compete for programs such as the Instrument Incubator Program, which will provide up to 3 years of support to develop an instrument concept and technology to the point where it is ready

* NASA, "About New Millennium Program," World Wide Web page, URL http://nmp.nasa.gov/program/program.html

for a mission proposal. The Instrument Incubator fosters the development of innovative remote-sensing concepts and the assessment of these concepts in ground, aircraft, or engineering model demonstrations.* IIP provides for concepts that are 4 to 6 years away from launch.

ACT Component Development: If a concept requires more than 3 years of development before it is ready for a mission proposal, ESE provides opportunities to compete for the Advanced Component Technologies (ACT) program.† This provides for concepts that are 7 to 9 years away from launch.

NIAC Advanced Concepts: Concepts that are more than 10 years away can compete for funding from the NASA Institute for Advanced Concepts.‡ ESE actively participates in and encourages the Earth science community to propose to the NIAC.

Organizations including aerospace companies, universities, and NASA centers see future business opportunities in NASA Earth Science Enterprise solicitations. The Enterprise's role is to encourage the development of innovative mission concepts. NASA attempts to create an atmosphere that supports the development of innovative ideas, provides enough funding to allow these ideas to develop and mature, without narrowly specifying a particular solution.

4.3.2 New Mission Platform Technologies

For the most part, the current concept for the development of new mission platform technologies is to rely upon the development efforts of other stakeholders. The NASA Earth Science Enterprise has done some planning for a dedicated platform technology program. However, it does not currently have one. This is in part a recognition that other stakeholders in the space "value web" have more pressing needs for platform technology innovations.

NASA planetary missions require high-energy trajectories to reach interplanetary destinations, and this puts a premium on the mass of interplanetary spacecraft, leading the Space Science Enterprise to pioneer spacecraft miniaturization for NASA. Planetary missions also require extensive on-board autonomy, as planetary destinations are many light-minutes away, making real-time communication and control impossible. NASA's astronomy missions have more demanding attitude and instrument pointing requirements. In addition to technology programs in support of planetary and astronomy missions, NASA encourages and promotes innovations in the components for spacecraft through programs such as the Small Business Innovation Research (SBIR) program, targeted at the small companies that often provide key components.§

* NASA, "Instrument Incubator Program," World Wide Web page, URL http://www.esto.nasa.gov/programs/iip/
† NASA, "Advanced Component Technologies (ACT)," World Wide Web page, URL http://www.esto.nasa.gov/programs/act/
‡ USRA, "NASA Institute for Advanced Concepts," World Wide Web page, URL http://www.niac.usra.edu/
§ NASA, "Small Business Innovation Research, Small Business Technology Transfer," World Wide Web page, URL http://www.sbir.nasa.gov/

For commercial space stakeholders, the competitive environment in the commercial communications segment motivates continued efforts to improve spacecraft platform technologies. NASA has benefited from these investments. The author believes this is one of the main reasons that it is now possible for the Rapid Spacecraft Development Office to provide a "catalog" of standard spacecraft busses, while earlier efforts to develop "standard" spacecraft were not nearly as successful.

For Earth-based and *in situ* observation missions, it is beyond the scope of this effort to categorize and analyze all of the possible platforms, such as balloons, buoys, piloted and unpiloted air vehicles, stationary weather stations, instrument packages on commercial air liners and ocean freight vehicles, etc. These platforms could benefit from a broad variety of new technologies. NASA has some programs actively working in this area. For example:

- The Environmental Research Aircraft and Sensor Technology (ERAST) program is developing unmanned air vehicles (UAVs) for science research.[*]
- NASA is the lead agency for the *in situ* exploration of all the other planets of the solar system, and is making unique investments in these technologies, some of which will have benefits for Earth-based sensing missions. In addition NASA often uses terrestrial locations as test-beds for planetary exploration technologies. For example, NASA used the Dante robot to acquire samples and data from volcanoes that are too hazardous for humans to approach, while gaining valuable experience for later robotic exploration of other planets.[†]

For Earth-based sensing, the distinction between platform and deployment mechanism may be unclear. In general, this thesis considers systems that support and remain with the observation capability throughout the life of the mission as part of the platform, while those that are only used for part of the mission to convey the observation capability to the desired location are considered as part of the deployment system. For example, an unmanned air vehicle (UAV) that carries a suite of instruments while dropping radiosondes and ocean buoys is a platform for the instrument suite and at the same time the deployment system for the radiosondes and buoys.

4.3.3 Mission Development Process Improvements

The author identified multi-mission development system concepts for both maintaining and upgrading the multi-mission system and for leveraging economies of scale. The views for the next two chapters also highlighted aspects of the development system. These include the multi-mission development system infrastructure (chapter 5, form) and the need for improvements and flexibility in the multi-mission development system (chapter 6, driven by timing and operation considerations). For readability and consistency, the discussion of the multi-mission development system is consolidated in this section.

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[*] NASA, "Welcome to ERAST," World Wide Web page, URL http://www.dfrc.nasa.gov/Projects/Erast/erast.html

[†] NASA, "Spacelink - Dante," World Wide Web page, URL http://spacelink.nasa.gov/NASA.Projects/Space.Science/Solar.System/Dante/

Concepts discussed include the expected evolution of the multi-mission development process; concepts for streamlining develop, such as the "Faster, Better, Cheaper" development approach and possible future innovations; improving relationships with mission developers; multi-mission development tools and facilities; mission development expertise, training and skill development; and risk reduction for multi-mission developments.

Multi-Mission Development Process Evolution

The following figure illustrates the natural progression from one-of-a-kind artisan and craft development towards multi-mission capabilities.* As a general rule, industries tend to follow the diagonal of this chart, evolving over time from the upper left to the lower right, although individual companies may seek to gain competitive niche markets by positioning themselves slightly off this diagonal. The mission "product" or technology tends to improve, as does the development process, with innovations that lead to a shorter and more continuous development flow.

Table 16: Stages of Space Mission Product and Process Life Cycles

Space Mission Life Cycle Stages		**Product Life Cycle Stage**			
		I. Low Volume – Low Standardization, One-of-a kind	**II. Multiple Products, Low Volume**	**III. Few Major Products, Higher Volume**	**IV. High Volume – High Standardization, Commodity Products**
Process Life Cycle Stages	**I. Jumbled Flow (Job Shop)**	Most Satellites to Date			
	II. Disconnected Line Flow (Batch)		Communications Satellites, RSDO Catalog Satellites		
	III. Connected Line Flow (Assembly Line)			Iridium	
	IV. Continuous Flow				

* Modeled after the diagonal chart in Hayes, R., and Wheelwright, S., "Link Manufacturing Process and Product Life Cycles," Harvard Business Review, Jan-Feb 1979.

The general pattern is that early in the development of a technology or industry, the majority of innovations are product innovations, as new product features and capabilities are tried and either adopted or replaced. Later, once a "dominant architecture" or "dominant design" has emerged, the focus of competition and invention tends to shift from product and features to process and price. Although the author has not done an extensive study, experience suggests that the space industry is moving from an emphasis on component innovation centered on mission features towards more process-oriented innovations to reduce mission price.

Evidence that this is occurring in the space industry can be seen in the current "catalog" services, as illustrated in the last Earth System Science Pathfinder (ESSP) Announcement of Opportunity (AO).[*] This solicitation described several standard services available to the proposing community. These are the standard NASA Provided Launch Services, the Rapid Spacecraft Development Office (RSDO) catalog of spacecraft busses, and the Space Operations Management Office (SOMO) mission operations (tracking, etc.) services. The AO states that it expects that more "standard" capabilities will be available in future AOs, so that investigators may focus their effort on the unique aspects of the mission.

Streamlining Development through "Faster, Better, Cheaper"

The following text examines the "Better, Faster, Cheaper" as a concept for improving the mission development process. It proposes that this innovation was a "disruptive" technology in the sense used by Christensen that caught NASA large mission developers "by surprise." The author presents an explanation and supporting data for why the "Better, Faster, Cheaper" approach works better for some missions than for others.

The "Faster, Better, Cheaper" concept for mission implementation ranked other attributes over "total" cost, seeking simplicity and predictability, flexibility, and faster mission development cycle times. These missions tend to be simpler and more predictable by avoiding situations where a large integrated mission is "on hold" due to problems with one instrument. The flexibility of these missions allows rapid response to changing science questions. The faster mission development cycle times result in less work in progress" and more rapid demonstration of partial progress. This is an important consideration for activities that depend upon public support and political consensus.

Initially the predicted accumulated cost of these small missions appeared more expensive than the cost of the same capabilities using the larger mission approach. Small missions were best suited for low capability, niche mission applications. Conceptually, this "invasion" of missions that appear (by the old measure) to be clearly inferior fits the model of a "disruptive technology" or "disruptive innovation" developed by Christensen.[†] The following figure applies

[*] NASA, "Earth System Science Pathfinder (ESSP) Missions NASA Announcement of Opportunity," AO-01-OES-01, May 18, 2001.

[†] Christensen, C., *The Innovator's Dilemma*, Harvard Business School Press, 1997.

Christensen's approach of plotting performance and demand trajectories. This plot is notional, as the axes are not quantified.

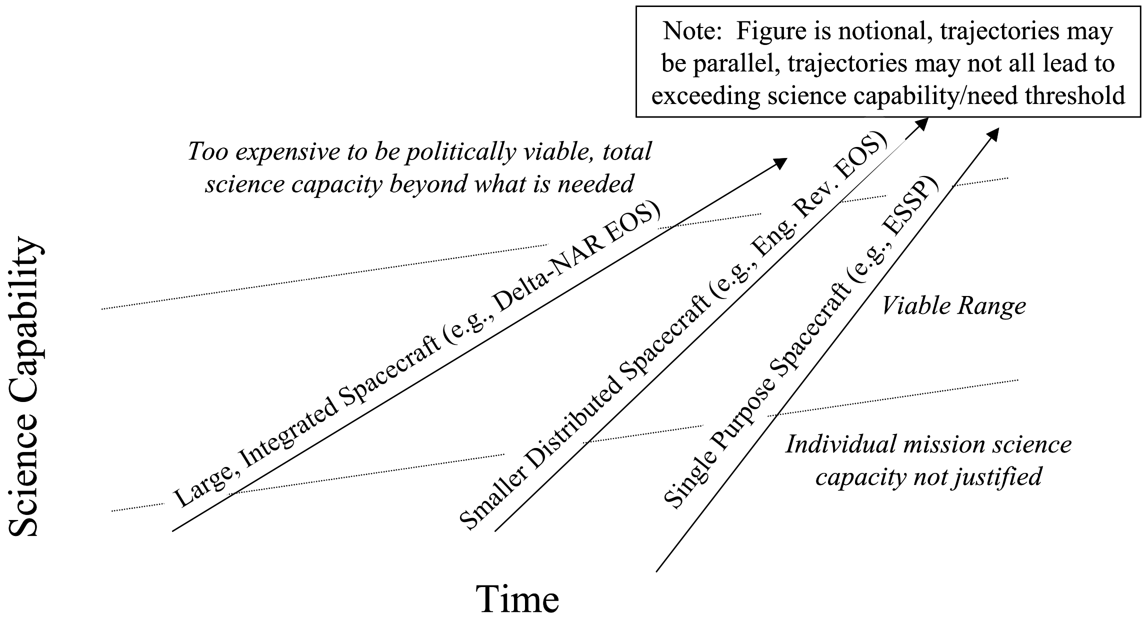

Figure 13: "Faster, Better, Cheaper" as a Disruptive Innovation?

An unstated tenet of the "Faster, Better, Cheaper" mission implementation approach was that these missions would also be simpler. The National Academy recognized this in a review of small missions for Earth observations.* This report noted that the benefit of smaller missions is derived as much from the relative simplicity as from the size. The study further observed that small satellites for a larger mission involving a number of sensors requires a mission architecture trade-off study, and that the architecture with the lowest life cycle cost is mission specific.

David Bearden of the Aerospace Corporation developed a complexity measure and applied it to 41 small missions.† Bearden's work shows a clear relationship between this complexity measure and impaired or failed missions:

- All 10 failed or impaired missions had complexity measures greater than 0.8, and only 1 was in the 0.7 to 0.8 range

* Committee on Earth Studies, Space Studies Board, National Research Council, "The Role of Small Satellites in NASA and NOAA Earth Observation Programs," Chapter 8, Findings and Recommendations, National Academy Press, 2000.

† Bearden, D., "A Complexity-based Risk Assessment of Low-cost Planetary Missions: When Is A Mission Too Fast and Too Cheap?" Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2-5, 2000.

- All 31 successful missions had complexity measures between 0.0 and 0.8, and only 4 had score in 0.7 to 0.8 range

The author of this thesis may disagree with a few of the specific assumptions made by Bearden. However these would only shift a few points and the overall trend and value of this insight would remain valid. The following figure is interpreted from the x-axis of figures in Bearden's paper, and shows this relationship between the complexity measure and the impaired or failed missions.

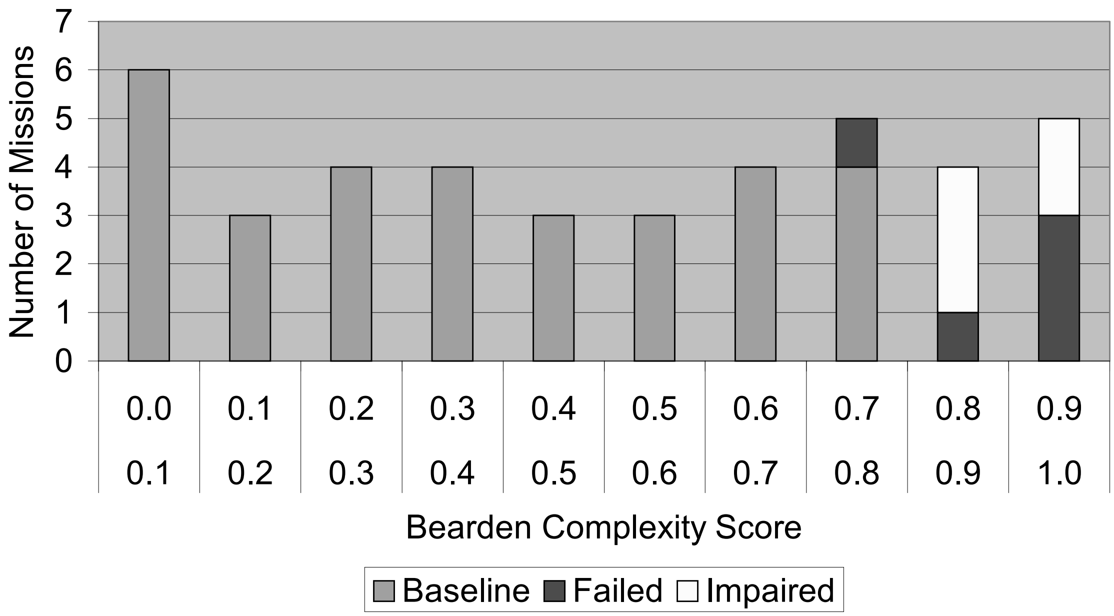

Figure 14: Complexity Score and Mission Success (Bearden)

Bearden did not publish the complexity scores for specific missions in order to protect proprietary spacecraft bus cost data. It is not possible from his publicly available data to relate complexity scores to the individual missions that he assessed. It would be interesting to examine his data for other trends, such as a "learning curve" of early failures as each organization begins development of small missions, or an increase in failure rates over time as expectations for mission performance (and the resulting mission complexity) increase.

Possible Future Disruptive Mission Development Innovations

The author speculates on future innovations that may also be "disruptive" and that may, for example, lead back towards larger and more integrated platforms. There may be other, low cost ways to get the attributes of simplicity, predictability, flexibility, and faster mission development cycle times. Other attributes may become more important in the future. An important part of strategy is to remain aware of the forces that led to the current approach, and how (and when) they may change.

For example, technical innovations in mission development capability could change the assumptions about how missions are built, enabling virtual design and rapid production, or the reliable prediction and modeling of spacecraft-to-payload integration (plug and play). Developing these capabilities should bring considerable benefits, and could change the basic model or approach for developing missions. It is the author's experience that the greatest source of uncertainty is in instrument development. If a rapid development and "plug and play" capability were available for the rest of the spacecraft, it should be possible to resolve instrument uncertainties before making the final platform commitment and investment. This should reduce both total mission uncertainty and cost. This could add flexibility to the mission development cycle by deferring decisions as long as possible.

In order to defer decisions as long as possible, it may be desirable to separate the instrument development from the spacecraft bus procurement. This is counter to the current approach of soliciting "PI-led" missions in which the entire mission package is proposed at once. However, separating the selection of the spacecraft bus from the selection of the instrument, and deferring the bus decisions as long as possible may allow more flexible packaging of available instruments at time of bus selection. This could be considered as part of a systematic reexamination of procurement approaches and relationships (discussed below), in conjunction with revisit of government/proposer relationship structure. One concern is that under current procurement rules, this approach could shift responsibility and risk from the proposer/mission developer to NASA.

The *Quikscat* mission demonstrated one year from decisions to launch. This mission was a special case. It was a rapid recovery from the loss of a previous mission. The availability of the spare instrument meant that there was no uncertainty in the instrument development and no ambiguity in the instrument interface. While one datum does not make a trend, this case supports the benefit of reducing instrument ambiguity and uncertainty.

Improving Relationships with Suppliers for a "Lean" Development System

The following table describes the approximate timeline for NASA Earth Science Enterprise mission development. One of the implications of this timeline is that the Earth science community is currently beginning the design of missions that will be operating 10 years from now.

Table 17: Representative NASA Earth Science Mission Development Cycle

Development Stage	Time From Launch
Concept and Technology Development	-5 to -10 Years
Solicitation Definition (Two or Three Stage)	-4.5 Years
Proposal Generation and Evaluation (2 or 3 Stage, Equivalent to Phase A, Mission Concept Studies)	-4 Years
Post-Selection Definition and Preliminary Design	-3.5 Years
Mission Detailed Design (ends with CDR)	-3 Years
Mission Development and Launch	-2.5 Years
Mission Operations and Data Analysis, Archival, and Dissemination	1 to 7 Years

An interesting area requiring further research is ways that NASA, under the constraints of Government procurement regulations, may work cooperatively with industry. It may be possible to improve the solicitation and proposer relationship. The current implementation of government procurement rules imposes a "stand-off" relationship. The lean manufacturing approach emphasizes establishing longer-term relationships with suppliers, and giving all parties incentives to share information and develop innovative approaches to improve.* The demonstrated benefits of lean manufacturing in industry suggests that NASA investigate approaches for changing supplier relationships from "win/loose" to "win/win." Changing this relationship may help develop faster and more cooperative concept and proposal development and evaluation approaches.

It is not clear how to apply this approach under government procurement rules. However, NASA, through the Rapid Spacecraft Development Office (RSDO), has used an Indefinite Delivery, Indefinite Quantity (IDIQ) contract to create a "catalog" of spacecraft busses. This or other mechanisms may be able to provide industry and NASA the proper incentives to work cooperatively, streamlining and shortening the entire mission development cycle, from proposal to launch.

The NASA Earth Science Enterprise is already taking steps to improve the solicitation, proposal preparation, and proposal evaluation process. It is in the interests of both the proposer and NASA to seek ways to improve the quality of the concepts proposed as well as the clarity of the proposal. One current step is to provide mechanisms for proposers to ask questions that help clarify the solicitation. For example, in the last Earth System Science Pathfinder Announcement of Opportunity, NASA decided that enough of the content of the AO had changed from previous ESSP AOs that NASA would release a draft Announcement for community comment. In addition, after the release of the final AO NASA provided for a question and answer period.

* Womack, J., Jones, D., and Roos, D., *The Machine That Changed the World*, Harper Perennial, 1991 (originally published in hardcover by Rawson Associates/Macmillan Publishing Company, 1990), chapter 6, "Coordinating the Supply Chain," pages 138-168.

Another step to improve the proposal preparation process is to debrief the proposing teams, providing them with detailed evaluation comments. NASA recognizes the long-term nature of the relationship with the proposing community. For most programs, NASA runs solicitations every two years. Particularly for space mission proposals, it is common for the same concept to be proposed for several solicitations. By providing the proposers with detailed feedback as well as insight into the issues that affected the evaluation results, NASA hopes to improve the scientific and technical quality of the mission concepts, as well as the clarity of the proposal submissions.

Multi-Mission Development Tools and Facilities

An example of dedicated infrastructure for the multi-mission development process is the JPL Flight System Testbed.[*] This test-bed is a simulated spacecraft that facilitates the design, evaluation, prototyping, and test of spacecraft systems by providing the capability to create a system-level mix of real and/or virtual components. NASA has developed equivalent capabilities at GSFC, and similar capabilities exist in industry. These multi-mission facilities support the rapid scoping and refining of mission concepts, designs, models, analyses, and simulations. The benefits of such facilities are amplified when they are co-located. This facilitates informal contacts and the transfer of tacit design knowledge about the mission design and operation.

Other multi-mission development capabilities include multi-mission facilities for spacecraft development and test. For example, the NASA Goddard Spaceflight Center (GSFC) operates the Environmental Test and Integration Facility.[†] As stated in the reference press release, "This facility is one of the most complete and comprehensive within the United States government for environmental test and qualification of space flight hardware. The facility includes clean-room assembly and check-out areas, thermal vacuum chambers, a high capacity centrifuge, an acoustic test cell, electro-dynamic shakers, static-load test facilities, a modal test facility, electromagnetic compatibility test facilities and a magnetic characterization test facility."

These types of facilities, along with commercially available tools such as Satellite Took Kit that support mission design as well as mission operations are examples of multi-mission tools that facilitate the mission development process.

Mission Development Expertise, Training, and Skill Development

As important as facility and infrastructure investment may be, perhaps the most important capability that enables and improves multi-mission development is the expertise of the people at NASA, elsewhere in the government, at universities, and in industry.

[*] NASA, "About the FST," World Wide Web page, URL http://fst.jpl.nasa.gov/about
[†] NASA, "Virginia Firm Wins $82 Million Contract From NASA Goddard," Press Release: c02-a, Jan. 30, 2002, URL ftp://ftp.hq.nasa.gov/pub/pao/contract/2002/c02-a.txt

Maintaining this expertise requires continued training and skill development for project staff. An example is the NASA Academy of Program and Project Leadership. This program is sponsoring the author's participation in the System Design and Management program at the Massachusetts Institute of Technology.

Risk Reduction for Multi-Mission Developments

Many of the concepts mentioned above that enable earlier prototyping and testing of components, and that reduce the ambiguity and uncertainty in the mission development process, will result in reduced risks as well. Other concepts for multi-mission safety and risk management include standardized program and project management procedures, Mission Risk Management Plans, and Mission Assurance Guidelines and Requirements.* From proposal evaluation to operations, NASA uses the implementation of these plans to monitor the mission's progress.

4.3.4 Servicing, Repair, and Partial Replacement

There are several current concepts for mission servicing, repair, or partial replacement. For Earth-based missions, visits by field technicians are may be routine. For space missions, NASA services selected large space infrastructure investments such as the Hubble Space Telescope. The Space Shuttle has demonstrated the capability to rendezvous, capture, and repair or return missions that are in Shuttle-compatible orbits. In general the economics of these approaches, and the limitation of the Space Shuttle to low Earth orbits with inclinations less than about 60 degrees, restricts the concept of Astronaut servicing for NASA Earth Science Enterprise missions.

In contrast, the International Space Station is ideally suited for servicing. With its Earth-facing optical window, the ISS provides a "shirt-sleeve" environment for Earth science observations compatible with the properties of the window. A number of external locations on the ISS provide opportunities for Earth observation instruments, and all of these locations are accessible for servicing.

Future concepts to maintain and upgrade the overall system involve remotely or robotically updating assets after deployment. Reprogramming software and reconfiguring hardware without physical contact with the mission could implement system maintenance and upgrades. Allowing for this capability would mean originally including additional memory and/or processor capability for future updates as well as reconfigurable or reprogrammable systems such as the science instruments and the mission-to-mission interfaces (e.g., software radio).

* NASA, "Management of Major System Programs and Projects," NASA Procedures and Guidelines (NPG) 7120.5.

Other concepts could involve physically deploying assets to rendezvous with the mission. Robotic satellite servicing missions could repair or replace components, or provide additional or replacement capabilities. Approaches could include a servicing mission that rendezvous, services and departs; a dedicated, hard docking unit that attaches and remains with the mission to add or replace capabilities; or a dedicated unit that joins in local formation flying to add or replace capabilities. Finally, service missions could recover and return the observation mission for repair.

4.3.5 End-of-Life Disposal

For spacecraft, NASA has established a clear policy for limiting orbital debris generation.[*] For spacecraft in low Earth orbit (LEO), the concepts include natural decay (if it will occur in less than 25 years) or propulsive reentry. Possible future concepts include an inflatable structure to increase drag and increase the decay rate, or a vehicle designed to rendezvous with, dock, and de-orbit missions for safe disposal. For spacecraft in geostationary Earth orbit (GEO), the current concept is to reposition the mission orbit away from geostationary location at the end of life.

Safe disposal is also an important consideration for Earth-based sensor. It is beyond the scope of this effort to consider all of the possible scenarios for Earth-based sensor end-of-life disposal. The design of missions involving balloons, buoys, fixed ground stations, etc., must consider what will become of these assets at the end of life, and whether they pose any risks or hazards.

[*] NASA, “NASA Policy for Limiting Debris Generation,” NASA Policy Directive (NPD) 8710.3.

4.4 Concepts to Leverage Multi-Mission Economies of Scale

4.4.1 Conveying Observation Results

The three main concepts for conveying observation results from space- and Earth-based missions are to physically return samples or recorded media, to use radio frequency to communicate, and to use optical communications. For some specialized applications, such as sub-surface ocean buoys and for local *in situ* networks, sonic communications is another option not discussed further in this thesis.

Physical Return of Samples or Data Recording Media

The physical return of samples or recorded media is often used for ground-based sensing. Examples include the manual collection of samples for laboratory analysis and the filming or recording of data during aircraft flights for development or playback upon return.

The physical return of samples or recorded media is also used for space missions. Space Shuttle experiments will often record data for playback after the Shuttle's return to Earth. The Russian RESURS-F2 high-resolution space-based remote sensing missions return their data in the form of exposed film.[*] Until the mid-1970s US spy satellites also returned their results by physically returning film canisters. The US Air Force maintains facilities that will be used by NASA for the physical return of interplanetary samples.[†] These facilities could be available for any mission where this approach makes sense.

Radio Frequency Communications

Two main concepts for radio frequency communications are to relay data through other satellites or to communicate directly with the ground. Space-to-space relay concepts may use dedicated relay satellites such as the NASA Tracking and Data Relay Satellite System (TDRSS), or include relay capability as part of the observing system as described in some of the sensorweb concepts. Space-to-ground communications concepts may link to central ground stations that are connected to the global information system, or may provide direct links to the user.

Several issues are common to all radio frequency communications concepts. If the communications system cannot provide continuous, live coverage, the system must either accept these gaps or include the ability on the missions to store and playback data. For spacecraft in low Earth orbit (LEO), space relay is the only practical concept for continuous or nearly

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[*] Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002, page 27.

[†] NASA, "Genesis Spacecraft Begins Mission to Collect Samples of the Sun," Press Release: 01-238, Dec. 3, 2001, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2001/01-238.txt

continuous coverage. If the data are stored for playback to a ground station, a playback "rule of thumb" is that the downlink rate should be about ten times orbit-average data rate.* With the trend towards close formation satellite configurations many satellites will be over a ground station at same time. This further reduces the tracking time the station can devote to each satellite. The playback "rule of thumb" may need adjusting for the future, multi-satellite environment. Increasing the playback burst rate data for store and playback systems could help reduce station conflicts and simplify operations.

The International Telecommunications Union (ITU) internationally and the Federal Communications Commission (FCC) within the US tightly control radio frequency spectrum allocations and use. Only certain frequencies are allocated for spacecraft communications. NASA tends to refer to radio frequency spectra by letter codes, such as S-Band at about 2 GHz, X-Band at about 8 GHz, Ku-Band at about 14 to 15 GHz, and Ka-Band at about 22 to 28 GHz, although these letter designations are not universally defined.† Early space systems tended to use S-band communications. However, the data rate that a link can support is related to the link radio frequency. As data rate demands have increased, the capabilities for X-band, Ku-band, and now Ka-band have been added, either for space-to-ground or space-to-space communications. These capabilities are discussed in the following sections.

Wende has projected the data rates of currently approved and likely future NASA Earth Science Enterprise missions and used these to forecast cumulative average data rates. He developed the following figure that graphically represents these data rates.‡ The vertical scale is logarithmic. His analysis identifies three categories of missions, "Baseline," "ESSP+NMP," and "VHBW:"

- **Baseline** represents the projection of currently approved and planned missions for which the concepts and projected data rates are relatively clear.

- **ESSP+NMP** represent future Earth System Science Pathfinder and New Millennium Program missions. These missions are selected in response to competitive solicitations, and the projected data rate depends upon the particular concept selected. Wende has estimated the data rates for these missions by assuming alternating 2 Mb/s and 10 Mb/s average data rate missions.

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* Wende, C., "Communications Outlook for NASA's Earth Science Enterprise (ESE)," viewgraph presentation dated January 23, 2001. This presentation is an update to Wende, C., "NASA Remote Sensing Missions and Frequency Issues," IGARSS 2000, July 24-28, 2000.

† U.S. Department of Commerce, National Telecommunications and Information Administration, "Tables of Frequency Allocations and Other Extracts From: Manual of Regulations and Procedures for Federal Radio Frequency Management," September 2000 Edition, page 6-30. "Such designations create confusion, because the band limits vary from one designator system or user group to another."

‡ Wende, C., "Communications Outlook for NASA's Earth Science Enterprise (ESE)," viewgraph presentation dated January 23, 2001. This presentation is an update to Wende, C., "NASA Remote Sensing Missions and Frequency Issues," IGARSS 2000, July 24-28, 2000.

- **VHBW**. The dominant effect is from this category, representing the potentially very high data rates of synthetic aperture radars (SARs) and hyperspectral instruments. These cannot be accommodated in X-Band, would stress the capabilities of Ka-Band, and will likely to force use of optical communications. Although the most speculative of the three categories, the potential that future missions will require extremely high data rates cannot be ignored.

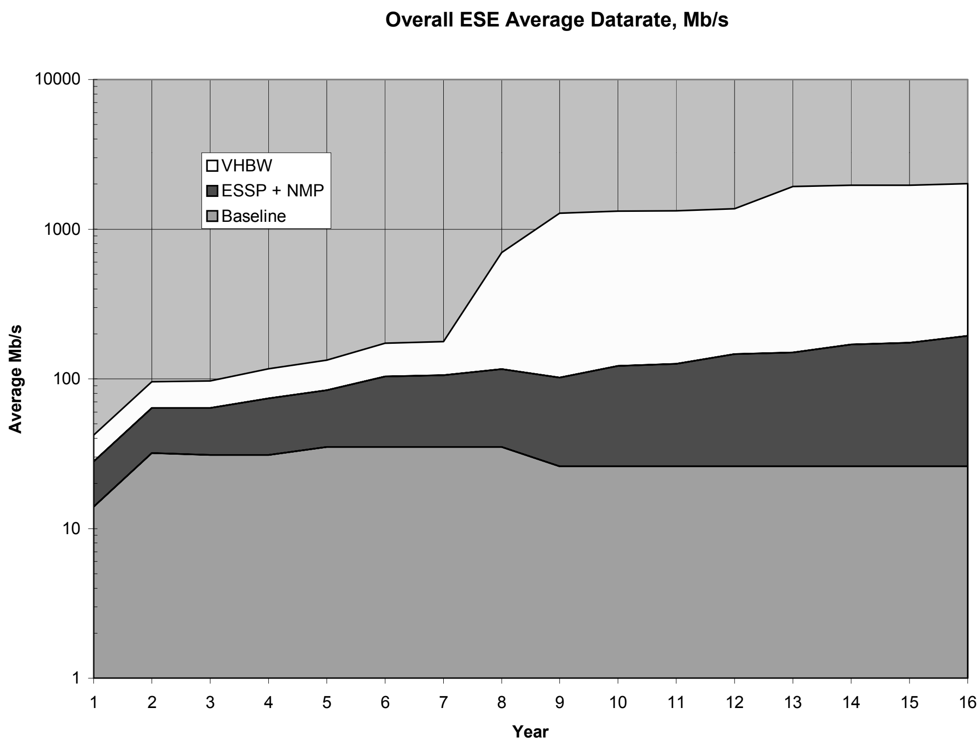

Figure 15: Total NASA ESE Planned and Projected Downlink Data Rates (Wende)

Radio Frequency: Space to Space

Current concepts for space-to-space radio frequency relay include the NASA Tracking and Data Relay Satellite System (or other, replacement US government systems), use of commercially available space-to-space relay systems, and the direct interconnection of observing missions, as described in the various sensorweb concepts. Replacement US Government relay systems beyond the current TDRS Replenishment Program will be discussed in the section on optical communications concepts.

With the recent launch of TDRS-I, NASA is in the process of updating its Tracking and Data Relay Satellite System.* There are now eight TDRSS satellites in orbit. TDRS-I is the first of three future satellites in the $840 Million TDRS Replenishment Program. This replenishment program also includes modifications to the White Sands ground station complex.

The new satellite continues to support single use access at both S-band and Ku-band, with two steerable antennas that can support either frequency. Applications of S-band single access include links to user satellites with smaller antennas and telemetry from expendable launch vehicles during launch. Applications of Ku-band single access include higher bandwidth for user satellites, high-resolution digital television for Space Shuttle video, and the transfer large volumes of data from NASA scientific spacecraft data recorders.

The three new satellites (including the one just launched) will include several new capabilities. The Ka-band single access increases the TDRSS data rate capability to 800 Megabits per second to provide communications with future missions requiring high bandwidths, such as multi-spectral instruments for Earth science applications. In addition, a multiple access capability using an S-band phased-array antenna will allow the TDRS satellites to receive and relay data simultaneously from five lower data-rate users, while transmitting commands to a single user.

In addition to this NASA TDRSS capability, there are a number of commercially available space-to-space relay systems and space-to-ground services. In some cases, a system designed for space-to-ground communications may be able to support a space-to-space link. For example, it appears technically feasible that a satellite with a low data-rate requirement could appear to a commercial communications system as if it were just another phone (that happens to be traveling at 7 kilometers per second).

Finally, a number of the sensorweb concepts assume that the observing nodes have the capability for direct interconnection of observing missions. Since these concepts stress near real-time adaptation and response to changing Earth phenomena, these would almost certainly involve use of a space relay capability, either dedicated to the sensorweb or provided as a service by some larger commercial, government, or joint system.

Radio Frequency: Space to Ground

The infrastructure to support space-to-ground radio frequency communications links includes Government, commercial, and International tracking stations, as well as direct to user downlink capabilities. All of the space-based relay systems discussed in the previous section use one of these approaches as the final link to the information system and the user. The TDRSS ground station is in White Sands, New Mexico.

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* NASA, "Advanced NASA Communications Satellite Gives Broadband Access New Meaning," Press Release: 02-40, March 5, 2002, URL ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-040.txt

NASA's original plan for the Earth Observing System (EOS) was to use TDRSS for all large Earth Science Enterprise spacecraft, along with a direct-to-ground X-band that would provide a back up for science and a direct broadcast capability for rapid science access. However, the move to smaller spacecraft led to a shift towards direct X-band downlink as the primary communications link. NASA built two ground stations to support this policy, one at Poker Flat, Alaska and the other at Longyearbyen, Svalbard (Spitzbergen).[*]

Many other operational, commercial, military, and International ground station facilities exist. Agreements, exchanges, or purchases may be used to access these facilities. For NASA missions, tracking, control, communications, and other operations services are available through the NASA Space Operations Management Office (SOMO), which has established contracts with commercial providers.[†] More information on concepts and the design of the ground system is available in Whitworth.[‡]

Optical Communications

As shown in the figure developed by Wende above, the potentially large data rates of future missions suggest that NASA consider the development of optical communications. NASA currently maintains a worldwide network of Satellite Laser Ranging stations that support navigation functions by illuminating corner-cube reflectors on satellites. These stations autonomously track satellites and have optical receive capabilities. An effort is currently underway to investigate adapting some of these Satellite Laser Ranging stations to support laser communications.

NASA is not the only U.S. agency engaged in space activities that anticipates massive data rates and the need for real-time data access for future missions. Little current information is publicly available about concepts for any future, merged Civil and National Security communications infrastructure. However, the level of investment that the military and intelligence communities are likely to make could have a significant impact on the capabilities available for civil use, even if the specific systems are not open for unclassified users.

There is some indication of interest in systems that support both intelligence and civil use. In mid-1999, the Office of the National Security Space Architect released a Request for Information regarding Mission Information Management, compromising "all aspects of gathering mission-essential information from data and information collection to providing the resulting information

[*] Wende, C., "Communications Outlook for NASA's Earth Science Enterprise (ESE)," viewgraph presentation dated January 23, 2001. This presentation is an update to Wende, C., "NASA Remote Sensing Missions and Frequency Issues," IGARSS 2000, July 24-28, 2000.

[†] NASA, "Earth System Science Pathfinder (ESSP) Missions NASA Announcement of Opportunity," AO-01-OES-01, May 18, 2001.

[‡] Whitworth, G., "Ground System Design and Sizing," chapter 15 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

and knowledge to mission-executing entities."* This RFI goes on to state: "Providers include national and tactical Intelligence, Surveillance, and Reconnaissance (ISR) systems, as well as commercial and open source systems. Networks include commercial and Government space and terrestrial communications networks." The RFI makes it clear that the expected users of such a system include both the Intelligence Community and other Civil Agencies, specifically naming NASA.

4.4.2 Communicating Command and Engineering Data

Although the data rates are significantly lower and the need for continuous coverage often higher, the basic concepts for communicating command and engineering data are the same as those for communicating the science data.

One unique and important consideration that is often overlooked is the need to build into the system the ability to learn from failure by returning sufficient information about the state of the mission to reconstruct the reasons behind a catastrophic loss. Often, this feedback does not provide any information that is useful for mission recovery efforts. This leads engineers and mission designers to consider eliminating these capabilities as unnecessary and possibly even distracting when working to optimize the individual mission. However, when taking the multi-mission view, this learning and the opportunities it brings for mission improvement are essential.

4.4.3 Launching and Deploying Missions

Information on space mission launch infrastructure is readily available from sources such as:

- The Aerospace Source Book, an Annual Publication from Aviation Week and Space Technology (most recently 2002), which provides an assessment of launch services market and industry trends, and a table summary of worldwide launch capabilities.†
- The Chapter on Launch Systems in the book *Space Mission Analysis and Design*.‡
- The Section on Space Transportation in the report "Trends in Space Commerce."§

The author sees little value in reproducing all but a summary in this thesis. The following two figures are from the "Trends in Space Commerce" report.

* Commerce Business Daily, "National Security Office Seeks Help," Request for Information, May 28, 1999.
† Aviation Week and Space Technology, "2002 Aerospace Source Book," January 14, 2002, vol. 156, no. 2.
‡ Loftus, J., and Teixeira, C., updated by Kirkpatrick, D., "Launch Systems," chapter 18 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.
§ U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, Section Two, "Space Transportation," URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

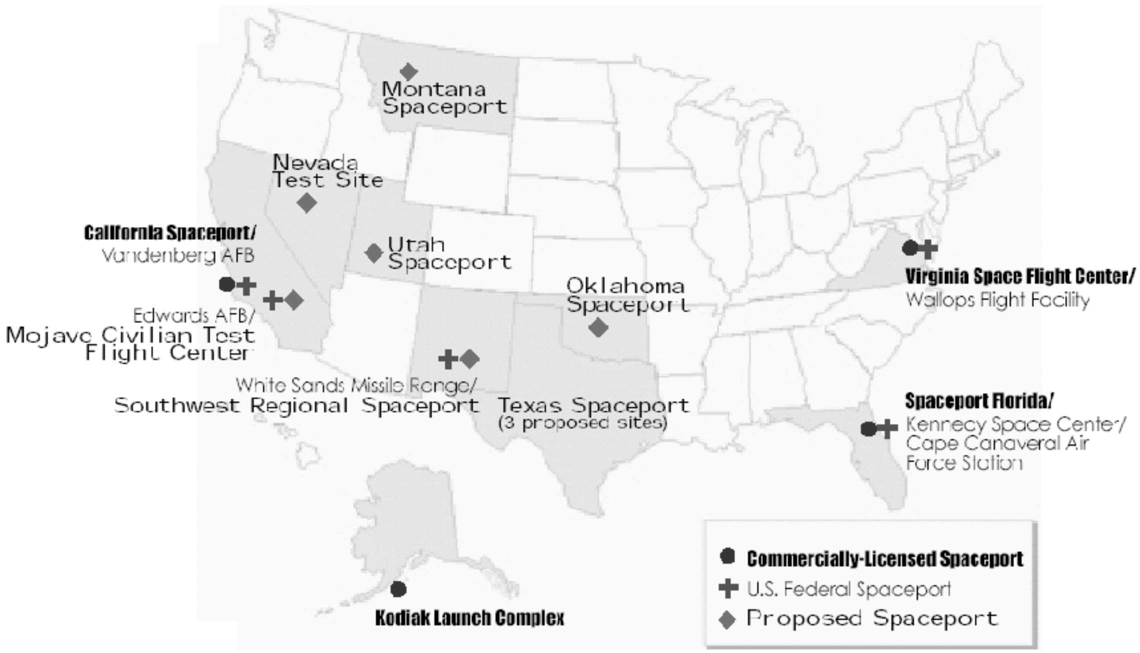

Figure 16: Current and Proposed US Launch Site Facilities (Dept. of Commerce)

Figure 17: Active Non-US Launch Sites Facilities (Dept. of Commerce)

Implications of launch site latitude on the orbits that can be supported will be discussed in the next chapter on system form.

It is beyond the scope of this study to assess all of the possible deployment mechanisms for Earth-based and *in situ* measurement capabilities. Many concepts, such as radiosonde balloons, are in worldwide use daily as part of the world's weather forecasting capability.

4.4.4 Navigating Missions

The following summarizes the numerous concepts for guiding and navigating multiple space-based missions. These same approaches can also support Earth-based sensing, although in some cases additional infrastructure investments would be needed. With the exception of the Satellite Laser Ranging and the DORIS systems, a description of these approaches is available in the book *Space Mission Analysis and Design*.[*] Kramer also provides a discussion that includes the historical development of capabilities and a description of the laser ranging network.[†] The information on DORIS is from a Centre National d'Etudes Spatiales (CNES) video distributed by CD-ROM.[‡]

Some individual mission guidance and navigation concepts are independent of any multi-mission infrastructure. These include star, limb, Sun, Moon, and/or Earth limb/feature detection and/or recognition systems. Several specific products and approaches are mentioned in the *Space Mission Analysis and Design* book. In addition, satellite cross-links built into a constellation design can provide navigation relative to other satellites (e.g., to maintain spacing in multi-satellite constellations), although this does not provide absolute position information relative to the Earth.

Many past and current guidance and navigation concepts rely upon multi-mission infrastructure and include the ground-in-the-loop for calculations. These systems measure either the time delay to calculate range, the frequency shift to calculate rate, or both, between the mission and one or more multi-mission infrastructure assets. The mission operations system then uses this information to calculate and forecast the mission's position and momentum. Current systems include ground communications station range and rate tracking, ground beacon rate tracking (e.g., DORIS), relay satellite range and rate tracking (e.g., TDRSS), and satellite laser ranging.

Advances in computing technology now make it possible for missions to use the available infrastructure to autonomously calculate their positions onboard in real-time. The most ubiquitous approach is to use satellite navigation services such as GPS, GLONAS, and the planned Galileo system. Another concept currently in use is ground beacon rate tracking (e.g., DORIS) with on-board processing. In general, these systems are designed for terrestrial or low

[*] Wertz, J., "Guidance and Navigation," chapter 11.7 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

[†] Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002, chapter 1.7, "Navigation."

[‡] CNES, "Doris, the surveyor from space," Centre National d'Etudes Spatiales (CNES), video distributed by CD-ROM, March 2001.

Earth orbit use. The signal strength tends to drop off quickly with altitude. Although some work has been done on using the GPS signals that “spill over” the Earth’s limb for geostationary orbit locations, mission designers should not assume that current navigation systems would work in orbits other than low Earth orbit. In addition, future navigation system concepts should consider the costs and benefits of supporting other orbits. This and a related consideration for data relay systems are also noted in the chapter on system form, under the discussion of the supported orbits and vantages.

The ground infrastructure investments that support these capabilities include ground radio frequency communications stations, ground radio frequency beacon networks (e.g., DORIS), and the satellite laser ranging station network. In order to provide full orbit coverage, these stations must be globally distributed. The space infrastructure investments that support these capabilities include relay satellites (e.g., TDRSS) and navigation satellites (e.g., GPS, GLONAS, and the planned Galileo system). In addition, dedicated navigation cross-links could be included in the specific design of a system.

Navigation and guidance are tightly coupled. Except in dead reckoning systems, it is not possible to control a mission’s location (guidance) without first determining the location (navigation). Concepts for improving the individual mission capabilities to navigate and guide that are related to individual mission capabilities rather than multi-mission infrastructures are not explicitly covered but would be part of the “New Mission Platform Technologies” in the “Concepts to Maintain and Upgrade the Multi-Mission Measurement System” section above.

In general, there are no current concepts for multi-mission infrastructure to support attitude determination or control. This capability is almost always self-contained within the individual mission. A technique has been demonstrated for using GPS for attitude determination. This concept relies upon the differential arrival of GPS signal at separated antennas on spacecraft structure. Its accuracy depends upon antenna separation, which is related to satellite size. It is currently of low accuracy, especially for small satellites, and if used it is for backup capability only. A description of this approach is available the reference by Eterno.[*]

Earth-based missions can use many of these same concepts. Hand-held GPS units are now common. The details of the implementation may vary, but the concepts would be related. For example, corner cubes and laser ranging could be used to track a balloon, but the existing Satellite Laser Ranging network would be too sparse to provide adequate coverage, and more local, dedicated ranging stations would have to be used.

[*] Eterno, J., “Attitude Determination and Control,” chapter 11.1 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

4.4.5 Operating Missions

One very common multi-mission operations concept is the development and use of multi-mission operations centers. It is rare for an operator to establish a unique facility for a new mission if they already have a facility operating other missions. Most experienced spacecraft operators have established a multi-mission operations center for their missions. In addition, the NASA Space Operations Management Office (SOMO) has established contractual arrangements with commercial space operations system providers, as part of an approach to offer NASA mission developers a standard menu of capabilities. See Carraway et al and Whitworth for more information.[*, †]

Another important aspect of multi-mission operations is time synchronization. Highly accurate time synchronization among distributed systems can improve the performance of electronic switching, time-dependent communications approaches such as time division multiple access (TDMA), security systems that depend upon certified time of transaction, and approaches to network routers and switches.[‡] Some of these approaches may be essential to the successful implementation of future sensorweb concepts. The extremely accurate atomic clock signals from the GPS and other satellite navigation services facilitate multi-mission operations and coordination.

As a future concept, it is conceivable that this could be used to eliminate the need for any on-board clock. Clockless chips are a concept for very low power systems, as the constant clock cycle is often a driver of computer chip power consumption. It is unlikely that this technology would be ready for mission use any time soon.

In addition to "beaming" accurate timing, speculative future concepts for multi-mission physical support include "beaming" spacecraft power and control.

- As part of an effort to identify applications for large ground-based laser systems using adaptive optics to adjust for atmospheric distortions, the author recalls (but did not find a reference on) past studies of optically beaming power to satellites in orbit from the ground. A possibly useful application was to illuminate geostationary satellite solar panels during the season when these satellites pass through the shadow of the Earth. This could allow the extension of mission life when the power system has degraded to the point where satellite loss is possible during occultation. In theory, it would be possible to

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[*] Carraway, J., Squibb, G., and Larson, W., "Mission Operations," chapter 14 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.
[†] Whitworth, G., "Ground System Design and Sizing," chapter 15 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.
[‡] Haller, L., Sakazaki, M., "Commercial Space and United States National Security," prepared for the Commission to Assess United States National Security Space Management and Organization, January 2001, URL http://www.fas.org/spp/eprint/article06.html

match the peak performance wavelength of the solar panels to that of the laser system, but this would likely lead to less performance in response to sunlight.

- Another speculative idea is the potential to “beam” spacecraft control, establishing a “master/slave” relationship in multi-satellite sensorwebs and virtual platforms/trusses. This could allow the “slave” satellite to carry little or no independent computing capability, reducing its cost and power requirements.

4.4.6 Mission Development and Manufacture

The mission development and manufacture process can benefit economies of scale, as well as being important for maintaining and upgrading the multi-mission measurement system. To improve readability, all of the mission development and infrastructure material is incorporated under the “Mission Development Process Improvements” section above.

Chapter 5: Analysis of Form for the Integrated Earth and Space-Based Observation System

5.1 Chapter Summary

This chapter builds upon the functions and concepts developed in previous two chapters. It decomposes the level 2 form of the Earth- and Space-based Observation System. As was done for functions in chapter 3, the approach is to zoom to the individual mission level and expand the level 3 decomposition of individual mission form. The level 3 form decomposition is derived from the state-of-the-art in spacecraft mission design. The thesis uses this level 3 form decomposition to develop and check the completeness of a level 2 decomposition of the multi-mission system form. The Multi-Mission (Level 2) Elements of Form are:

- Observation Subjects
- Supported Orbits/Vantage Points
- Launch/Deployment Capabilities
- Command, Control, Communications, and Navigation Infrastructure
- Standard Space/*In Situ* Components
- Development Capabilities

Current and future examples of these form elements are discussed. In some cases the physical or structural implications of the level 2 form illuminated new aspects and insights into the system as a whole. This decomposition of form leads to an examination of the types of measurements, spectral regions, and spatial scales of interest; the types of vantages and orbits of interest; implications of orbits on the design of the navigation system and the physical locations of ground stations and launch facilities; and the topology options for inter-linking multiple missions for real-time, autonomous observation strategies.

5.2 Rationale and Approach to Form Decomposition

Worldwide, humanity has gained considerable experience in space mission design and development. Kramer indicates that as of as of October 20, 1999 humanity has launched 5,225 satellites, 2,634 that remain in Earth orbit (not all active), 90 "Space Probes" that are beyond Earth orbit, and 2,501 that have reentered from Earth orbit.* At the beginning of 2002 there were about 650 active satellites in space (based upon the 2002 Aerospace Source Book and a count of

* Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002, page 102 and 103.

satellites not included in the Source Book list).* About 65% of these are civil communications satellites, 15% are other civil satellites such as Earth and space science missions, and 20% are military satellites. The Aerospace Source Book also projects that in 2002 an additional 108 satellites will be launched worldwide at a total value of $8.9 billion.

This broad experience base and state-of-the-art practice is captured in modern books on space mission design. This thesis draws upon the book edited by Wertz and Larson, *Space Mission Analysis and Design*.† Wertz and Larson represent a well-constructed definition of a generic space architecture for all mission types. This architecture reflects the practical and basic physical limits on the design of space missions. The individual mission level (level 3) decomposition of form used in this thesis is derived from the generic mission architecture as used in Wertz and Larson.

Wertz and Larson both graphically depict and describe in text a space mission architecture containing the basic elements that all missions include "to some degree."‡ The graphical figure lists the following elements of this generic space mission architecture:

Space Mission Analysis and Design Form Elements (from Wertz and Larson Figure 1-3):

- Subject
- Orbit and Constellation
- Space Element
  - Payload
  - Spacecraft Bus
- Launch Element
- Ground Element
- Mission Operations
- Command, Control, and Communications Architecture

The text in Wertz and Larson describes the following elements:

Space Mission Analysis and Design Form Elements (from Wertz and Larson text description):

- Subject: "the thing which interacts with or is sensed by the space payload."
- Space Element: "the payload and spacecraft bus together," also called the Spacecraft, Space Segment, or Launch Vehicle Payload.
  - Payload: "the hardware and software that sense or interact with the subject."
  - Spacecraft Bus: "supports the payload."

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* Aviation Week and Space Technology, "2002 Aerospace Source Book," January 14, 2002, vol. 156, no. 2.
† Wertz, J., and Larson, W., editors, *Space Mission Analysis and Design*, 3rd Ed., Microcosm Press and Kluwer Academic Publishers, 1999.
‡ Wertz, J., and Larson, W., "The Space Mission Analysis and Design Process," chapter 1 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

- Launch System: everything associated with placing the space element in orbit, including launch specific facilities, ground stations, launch vehicle, adapters, etc.
- Orbit: "the spacecraft's path or trajectory" including initial parking, transfer, final or operational orbit, and end-of-life disposal orbit.
- Communications Architecture: "the arrangement of components which satisfy the mission's communication, command, and control requirements."
- Ground System: "fixed and mobile ground stations."
- Mission Operations: "the people, hardware, and software that execute the mission."
- Command, Control, and Communications (C^3) Architecture: "the spacecraft, communications architecture, ground segment, and mission operations elements."

These graphical and text descriptions are not completely consistent in terminology. In addition, the text contains an apparently circular decomposition of the system. The text describes the Communications Architecture element as "the arrangement of components which satisfy the mission's communication, command, and control requirements," while the "Command, Control, and Communications (C^3) Architecture" element contains the Spacecraft, Communications Architecture, Ground Segment, and Mission Operations elements.

In order to clarify this, the level 3 decomposition of form used in this thesis considers the Command, Control, Communications, and Navigation element to include the Ground System or Ground Element, the Mission Operations, and the Communications Architecture elements as described by Wertz and Larson. This form structure merges the command, control, communications, and navigation elements. Although these are separate functions as identified in chapter 3 of this thesis, many of the concepts to provide these functions are merged systems as discussed in chapter 4. For example, it is common for the communications link to also provide spacecraft range and rate data for navigation. Some concepts such as GPS and DORIS use separate but related hardware for navigation. Similarly, some of the concepts for sensorweb autonomy with direct communications between missions represent a shifting of command functions from the ground to in-flight. Treating these as one element of form should facilitate the shifting of functions internal to this form element and simplify the multi-mission system design.

To generalize the description of form to include missions within the Earth system such as balloon, aircraft, or ocean buoy missions, the more generic term of "deployment" is added to "launch," the more generic term "vantage" is added to "orbit," and the "space element" is extended to include Earth-based and "*in situ*" elements.

5.3 Individual Mission (Level 3) Form Decomposition

The individual mission (level 3) decomposition of form used in this thesis is:

- Subject
- Launch/Deployment Element
- Orbit/Vantage
- Space/*In Situ* Element
- Command, Control, Communications, and Navigation Element

The author believes that the above is a useful decomposition of level 3 form. The following table is a mapping of the level 3 functional intent developed in functional goals chapter of this thesis to the level 3 mission form elements just developed.

Table 18: Mapping of Level 3 Functional Intent to Level 3 Mission Form

Level 3 Functional Intent	Level 3 Form Elements
Obtain Measurements	•Subject
Provide Measurement Results	•Command/Control/Communications/Navigation
Position the System for Measurement	•Launch/Deployment Element •Orbit •Space/*In Situ* Element •Command/Control/Communications/Navigation
Determine Actual Position of Measurement	• Space/*In Situ* Element •Command/Control/Communications/Navigation
Provide Required Measurement Physical Conditions	• Space/*In Situ* Element
Coordinate, Correct, and Adapt	•Command/Control/Communications/Navigation

As is often the case, this view of the individual mission does not capture the development system. The development system addresses the functional intent of maintaining and upgrading the overall multi-mission system. The next table summarizes the multi-mission (level 2) form implications of the mission (level 3) form decomposition, with the addition (in *italics*) of the supporting development system.

Table 19: Mission and Multi-Mission Form

Mission Elements/ Architecture	Multi-Mission Architectural Form Implications
Subject	"Data Fusion" – Multi-Mission Data to Address Subject
Launch/Deployment Element	Flexible, Multi-Mission Launch and Deployment Facilities
Orbit/Vantage	Range of Locations Compatible with Launch and Communications/Navigation Infrastructure
Space/*In Situ* Element	Standard "Platform" Options, Compatible Communications and Navigation
Command, Control, Communications, and Navigation	Multi-Mission Infrastructure in Communications, Tracking/Navigation, Command, Ground Stations, etc.
Development System	Multi-Mission Design & Simulation, Clean Rooms, Vibration/Shock, Thermal Vacuum, etc.

5.4 Multi-Mission (Level 2) Form Decomposition

The next figure graphically depicts the level 3 or mission-level decomposition of form for generic missions, along with the level 0 (Earth Science Enterprise level) and level 1 (Observing System, Information System, and Modeling System level) decompositions. Based upon these levels, this figure includes a level 2 (multi-mission level) decomposition of form that fills the gap between level 1 and level 3, considering the implications on form indicated in the table above.

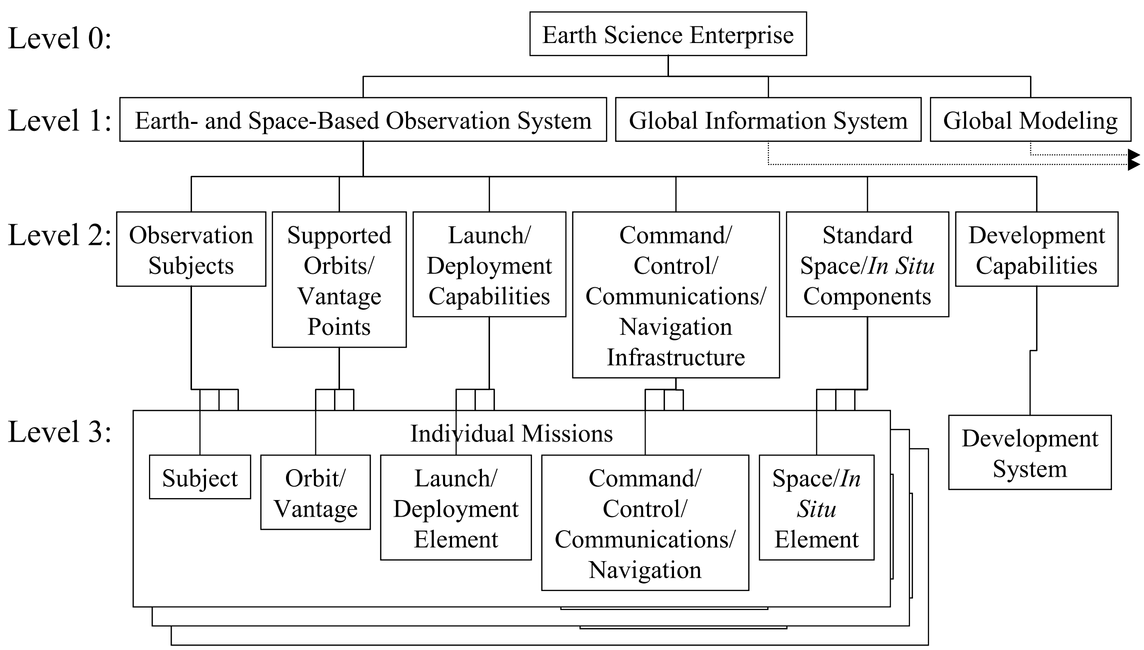

Figure 18: Multi-Mission Form Based On Individual Mission Decomposition

This leads to the following multi-mission decomposition of form that is used for this thesis:

Multi-Mission (Level 2) Elements of Form:

- Observation Subjects
- Supported Orbits/Vantage Points
- Launch/Deployment Capabilities
- Command, Control, Communications, and Navigation Infrastructure
- Standard Space/*In Situ* Components
- Development Capabilities

The next figure is a mapping between the (level 2) multi-mission functional intent (developed in chapter 3) and the (level 2) multi-mission system form (developed here). This mapping was one approach used to check these decompositions for consistency and completeness.

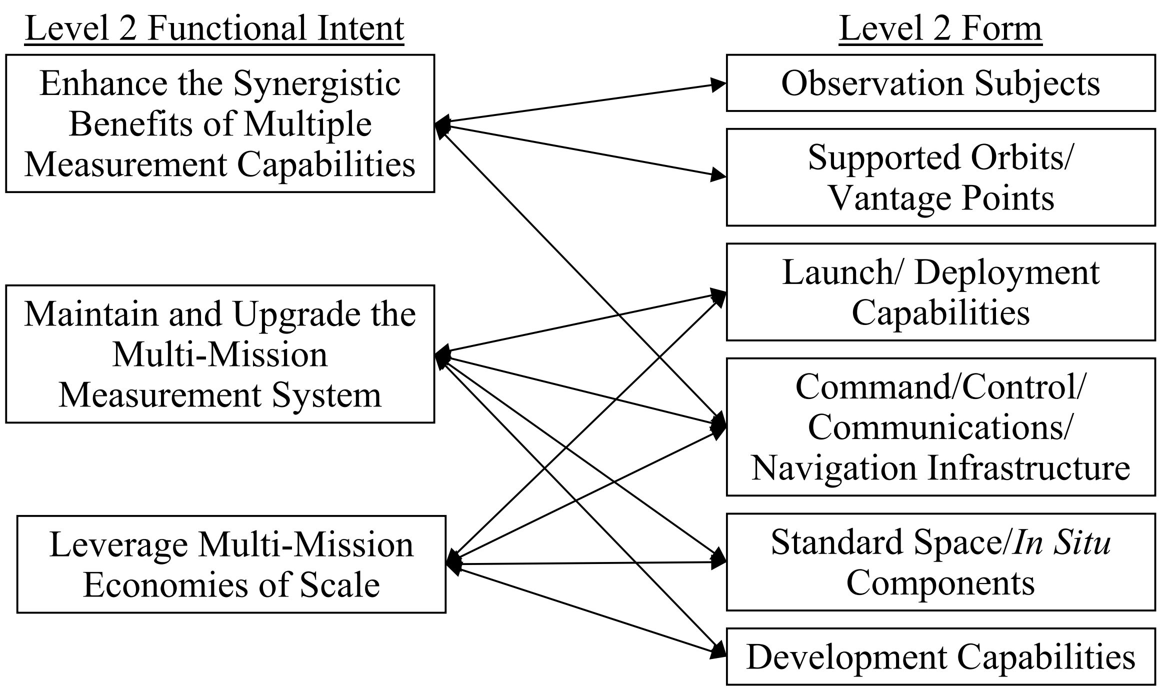

Figure 19: Mapping of Level 2 Functional Intent to Level 2 System Form

The remainder of this chapter further describes and develops the options and implications for these elements of multi-mission form.

5.4.1 Observation Subjects

Chapter 4 introduced the 23 measurements in the Science Research Strategy and the implications for classes of measurements (Systematic, Exploratory, etc.). Chapter 4 also developed a 3-attribute classification of co-observation approaches (based on attributes of vantage, similarity of observation, and degree of real-time coordination). These have form implications on the Observation Subjects, discussed here, as well as on the Supported Orbits/Vantage aspects of form discussed in the next section.

The earlier chapters emphasized measurement requirements and system function. This chapter emphasizes the implementation and the implications for system form. This includes physical sensing strategies, the electromagnetic spectrum, and the relationships between observation temporal and spatial scales. In addition, the implications of the mapping from measurement requirement to observation implementation are discussed.

Observation Subject Sensing Strategies

In order to provide flexibility to the individual mission planners and developers, the multi-mission system architecture should support any and all of the following sensing strategies:

- Passive Electromagnetic (e.g., Reflected Sunlight, Thermal Emission, Solar/stellar Occultation)
- Active Electromagnetic (e.g., Radar, lidar)
    - Monstatic (Transmitter & Receiver Co-located)
    - Bistatic (Transmitter & Receiver Separated, Including Occultation)
    - Multistatic (Multiple Locations)
- "Parasitic" Electromagnetic (e.g., Occulted or Reflected GPS) ("parasitic" is the term used by Kramer)
- Non-electromagnetic Remote (e.g., Gravity, Magnetic, Electric, Neutrino, etc.)
- *In Situ* Sensing (e.g., Mass Spectrometer, Thermometer)

The architectural structure developed in this thesis should provide the flexibility by treating individual missions as interchangeable modules at level 3.

Observation Subjects and the Electromagnetic Spectrum

The following figure summarizes where in the spectrum and for what purpose the above electromagnetic sensing strategies are typically used.

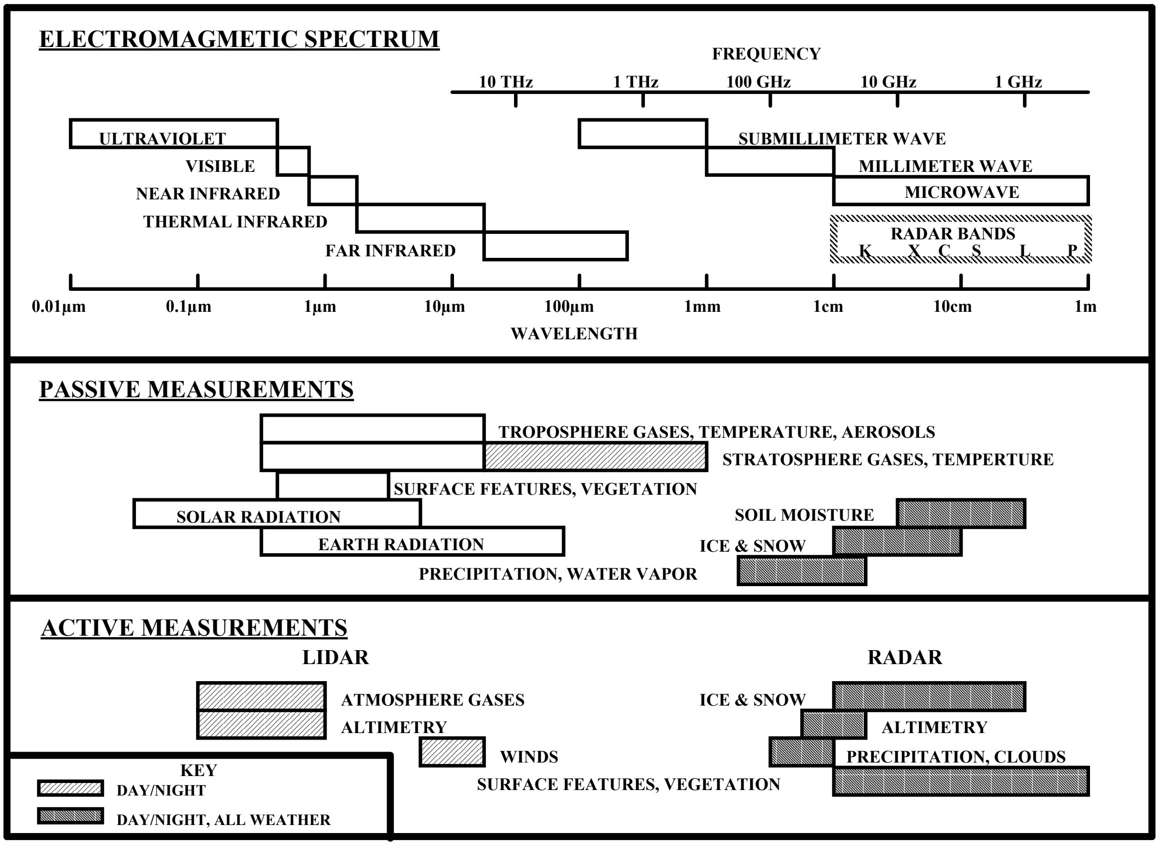

Figure 20: Earth Science Spectrum and Measurement Regimes (Gershman)

This figure was originally developed by Robert Gershman of the Jet Propulsion Laboratory as part of the Spacecraft Systems Analysis program. Versions of this figure have appeared in a number of publications.[*, †]

The radio frequency region of the electromagnetic spectrum is an area that requires particular care and attention. Earth observation missions have three uses for radio frequencies: active sensing of the Earth's surface and atmosphere (transmit and receive), passive sensing of the Earth (receive only) and for communicating with and navigating missions.[‡] The Radio

[*] Ad Hoc Review Team on Planet Earth Technologies, "Technology for the Mission To Planet Earth," Report of the Ad Hoc Review Team on Planet Earth Technologies of the Space Systems and Technology Advisory Committee for the National Aeronautics and Space Administration, 1989.

[†] Rosen, R., Johnston, G., "Advanced Technologies to Support Earth Orbiting Systems," paper no. IAF-92-0751, 43rd Congress of the International Astronautical Federation, August 28-September 5, 1992, URL http://ranier.hq.nasa.gov/Sensors_page/Papers/IAF92/IAF92.html

[‡] Wende, C., "Summary of Radio Frequency Bands Allocated to EESS and Used by NASA's Earth Science Enterprise," viewgraph presentation dated February 2002. This presentation is an update to Wende, C., "NASA Remote Sensing Missions and Frequency Issues," IGARSS 2000, July 24-28, 2000.

Regulations from the International Telecommunications Union set aside limited bands for these uses. Different bands have different levels of protection (primary, secondary, or footnote). There are many competing uses of radio frequency spectrum. Competition for allocations is increasing, driven mainly by the growth in commercial communications and wireless applications. As a result, there is potential for interference with observation capabilities. Although optical links are an option for communications, some measurement requirements have no implementation alternatives other than radio frequency observations. NASA needs to continue to actively engage with the International Telecommunications Union on issues of radio frequency allocation for passive and active remote sensing as well as for communications. This includes registering all radio spectrum uses, including passive uses, so that International users are aware of potential conflicts.

Observation Subject Characteristic Spatial and Temporal Scales

Different observation subjects tend to have different characteristic spatial and temporal scales. The following figure summarizes these characteristic scales.*

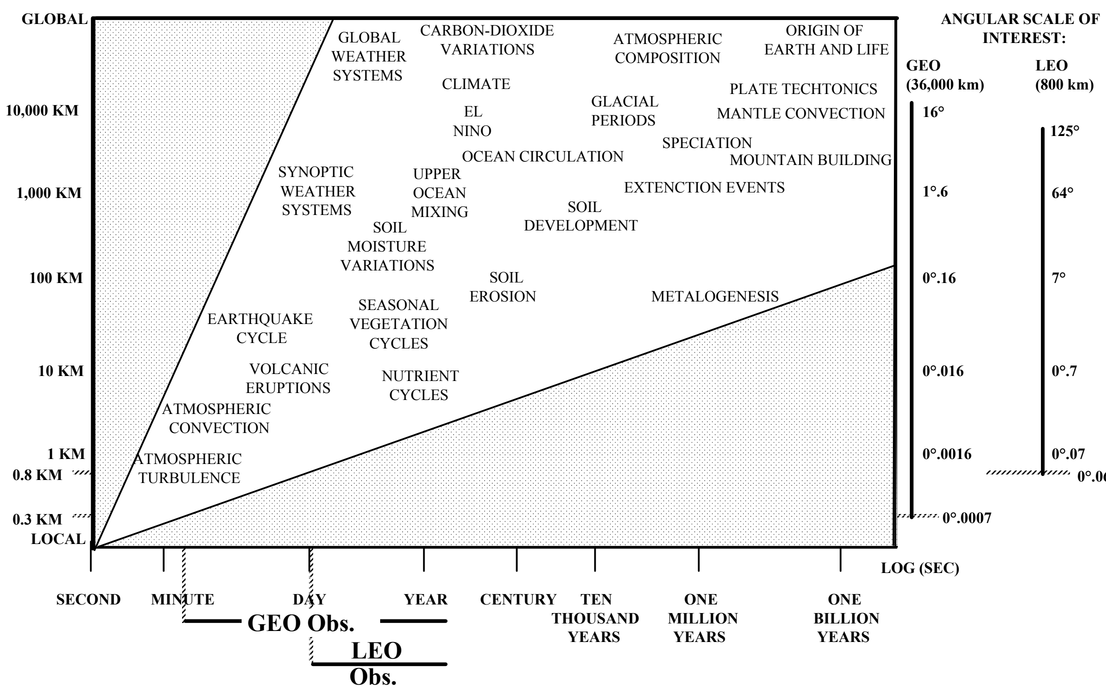

Figure 21: Characteristic Spatial And Temporal Scales

* Originally from the Bretherton Report (Bretherton, F., chair, "Earth System Science, A Closer View," Report of the Earth System Sciences Committee, NASA Advisory Council, January 1988), versions of this figure have appeared in a number of publications, including "Technology for the Mission To Planet Earth," Report of the Ad Hoc Review Team on Planet Earth Technologies of the Space Systems and Technology Advisory Committee for the National Aeronautics and Space Administration, 1989.

In order to provide flexibility to the individual mission planners and developers, the multi-mission system architecture should support (to the greatest extent possible) these diverse spatial and temporal scales.

Measurement Requirements and Observation Implementation

An issue is whether the individual mission observation subjects (form) should align with the Science Research Strategy Measurement Requirements (function). This represents a tradeoff between the benefits of modular independence and the potential for duplication of measurement capability.

The current Earth Science Enterprise approach for mission implementation emphasizes the flexible and modular approach, in which the observation subject of the individual mission is clearly focused on a subset of the measurement requirements. For example, the most recent Earth System Science Pathfinder (ESSP) Announcement of Opportunity (AO) specifically states that the science evaluation will consider, "The ability of the proposed mission to resolve the proposed scientific/applications questions through a focused mission."[*]

Experience has shown that having a clear and limited focus for a mission has many benefits. Maier and Rechtin argue that a key distinction between engineering and system architecting is the clarity of the goals.[†] Clear mission goals help in:

- Providing clearer criteria for resolving ambiguity and conflict during the mission design and implementation.
- Forming the basis for a common project vocabulary, one of the four essentials of project management identified by Foresberg, Mooz, and Cotterman.[‡]
- Providing flexibility by allowing trades of mission performance options as long as the overall focused objective is met.
- Providing modularity by establishing a simple, single link between the science measurement requirement and the mission implementation.
- Establishing a direct link between the goals of the mission and the ultimate use and users of the data. For many missions, the final implementation decision authority is vested in a lead scientific user, helping to ensure that the mission implementation provides data that is relevant and advances the state of knowledge regarding the Earth. These missions are called "PI-led" missions, and are managed by a single Principal Investigator (PI). The following quote from the most recent ESSP AO describes PI-Led mission management.

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[*] NASA, "Earth System Science Pathfinder (ESSP) Missions NASA Announcement of Opportunity," AO-01-OES-01, May 18, 2001, page 10.

[†] Maier, M., Rechting, E., *The Art of Systems Architecting*, 2nd Edition, CRC Press, 2000.

[‡] Foresberg, K., Mooz, H., and Cotterman,H., *Visualizing Project Management*, 2nd Edition, John Wiley & Sons, Inc., 2000.

> ESSP mission teams shall be led by a **single** Principal Investigator from any U.S. organization including educational institutions, industry, nonprofit institutions, NASA Centers, Federally Funded Research and Development Centers (FFRDCs) and Government agencies. The PI is responsible to NASA for the scientific integrity of the mission, as well as the management of the complete mission. Teaming and partnership arrangements are encouraged. Co-Investigators (CoI) **shall** have an identified role in the proposal, play a defined and necessary role in the investigation, and be covered in the funding plan. Teams are encouraged to use U.S. commercial suppliers, commercial off-the-shelf technology, and other arrangements to support U.S. industry to the greatest extent practical.[*]

However, this direct alignment of the measurement requirement and the observation subject is not without cost. Many of the implementation options for widely diverse measurement goals are closely related. As an example, a single instrument, a long wavelength passive microwave radiometer, could measure both soil moisture and sea surface salinity, addressing two very different measurement requirements. During an interview, a leading scientist expressed the concern that a proposal for a single mission to address two diverse measurement requirements would not likely be selected under the current evaluation criteria.[†]

An emerging trend in Earth science, one of the motivations for taking a systems approach to the study of the Earth, is a greater reliance on the "fusion" of data from multiple sources to answer science questions. This is manifesting itself in the trend towards formation and constellation missions to obtain complementary measurements. Many of the sensorweb concepts rely upon data fusion as a key concept in achieving their synergistic observation goals. However, an implication of this trend is the risk of losing capability with loss or delay of a critical mission.

As discussed in chapter 4 in the mission development process improvements section both research and experience with the evolution of other industries suggests that as uncertainties in needs and technologies are resolved, the focus will shift from "features" to "process." This shift will tend to emphasize greater linkage between elements to provide "global" optimum, often at the expense of architectural flexibility to changes in these linkages.

Future assessments of the architecture of the integrated Earth and space-based observation network for Earth science should consider the risks and benefits of cross-measurement optimization. NASA and the Earth Science Enterprise would benefit from the development of

[*] NASA, "Earth System Science Pathfinder (ESSP) Missions NASA Announcement of Opportunity," AO-01-OES-01, May 18, 2001, page 18.
[†] The author participated in several interviews under a blanket assurance of non-attribution. While the author believes that none of discussions were sensitive, the author is uncomfortable attributing specific comments.

tools and frameworks for the timely prediction and identification of when such an architectural switch is appropriate.

5.4.2 Supported Orbits/Vantage Points

This section examines the implications of physically placing the sensing mechanism on the orbits and Earth-based vantage points that the multi-mission system must support.

Earth-based sensing tends to be characterized by fixed (or near fixed) locations, such as weather stations, radiosondes, tethered balloons and ocean buoys, etc., or by slowly varying locations, such as floating ocean buoys, piloted and unmanned air vehicles, platforms of opportunity such as commercial or military shipping, etc. It is inherently difficult for the mechanisms that deploy Earth-based sensors to move anywhere near or faster than the speed of sound. The spatial scales supported for Earth-based sensing tend to be local in nature, and the vantages tend to be fixed or relatively slowly varying. Space-based sensing, on the other hand, involves orbiting spacecraft and space stations. The vantage tends to be inherently global.

Aspects of Orbit Value

This thesis systematically analyzes the key aspects of orbit value, develops a multi-aspect categorization and trade space, and uses this trade space for a gap/opportunity analysis to identify other potentially useful orbits. The three main aspects of orbit value are range, lighting/local time of day, and geocoverage/geolocation. In identifying examples missions that utilize these different approaches, the author drew heavily upon the valuable work of Kramer.[*]

The author has considered if new technologies may add options that significantly change this trade space. For example, solar sails have been proposed to "bias" geostationary orbits towards more populated latitudes.[†] While the constant thrust of reflected sunlight may help to shift orbits or maintain lighting alignment, only slight variations are likely for foreseeable future. Concepts for "pole-sitting" solar sail platforms are a long way from technical maturity, requiring ultra-low mass solar sails or other new propulsion technologies such as nuclear electric propulsion.

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[*] Kramer, H., *Observations of the Earth and Its Environment, Survey of Missions and Sensors*, 4th Edition, Springer, 2002.

[†] Forward, R., "Technical Note, Light-levitated Geostationary Cylindrical Orbits," Journal of the Astronautical Sciences, Vol. XXIX, No. 1, pages 73-80, January-March 1981.

Range

The first aspect of orbit value is range or altitude above the surface of the Earth. Common approaches for constant or near constant range include circular orbits, highly elliptical orbits, and Lagrange point orbits.

As a general rule, close range is desirable for high resolution and active sensing. The resolution of passive electromagnetic instruments is limited by diffraction, an effect of the Heisenberg uncertainty principle. At any given wavelength, diffraction limits the resolution of the measurement as a linear effect of the range to the subject and by a linear effect of the telescope aperture. Doubling of telescope aperture roughly results in a four-fold increase in telescope collecting area and an eightfold increase in telescope volume, with mass roughly scaling with volume. The range also strongly affects power required for active sensing, as the transmitted power tends to drop off as the square of the distance, and the return signal also drops off as the square of the distance. As a result, changes in range have steep, non-linear effects on both the mass and power requirements of many missions.

In contrast, distant range is desirable for coverage. Higher orbits provide more synoptic coverage. One of the interesting consequences of orbital mechanics is that even though increased orbital velocity raises the altitude of an orbit, the resulting rate of angular change relative to the central body decreases. The use of this effect to obtain constant or near-constant geolocation is discussed later in this section.

Designing an orbit to keep range constant can simplify the design and operation of instruments. A spacecraft in a circular orbit maintains a near-constant range and rate of spacecraft motion over the surface of the central body, and these constant values can simplify instrument scanning rates, etc.
Circular (or near circular) orbits by definition have effectively constant range. Distant circular orbits can achieve synoptic coverage, with the most common being the geostationary orbit, which is also discussed under constant geolocation below. Close circular low Earth orbits (LEO) are used for improved resolution or to reduce communications or active sensing (lidar/radar) power, as discussed above. Examples include the polar weather satellites, Landsat, RADARSAT, IKONOS, etc. The orbits for these missions are often also designed to maintain relative time of day coverage and repeat geolocation, as discussed below.

Some missions select higher LEO and even medium Earth orbits to optimize coverage and communications power. When the Iridium constellation was first designed, it had 77 satellites (the atomic number of the element iridium). However, re-optimization of satellite coverage and power requirements resulted in the current configuration of 66 satellites. Similarly, the Global Positioning System (GPS) navigation satellites are in relatively high 12-hour period orbits, increasing the likelihood that four satellites will be in view for the navigation solution.

Another approach to achieving near-constant range is to use highly eccentric orbits. Although the range will vary widely, by far most of the orbit is spent near apogee. The most common example is the Molnoyia orbit, although others are possible. In addition, either the Earth/Moon or Earth/Sun Lagrange points can provide constant and stable (but also very distant) locations.

Lighting and Time of Day

The second aspect of orbit value is lighting and local time of day of the subject. An orbit design can provide either similar or different lighting and time of day conditions. Similar lighting and time of day conditions can ease the comparison of measurements by eliminating diurnal effects. However, this can lead to aliasing (e.g., if the subject of the observation has a significant diurnal dependence, such as afternoon thunderstorms). In these cases sampling across different times of day may be desirable. In addition to these direct effects on the subject, there may be other time of day effects on the area of interest that may influence the orbit design. These could be correlations with cloud or fog cover that interfere with the observation or differential warming rates and unstable ground temperatures for thermal emission instruments. As a general rule for optical instruments, spatial resolution instruments prefer sun angles that enhance shadows for feature detection, while spectral resolution instruments prefer sun angles that reduce shadowing and enhance spectral contrast. The specifics depend upon the subject and measurement requirements of the particular mission.

Common approaches for obtaining constant or near-constant lighting or time of day include close circular sun-synchronous orbits and the Sun/Earth Lagrange points. A low Earth orbit sun-synchronous orbit always crosses the equator at the same relative time of day. This is because the secular variation in right ascension of the ascending node matches Earth's rate around the Sun. Sun-synchronous low Earth orbits are highly inclined, retrograde orbits, usually near circular to negate any effect on the argument of perigee. These orbits are in common use for weather satellites and missions such as Landsat, IKONOS, Terra, EO-1, etc. More recently the Earth/Sun Lagrange points have been identified for what are called sentinel missions. These orbital positions provide constant lighting, but at astronomical distances. For example the Lagrange point where the Sun's and the Earth's gravity are balanced provides constant high-sunlight viewing, but is about 1,500,000 km from the Earth, well outside the Earth/Moon system.

Often the mission requires variable lighting conditions. Any low inclination orbit, such as that of the Tropical Rainfall Monitoring Mission (TRMM) will span the entire range of times of day. The rainfall subject of TRMM benefited from this diurnal coverage. Similarly, the TIMED mission uses the same effect as sun-synchronous orbits, but with the opposite sign, so that the secular variation adds to the effect of Earth's motion around the sun. The orbit equatorial crossing moves from dawn to dusk four times per year. Distant circular orbits can provide variable lighting conditions. The most common is the geostationary (24 hour orbit period), which views a constant geolocation (as discussed below), across all local times of day.

Designing the orbit for constant, near constant, or slowly varying lighting can simplify the instrument design and operation, reducing the need to adjust or change instrument exposure or gain states, as well as more narrowly bound the aperture size needed to collect the light or the time required to collect adequate signal.

Even if the lighting conditions have no impact on the observation subject, missions may derive engineering benefits from considering the lighting and time of day of orbits. The orbit design can affect the spacecraft solar illumination as well as the reflected and thermal energy input from the Earth. These can be design considerations for missions with sensitive thermal or high power requirements. For example, a close sun-synchronous circular orbit with a 6AM/6PM equatorial crossing will remain in constant daylight, except for a short period around one of the solstices. In addition to providing continuous sunlight for power, these conditions keep nearly constant the direct solar thermal input as well as the reflected and emitted thermal input from the Earth.

Geocoverage/Geolocation

The third aspect of orbit value is geocoverage or geolocation. Spacecraft orbits are often designed for repeat ground-track. This can provide measurement subject benefits such as spatially correlated observations, the ability to directly compare time-dependent phenomena, and more predictable operations such as repeat instrument state changes for land/sea boundaries, ground-station passes, etc.

The most common example of a “repeat-track” orbit is a geostationary orbit. The one orbit per day results in constant geolocation. Other examples include the half-day orbits for Global Positioning System (GPS) satellites and Molnoyia satellites, the 8 day repeats (every 17 orbits) for the Russian GLONASS navigation satellites, or the 16 day repeats (every 233 orbits) for missions such as Terra, Aqua, etc.

As mentioned earlier, there is a correlation between distant range and near-constant geolocation. Distant range orbits can match or nearly match the Earth’s rotation rate, enabling constant or near-constant geolocation. The most common example is the geostationary orbit with constant geolocation. Another example is the Molnoyia orbit. For Molnoyia orbits the apogee alternates hemispheres over a constant groundtrack, and the satellite remains over nearly the same geolocation for 11 hours per day.

One of the ironies of orbital mechanics and Earth remote sensing, as illustrated in the following figure (repeated from before), is that to observe very fine time scales (on the order of hours to minutes, the sensing vantage needs to be either within and supported by the Earth system (e.g., airborne or *in situ*) or else it needs to be distant, 35,786 km away. Low Earth orbits enable observations of a given location or phenomena on a timescale of one to three days. Based on the above figure, this corresponds to a characteristic spatial scale of about 0.8 km and drives aperture size to enable approximately 0.06 degree resolution (assuming an 800 km altitude). On the other hand, geostationary orbits enable observations of a given location or phenomena on a time scale of approximately 10 minutes, which corresponds to a characteristic spatial scale of about 0.3 km. and drives the aperture size to enable approximately 0.0007 degree resolution. This is 100x the low Earth characteristic capability.

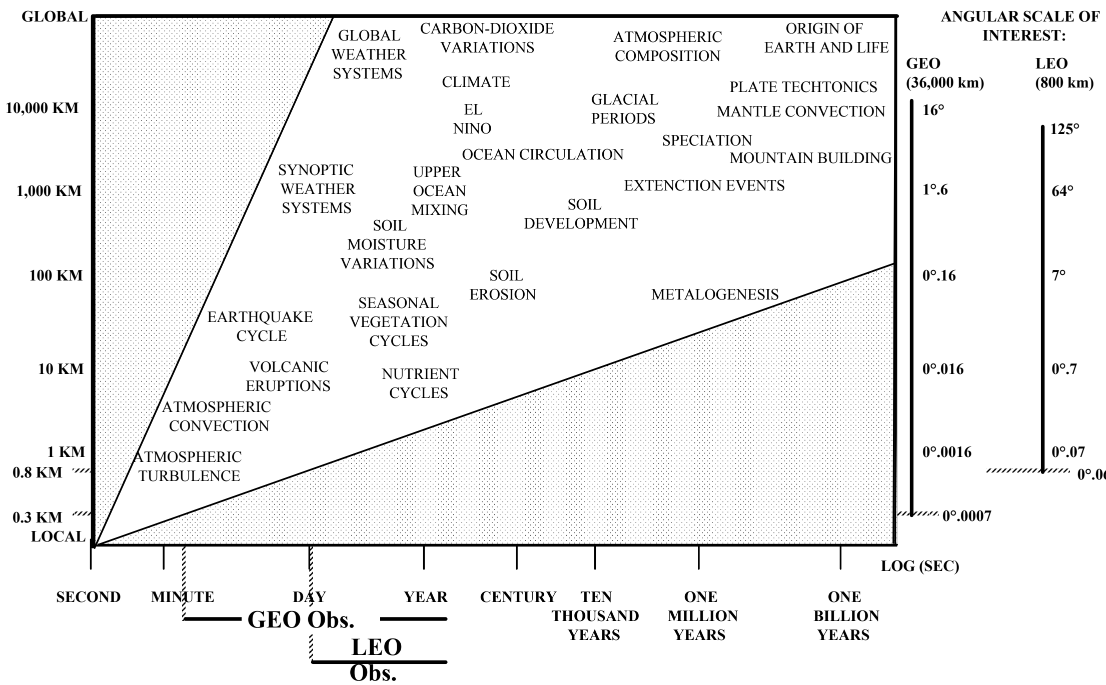

Figure 22: Characteristic Spatial And Temporal Scales

As a general rule, satellites need to operate further away to see finer time scales, while at the same time they need to operate closer to achieve higher resolution, running counter the empirical relationship between temporal and spatial scales of interest illustrated in the above figure.

In addition, geostationary orbits present a much more challenging thermal environment for optics than low Earth orbits. Over the course of the 24-hour geostationary orbit, the optics of geostationary orbit instruments pointed towards the Earth range from pointing nearly into the Sun (when the spacecraft is over local midnight) to pointing nearly away from the Sun (when the spacecraft is over local noon).

Analysis of Orbit Value Trade Space

The following table systematically summarizes these different aspects of orbit value, and includes examples for each combination.

Table 20: Orbit Value Trade Space

Range	Lighting/ TOD	Geo-Location	Corresponding Orbit Types
Close	Variable	Non-Repeat	Non-Repeating Non-Synchronous Orbits
Close	Variable	Repeating	Repeat Groundtrack Non-Synchronous Orbits
Close	Similar	Non-Repeat	Non-Repeating Sun-Synchronous (Retrograde Polar) Orbits
Close	Similar	Repeating	Repeat Groundtrack Sun-Synchronous Orbits
Distant	Variable	Non-Repeat	GEO Transfer Orbits, MEO, HEO, Earth-Moon Lagrange
Distant	Variable	Repeating	Geosynchronous Orbits, Molnoyia Orbits
Distant	Similar	Non-Repeat	Sun-Earth Lagrange Points, **Gap?**
Distant	Similar	Repeating	**Potential Gap: ESSE Orbits?**

This analysis suggests a gap in the types of orbits considered, in that the only approach identified for distant observations under similar lighting or time of day conditions is the Sun-Earth Lagrange point. The next section analyzes the potential for what are called (for lack of a better term) eccentric, Sun-synchronous, equatorial orbits (ESSE orbits or ESSEO) that provide distant coverage under nearly constant lighting and time-of-day conditions.

Eccentric, Sun-Synchronous, Equatorial Orbits

This type of orbit is similar to the Molnoyia and polar Sun synchronous orbits, and takes advantage of the orbit secular variations due to the Earth's oblateness (J_2).

- In Molnoyia Orbits, this effect causes apogee to remains fixed in geolocation. The Molnoyia orbit inclination is selected to cancel the secular variations in the argument of perigee.
- In polar Sun-synchronous orbits, the orbit plane remains approximately fixed relative to Sun. In this case, the secular variation in right ascension of the ascending node matches the Earth's rate around the Sun.
- In the ESSE orbits, the time of day at apogee remains fixed (e.g., at local noon). The secular variation in the argument of perigee matches the Earth's the rotation rate around the Sun.

An ESSE orbits that precess so that apogee remains over local noon would allow two satellites to provide continuous daytime coverage. To examine this possibility further, the author modeled options for these orbits. Detailed modeling using Satellite Tool Kit (version 4.2.1) with both J_2 and the more accurate J_4 propagation indicate a class of orbits that provide these conditions. The approximate formulas in the book *Space Mission Analysis and Design* indicate even more favorable orbit parameters. The results presented here reflect this Satellite Tool Kit modeling.

These orbits were propagated for one or two years with no noticeable change in the alignment of apogee with the Sun-Earth line.

The two cases modeled are:

ESSEO with 9 satellite orbits per 2 days:

- Two satellites provide continuous daytime coverage with at least one satellite always within about 2 hours 15 minutes of local noon.
- Effective daily repeat ground-track by alternating tracks every other day.
- Orbit Properties:
  - Period: 5 hr. 20 min. 10 sec.
  - Eccentricity: 0.57
  - Altitude of Perigee: 273 km.
  - Altitude of Apogee: 17,976 km. This represents the near maximum, as increasing the eccentricity would further reduce the altitude of perigee. Due to concerns over drag the author originally constrained the search to orbits with perigees above 300 km.

ESSEO with 5 satellite orbits per day:

- Two satellites provide continuous daytime coverage at slightly lower hand-off lighting conditions than the 9/2 case above, with at least one satellite always within about 2 hours and 45 minutes of local noon.
- Two satellites in the same daily repeat ground-track, 2 hr. 24 minutes apart.
- Orbit Properties:
  - Period: 4 hr. 48 min. 8 sec.
  - Eccentricity: 0.49
  - Altitude of Perigee: 1,025 km.
  - Altitude of Apogee: 15,120 km.

The following figure depicts these two orbits.

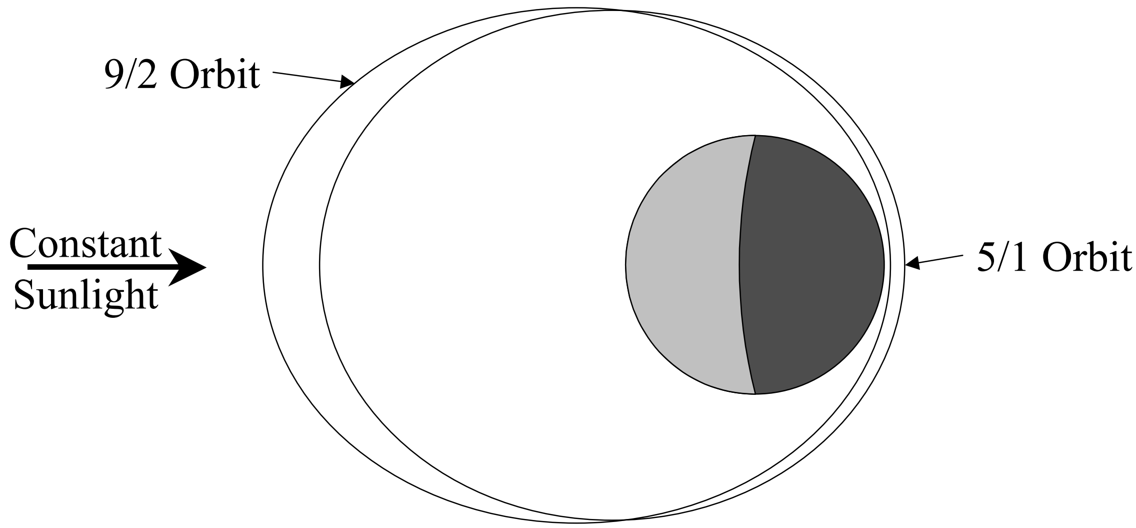

Figure 23: Close Up View of ESSE Orbits

This orbit and Earth polar view shows constant sunlight coming from the left. Throughout the year, these orbits will precess to keep this orientation relative to the Sun. The only variation in the lighting conditions at apogee will be due to the seasonal variation in the latitude of the sub-Sun point on the Earth. The longer period and more eccentric 9/2 ESSE orbit provides relatively more time at high-sunlight conditions.

For comparison with geostationary orbits, the following figure shows both these ESSE orbits and the geostationary orbit.

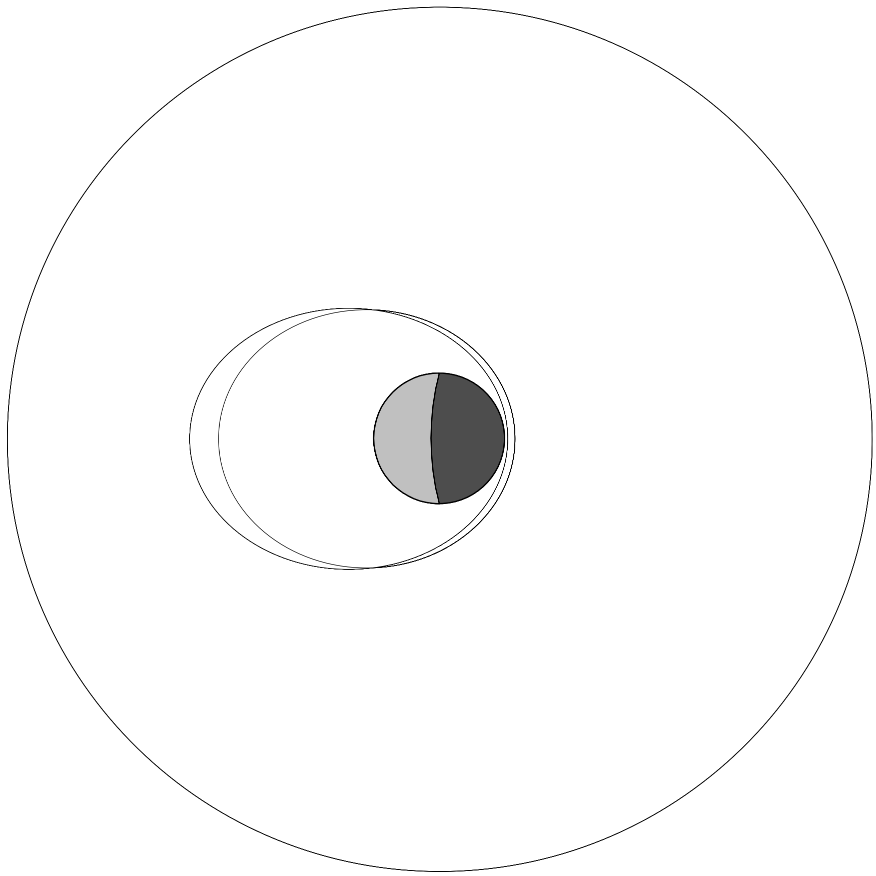

Figure 24: Comparison of ESSE and Geostationary Orbits

The range to the Earth at apogee from these orbits is approximately half that of a geostationary satellite, providing reasonably synoptic coverage under high-sunlight conditions.

The following figure, generated using Satellite Tool Kit, depicts the "hand-off" condition for the ESSE 9/2 orbit. This represents the time when both satellites are at the lowest Sun-angle or the furthest away from local noon. An asterisk represents the sub-Sun spot, with the day/night line or terminator (90 degrees away) marked as well. The season depicted in mid-May, with the sub-Sun spot in the northern hemisphere, so the terminator forms a broad "U" shape on the figure and the South Pole region is not illuminated. The sub-spacecraft points are labeled "Mini9to2a" and "Mini9to2b", with the circle surrounding these points depicting the extent of observation coverage to the limb of the Earth.

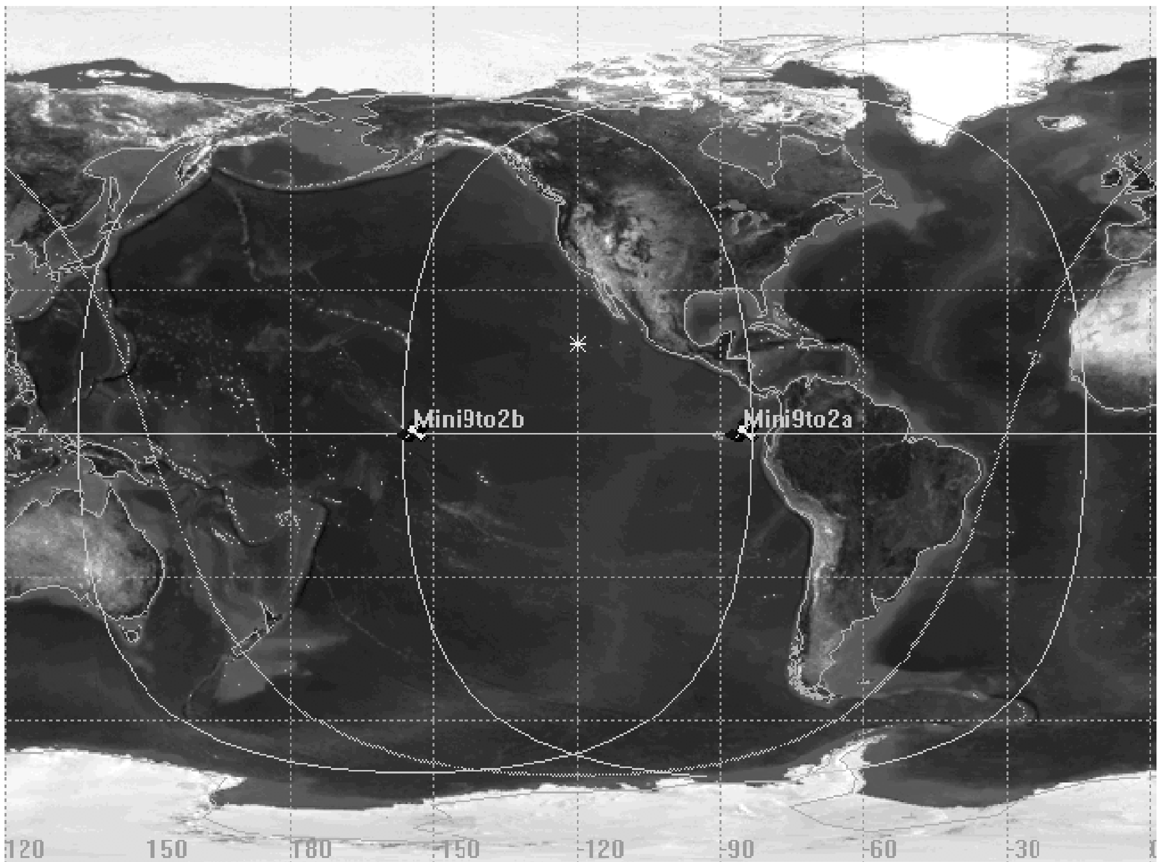

Figure 25: ESSE 9/2 Orbit Hand-off View

As the above figure illustrates, at this 9-to-2 ESSSO "hand-off" point the two sub-spacecraft points are both about 34 degrees in longitude away from the longitude of local noon, corresponding to a difference in time-of-day of about 2 hours 15 minutes. Two spacecraft could provide continuous daytime coverage, with the sub-spacecraft point of one spacecraft always within 2 hours 15 minutes of local noon.

The next figure is the corresponding view one quarter of a satellite orbit (2 hr. 40 min.) later, when one satellite ("Mini9to2a") is at apogee and the other at perigee. Only the apogee view is shown.

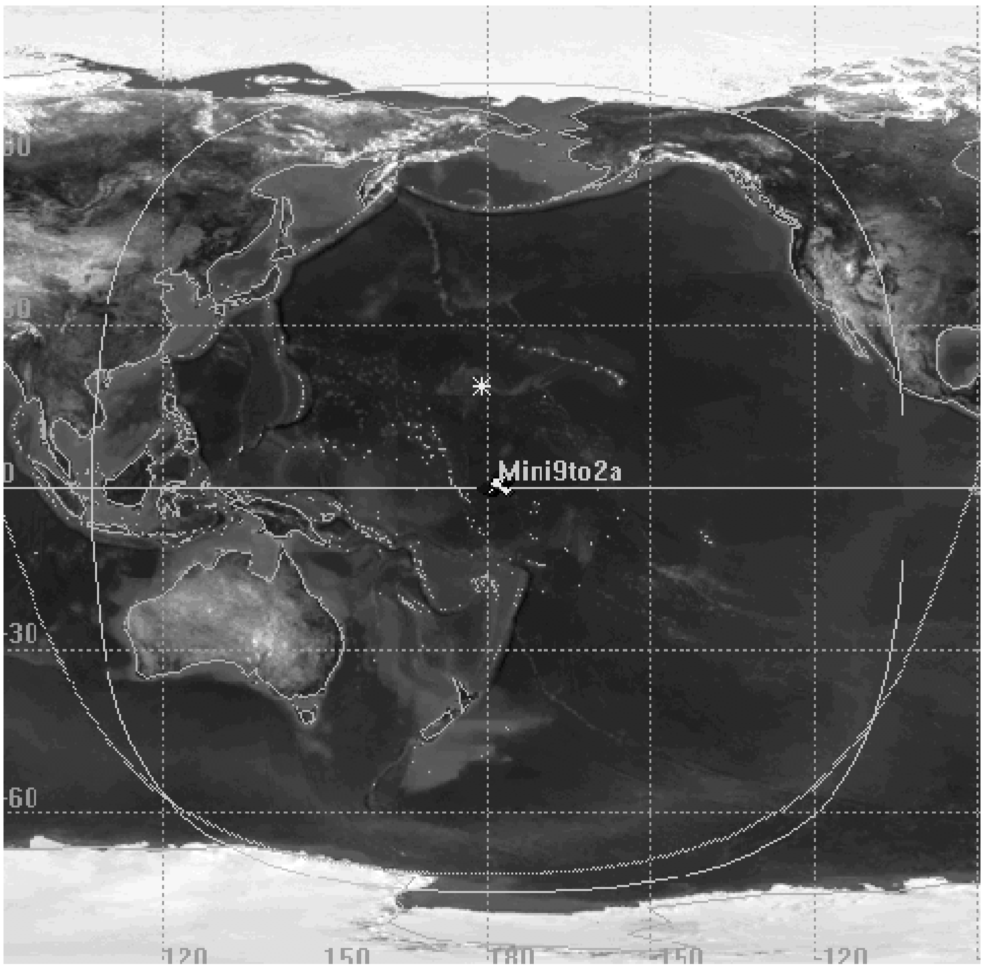

Figure 26: Apogee View of ESSE 9/2 Orbit

The next two figures show the corresponding views for the 5 to 1 orbit. These two views are 2 hr. 24 min. apart.

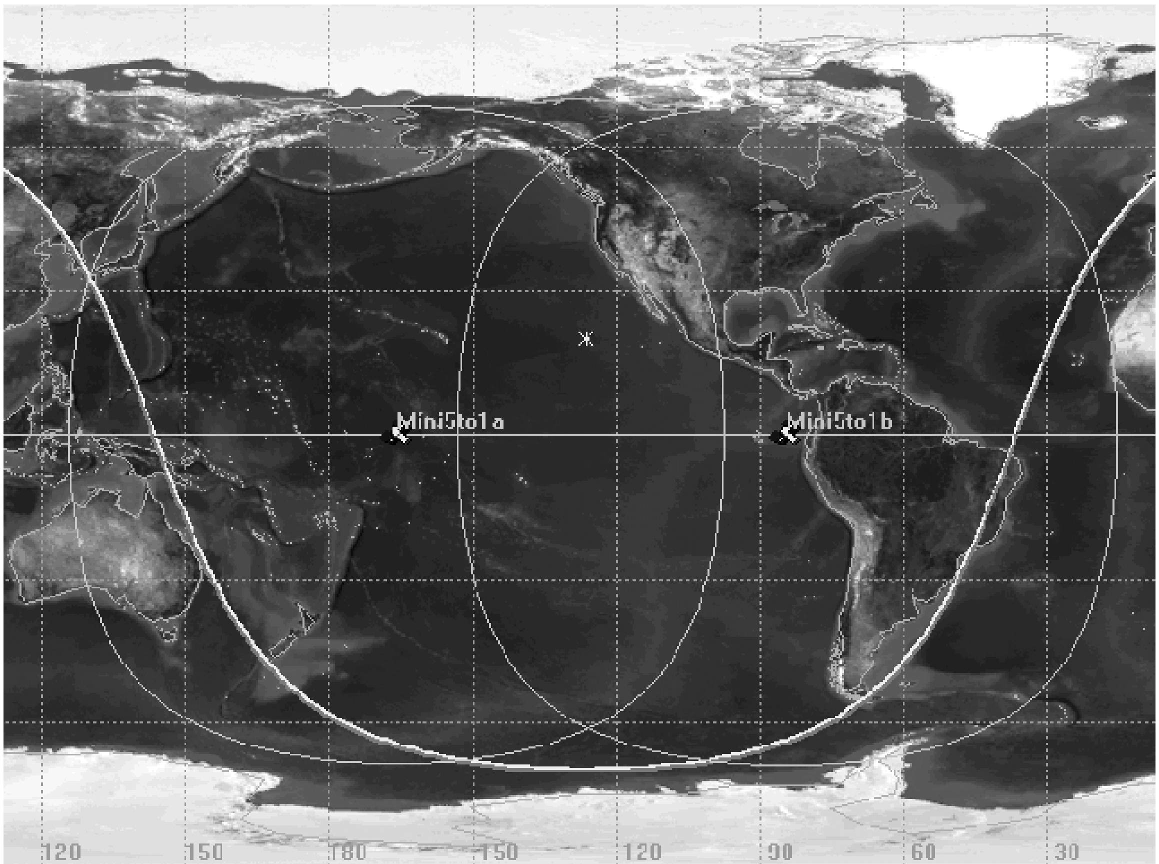

Figure 27: ESSE 5/1 Orbit Hand-off View

As the above figure illustrates, at this 5-to-1 ESSSO “hand-off” point the two sub-spacecraft points are both about 41 degrees in longitude away from the longitude of local noon, corresponding to a difference in time-of-day of about 2 hours 45 minutes. Two spacecraft could provide continuous daytime coverage, with one spacecraft always within 2 hours 45 minutes of local noon.

The next figure is the corresponding view one quarter of a satellite orbit (2 hr. 24 min.) later, when one satellite ("Mini5to1b") is at apogee and the other at perigee. Only the apogee view is shown.

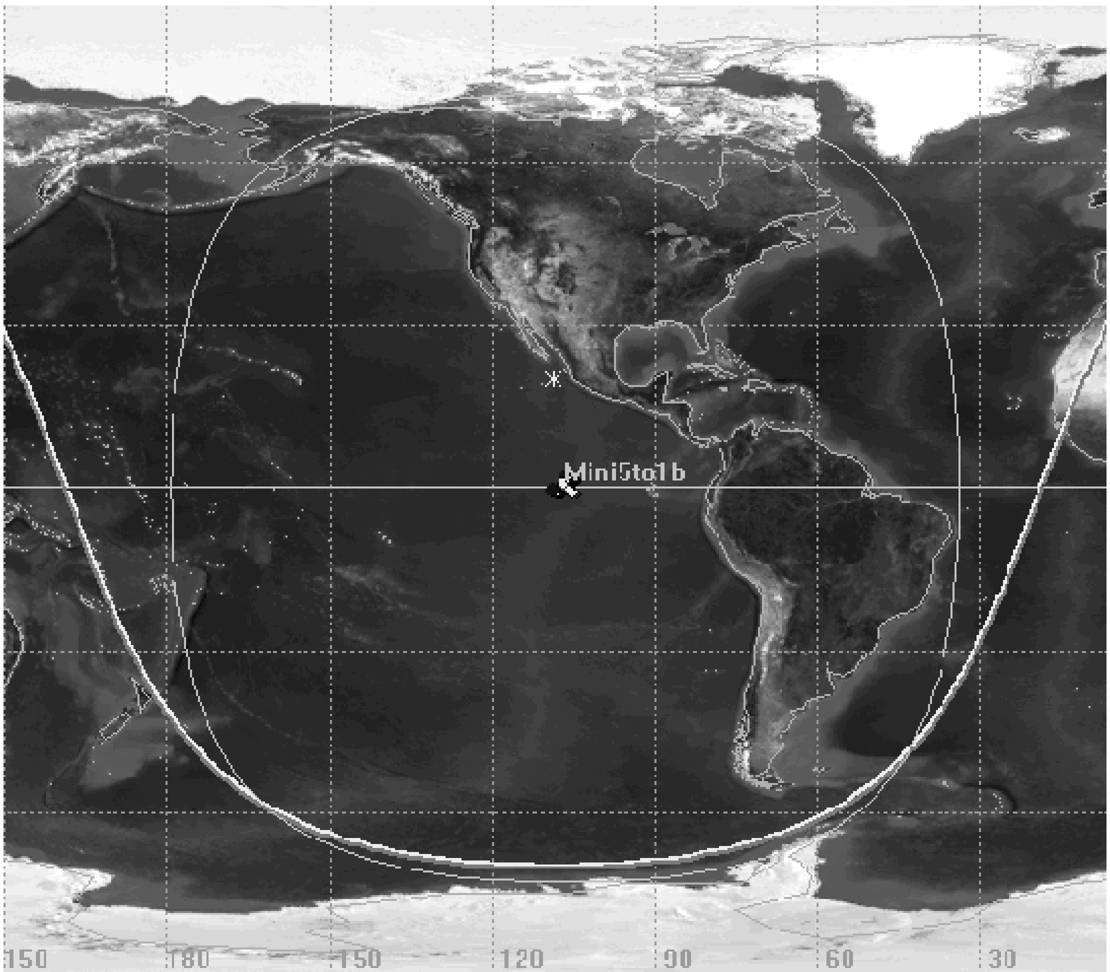

Figure 28: Apogee View of ESSE 5/1 Orbit

These orbit models do not include third body effects (e.g., effects of the Sun and Moon) or the effects of drag. Third body effects should be small compared to the J_2 effect inside geostationary distances. The effect of drag on the 9 to 2 ratio orbit could be a reason for selecting the 5 to 1 option, and was part of the reason both were studied. The author does not believe this will be a significant limitation.

It is rare to discover a new idea in this day and age. It is entirely possible that the concept of orbits of this type has been previously developed and published. If so, this work has been overlooked. The author is not aware of any past or present efforts to develop missions using such an orbit. If I have missed anyone's work, I apologize.

5.4.3 Launch/Deployment Capabilities

The concept chapter has already discussed the current National and International launch capability, and indicated that an extensive discussion of all of the mechanisms to deploy Earth-based and *in situ* sensors is beyond the scope of this effort.

One additional consideration is the relationship between the latitude of the launch site and the orbits that can be supported. As a general rule, the lowest energy orbit available from any launch site is the orbit with an inclination that matches the latitude of the launch site. It is desirable to pick a launch site that is close to the desired orbital inclination. In addition, vehicles destined for low inclination orbits benefit from launching near the equator, as the rotation of the Earth adds to their orbital velocity. On the other hand, vehicles destined for retrograde orbits such as sun-synchronous polar orbits must remove the rotation of the Earth, and therefore benefit from launching nearer to the Earth's poles. As another consideration, the current NASA launch sites avoid launching vehicles over populated areas, and this consideration places additional constraints on the launch options available from any particular site.

The launch capability has implications on individual mission design. Launch is typically one of the most risky and expensive phases of a mission. For example, of the six attempts by US companies to launch high-resolution commercial remote sensing satellites, three were lost due to launch problems, one was lost due to a spacecraft bus problem, and two have been successful. Many missions experience significant delays and cost overruns due to launch problems.

Designing missions for launch vehicle flexibility can mitigate these concerns. Approaches include designing for the static and dynamic envelop as well as the shock and vibration environments of all likely launch vehicles, including larger launch vehicles on which the mission may be paired with other missions.

Another launch concept concern is the market trend towards larger launch payloads.[*, †] This is driven by the trend towards larger commercial communications satellites. The trend raises a question about the commercial launch market's ability to support NASA's trend towards smaller satellites, and suggests this as an area for continuing monitoring and assessment.

A possible response is to increase the use of shared launch vehicles. This approach is not without risk, as this creates a coupling between otherwise independent missions, increasing the probability of schedule delays. If two independent missions each have an 80% probability of

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[*] Aviation Week and Space Technology, "2002 Aerospace Source Book," January 14, 2002, vol. 156, no. 2.
[†] U.S. Department of Commerce, Office of Space Commercialization, "Trends in Space Commerce," June 2001, URL http://www.ta.doc.gov/space/library/reports/2001-06-trends.pdf

meeting the launch schedule, the combined missions will have only a 64% probability of meeting schedule. Chapter 6 on timing and operation discusses and quantifies in a more general context the risk of coupling multiple missions.

5.4.4 Command, Control, Communications, and Navigation Infrastructure

Chapter 4 discussed current data relay, communications, guidance, and navigation concepts. Most of the discussion has been consolidated in this previous chapter and is not repeated here. This section on the form of these systems addresses three issues. The issues are the support of non-low Earth orbits, the physical location of ground stations, and an exploration of structures or network "link topologies" as they apply to concepts for interactive sensorwebs.

Support for Non-Low Earth Orbits

An important implication of the consideration of the form of supported orbits is the capabilities of supporting infrastructure for data relay and navigation. As discussed by Wertz, the current GPS system is designed for terrestrial use.[*] The antenna pattern of the GPS navigation signals drops off quickly with altitude. In effect, the ability to use GPS for satellite navigation is somewhat accidental, and it is not clear if there is enough "spillover" beyond the edge of the Earth to use GPS navigation for orbits other than LEO. Similarly, the TDRS system is designed for satellites in LEO and does not support GEO satellites.

Since satellites that are far from the Earth would have an unobstructed view of most of the sky as well as a large region of the Earth's surface, in should be possible to extend these capabilities with a small number of navigation and communications/relay sites. However, optimizing the infrastructure verses individual mission cost depends upon a number of assumptions, including the number of missions expected to use these capabilities and the relative costs of mission and infrastructure systems. Studies of future navigation and relay infrastructure investments should consider the costs and benefits of including other orbits and make deliberate design decisions about the types of orbits that these systems will support.

Ground Station Location

The physical locations of communications ground stations need to match the Earth orbit options. For geostationary orbits, the ground stations clearly need to be in view of the spacecraft (a trivial case). For low Earth orbit spacecraft, the frequency of occurrences of satellite passes tend to be maximized by placing ground stations at higher latitudes closer to the poles, provided that the latitude does not exceed the inclination of the orbit, putting the station completely out of view.

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[*] Wertz, J., "Guidance and Navigation," chapter 11.7 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

The following figure (from Wende) illustrates the relationship between ground station latitude and station coverage (in minutes per day) for representative Sun-synchronous, low Earth orbiting spacecraft.*

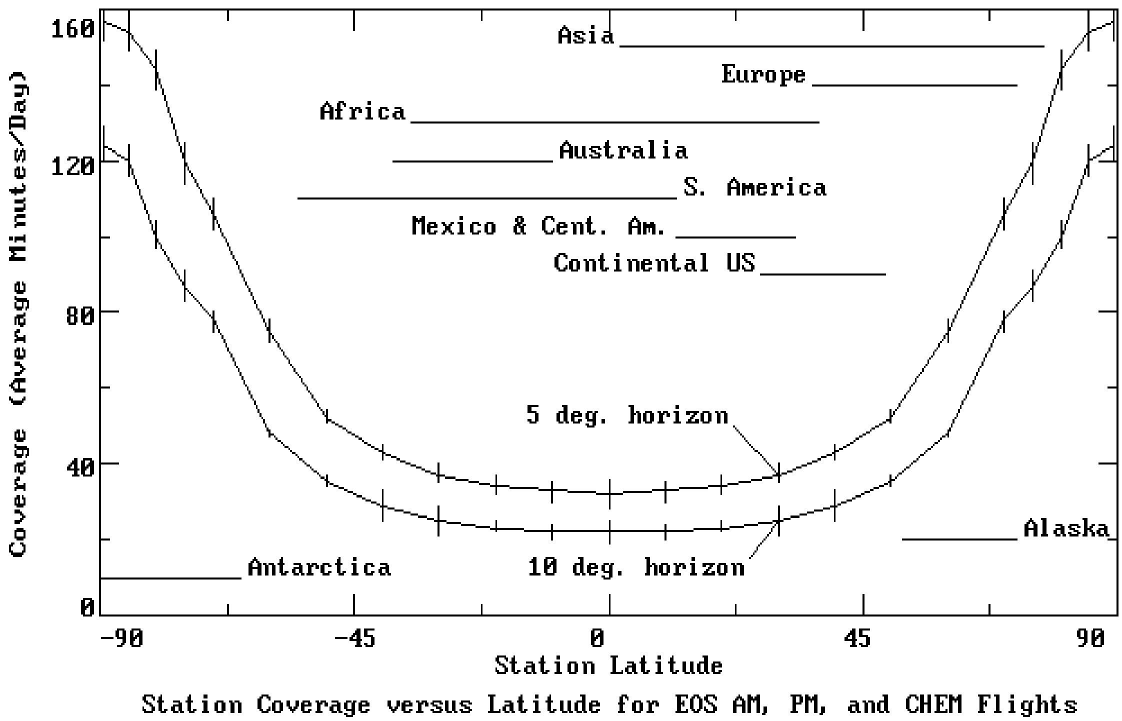

Figure 29: Ground Station Coverage vs. Station Latitude for Polar Orbiting Satellites

The relationship between mission orbit geometries and the implementation of the navigation system has also been covered earlier. Navigation approaches that depend upon ground stations for range and/or rate tracking must have those stations widely geographically distributed to provide adequate coverage of the orbits.

Sensorweb Link Topologies

This section considers options for the form of future sensorwebs, in terms of the structure of the links between nodes in the web. This section introduces metrics for evaluating sensorweb network link topology options, considers the effect of relative motion due to orbital velocities on link structures, and develops a classification of options.

* Wende, C., "Communications Outlook for NASA's Earth Science Enterprise (ESE)," viewgraph presentation dated January 23, 2001. This presentation is an update to Wende, C., "NASA Remote Sensing Missions and Frequency Issues," IGARSS 2000, July 24-28, 2000.

Network topologies are complex and difficult to assess. This basic examination and classification is only a rough beginning. It has resulted in some insights, but is not sufficient to lead to clear answers. This area needs future work, including the development of simulation and evaluation tools.

The following classification uses the concept of "type." This concept of is left purposefully vague to allow for the possibility that "type" could be dynamic and assigned by the system. For example, "type" could be an alert structure that sensorweb nodes can autonomously join or leave as conditions change. It may be desirable to have all satellites that can view the oceans autonomously and dynamically subscribe to one type, while all satellites that can observe any volcano autonomously and dynamically subscribe to another. Under this concept, satellites could belong to many types. One the other hand, "type" may represent missions that use a particular radio link interface standard, implemented in hardware. In this case, "type" is fixed once the mission is built.

Finally, it is entirely possible to have the physical links that connect the nodes differ from the logical structure that defines how the nodes self-organize and behave. This discussion is based mainly upon the physical implementation of the communications links.

Discussion of Metrics for Evaluating Options

According to an Internet Protocol Journal article by Krebs, the design of networks must balance three competing goals:[*]

- Reducing hop count.
- Reducing available paths.
- Increasing failure tolerance.

Popular network centrality measures are:

- Activity: the number of direct connections to a node.
- Betweenness: the role of a node in connecting other nodes.
- Closeness: the length of paths to other nodes.

The article by Krebs discusses these competing goals, popular network centrality measures, and how they apply to common network topologies. These goals and measures often conflict. For example, reducing available paths can simplify network design, but removes redundancy and decreases tolerance to failures. Since these goals and measures must be balanced, it is difficult to identify a clear preference for a network topology without developing models and making

[*] Krebs, V., "The Social Live of Routers, Applying Knowledge of Human Networks to the Design of Computer Networks," The Internet Protocol Journal, URL http://www.cisco.com/warp/public/759/ipj_3-4/ipj_3-4_routers.html

assumptions about factors such as the number of nodes, data rates, latency requirements, speed at which the network must reconfigure, etc.

This last factor, the speed at which the network must reconfigure, could have a significant impact on the design of a sensorweb that contains both Earth-based and space-based nodes. These nodes will be traveling at orbital velocities relative to each other. This implies the need for frequent and rapid reconfiguration. There may be significant hand-off and redundancy issues. Only if the sensorweb nodes are all Earth-based, or if they are all co-orbiting assets (e.g., aligned and precise orbit/vantage) would the node maintain the same physical configuration for any significant period of time. The rapid pace of change imposed by orbital motions (and the likely limit of line-of-site communications) suggests that topologies with computationally easy and robust link decisions based on local information would be beneficial.

The following classification of sensorweb link topologies makes a distinction between "interwoven" and "interconnected" sensorwebs. Interwoven sensorwebs have separate link structures for different mission "types." Interconnected sensorwebs apply a single, system-wide structure. The link topologies are those commonly used in computer networks, such as bus, tree, ring, star, and mesh. This analysis includes simplified illustrations and discussions of each type of sensorweb link topology.

For "interwoven" sensorwebs, each "weave" is relatively independent. Potentially, this makes this sensorweb approach easier to implement and modify, requiring less coordination with other sensorweb "weaves." Implementation of the interwoven sensorweb approach does not depend on "universal" standards and protocols. For example, the fleet of satellites that will make up the Global Precipitation Monitoring (GPM) could form a sensorweb "weave" by carrying hardware and software that allows them to communicate with each other and coordinate their observations. This could be a dedicated system optimized to meet the needs of GPM, with no ability to link to other satellite sensing nodes. At the same time, other satellites, such as space-based total lighting mappers, could be obtaining completely different observations, linked in real time to ground based sensors to distinguish cloud-to-ground lightning. The links between these space and ground-based sensors could form their own dedicated sensorweb "weave," with no capability to communicate directly to the GPM constellation. These two sensorweb "weaves" may observe the same part of the Earth and be "interwoven" in that they are occupying similar regions of space, but they are not "interconnected."

An advantage of this "interwoven" approach would be its functional or "type" independence. This reduces complexity and ambiguity, particularly when future functional needs and standards are unclear. The relative independence of each "weave" allows it to be optimized to function-specific performance. This independence also limits risk to one "type," as faults or failures are contained within a single "weave."

A disadvantage of this approach is that the lack of interconnection would make it harder to link across "types" or functions. Messages and alerts must propagate up and across top of hierarchy to another "weave." Continuing the GPM and Lightning sensorweb examples, if it became important to focus precipitation measurements on areas with severe cloud-to-cloud lightning (say for tornado warning, etc.), the "alert" that the lightning sensorweb has detected a high rate of cloud-to-cloud lightning would have to pass through the ground system, as no direct link capability is built into the system.

In addition, each "weave" would have to establish its own web structure, resulting in duplicated capability and hardware. This could result in a less optimum allocation of links, as the best or closest hub may not be the right "type." "Interwoven" sensorwebs would have increased overhead and latency. Also, with less ability to share links and nodes, the "weave" could have less redundancy.

In contrast, the "interconnected" sensorweb approach avoids duplication of web structure. This could result in a more optimum allocation of links, as the system can use the "best" hub even if it is a different function. This would make it easier to link across functions, as messages and alerts can propagate directly.

However, this would result in broad interdependence across the entire sensorweb. Standards would have to be set early, and would be harder to evolve or modify. Potentially this would require much greater up-front coordination with other sensorweb element developers, such as commercial or International partners. The development of an "interconnected" sensor web would be dependent on "universal" standards and protocols. This interconnection also means they are interdependent. The network structure would likely be optimized for the system-wide performance, and this may be suboptimum for any specific function. In addition, faults or failures may be able to affect the entire system.

Consider the GPM and lighting monitor missions again. If these were part of an "interconnected" sensorweb, the communications interfaces and dynamically adjusting (due to orbital motions) node structure would tie across both GPM satellites and the various lightning instruments. For example, a low power ground-based cloud-to-ground lighting detector would link to the nearest relay connection, which may be on the Earth, an orbital lightning sensor mission, or one of the GPM missions. They would all form a single sensorweb dedicated to multiple functions, and the lightning monitor sensor would be able to pass alert information through global precipitation nodes. Such an approach could have fewer duplicated capabilities, due to shared links and nodes, and this could provide greater redundancy.

All in all, the "interwoven" sensorweb structure is probably the best approach, due to the uncertainty and ambiguity in requirements and standards. It may be best to gain experience developing and operating sensorwebs before attempting to establish "universal" standards. The "interconnected" approach may be best sometime in the future when requirements and standards are well established.

Network Topology Options

The following table summarizes the common network topology options that could apply to the sensorweb concept and that are illustrated in this section.

Table 21: Summary of Link Topology Options

Topology Name	Organizing Principle	Comments
Bus	Information Broadcast to All Nodes	• Link Can Become Jammed
Spanning Tree	Nodes Connect to Nearest Neighbor	• Nodes Must Support Multiple Links • Data Passes Through Nodes
Chain	Linear Path through Nodes	• Nodes Only Support Two Links
Ring	Closed Loop through Nodes	• Loop Can Close at Peer Level, or at Level Above • Most Nodes Only Support Two Links • Data Passes Through Nodes
Star	All Nodes Directly Linked to Central Node	• Central Node at Peer Level or at Level Above • All But Central Node Only Support One Link • All Data Passes Through Central Node
Mesh	All Nodes Directly Linked to All Other Nodes	• Complexity Grows with Number of Nodes • All Nodes Support Multiple Links
Hybrid	Mixture of Any of Above	• Mixture Can Balance Advantages and Disadvantages

The following diagrams and text illustrate and discuss these common network topology options. In these illustrations two "types" are illustrated by white or gray shading. The "interwoven" version is shown on the left while the "interconnected" version shown on the right.

Bus Topology: In bus links, the same information is "broadcast" to all nodes. Bus link topologies should be relatively robust to failure of any one node or link. If many nodes need two-way connection, the link may become jammed.

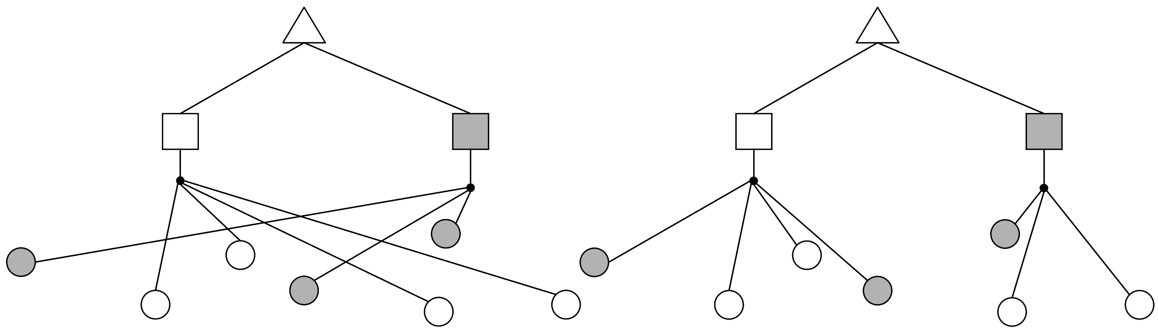

Figure 30: Interwoven and Interconnected Bus Topologies

Spanning Tree Topology: In spanning links or tree structures, neighbors connect. Calculating the minimum spanning tree is computationally easy and depends only upon local information. This should enable fairly simple and rapid reconfiguration in response to orbital motion or recovery from node or link failure. The information passes through peer nodes, which means that the nodes need to be able to pass data from multiple connections. This may place an undue burden on nodes if the data rates are high or if the dynamic configuration is such that a large number of links pass through a single node. Finally, all data on one "limb" of a tree passes through a single node next to the upper level, and this single path lacks redundancy. Several of the sensorweb concept papers describe use of this "nearest neighbor" approach.

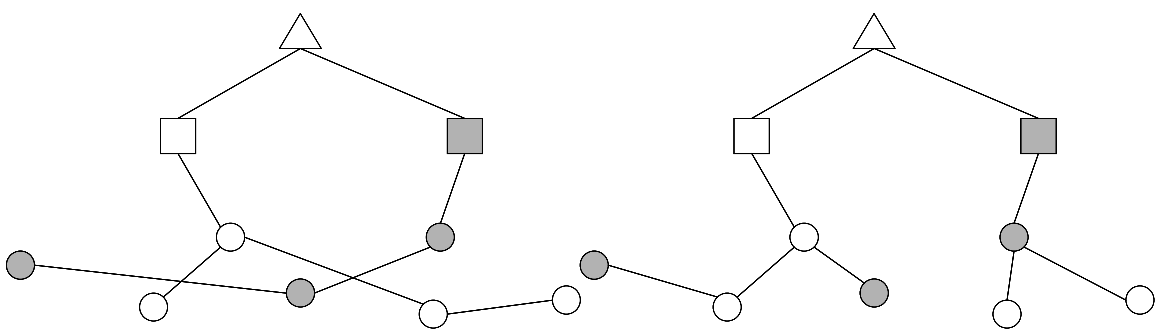

Figure 31: Interwoven and Interconnected Spanning Tree Topologies

Chain Link Topologies: In this topology a single linear "chain" connects the nodes. It is unclear if this path is computationally easy to determine or dynamically reconfigure. Each node has only two connections, however all of the information in the chain passes through the nodes further up the chain, and this may place undue burden on these nodes if the data rates are high or if there are a large number of nodes in the chain. Also, since all data passes through the single node next to the upper level, this single path lacks redundancy.

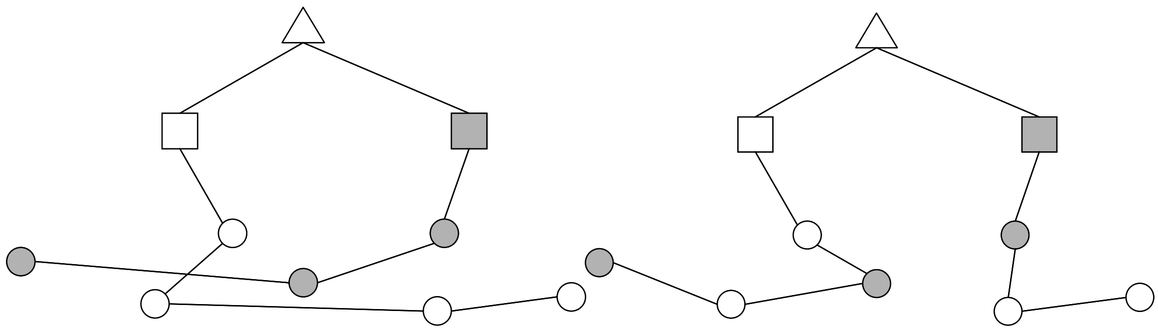

Figure 32: Interwoven and Interconnected Chain Link Topologies

Ring Links (Peer or Upper Level): Adding one more link to "chain" can form a ring topology, a topology commonly used in local area networks. The diagrams illustrate completing the ring at the peer level or to the next higher level. This one additional link improves closeness and reduces hop count. It also provides a redundant path to each node. Since the "traveling salesman" problem is computationally hard to optimize, it is computationally difficult to determine or dynamically reconfigure the optimum ring link topology. However it is probably easy to dynamically develop near-optimum configurations.

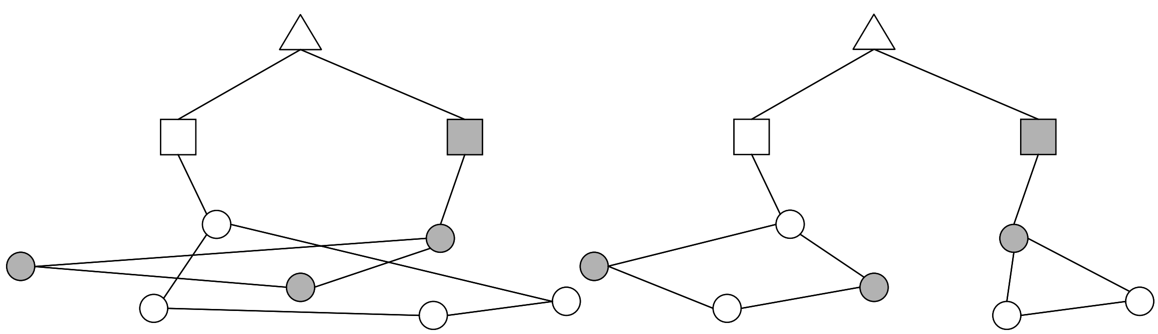

Figure 33: Interwoven and Interconnected Peer Ring Topologies

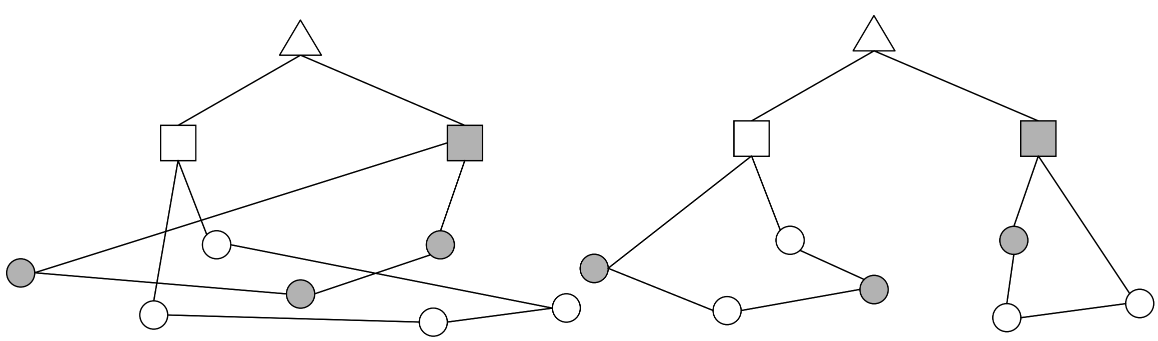

Figure 34: Interwoven and Interconnected Ring Link (to Next Level) Topologies

Star Links and Direct Links: In the star link topology, each node has a direct link to a central node. This may be a peer node that has been elevated to central hub role, or it may be a direct link to a central hub at an upper level in the hierarchy. An advantage of star links is that they have relatively short paths between nodes. Except for the central node the number of links per node is limited. This limits the impact of failure of any node except the central node. The disadvantages are that the central node can be choke point and a single point of failure.

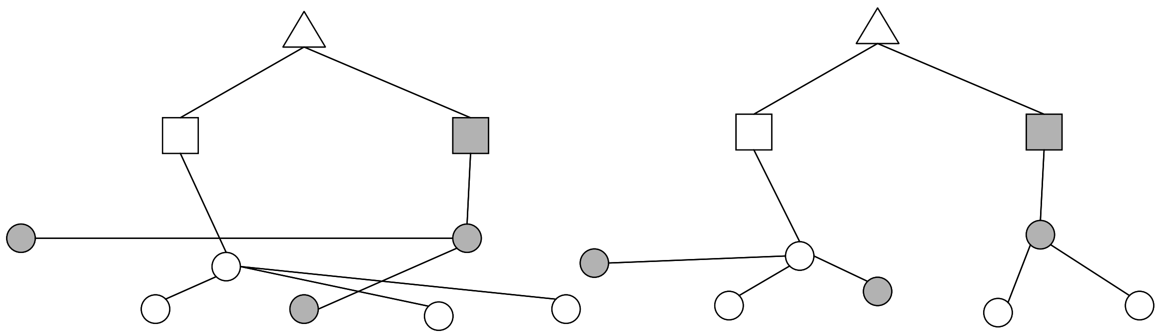

Figure 35: Interwoven and Interconnected Peer Level Star Link Topologies

Some of the sensorweb concept papers describe the use of high-capacity optical relays. These direct links would be an example of a "next level" star link topology.

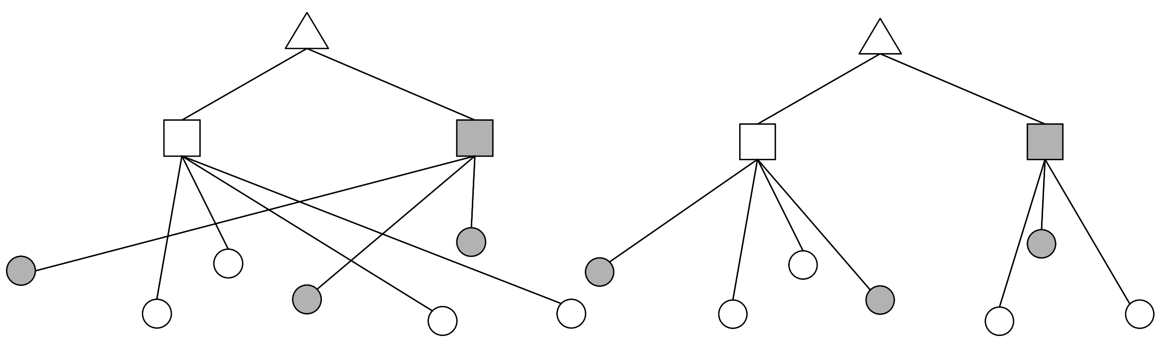

Figure 36: Interwoven and Interconnected Next Level Star Link Topologies

Mesh Links: In a mesh link topology, each node has a dedicated link to every other node. This provides the minimum possible path lengths and number of hops. Mesh networks have many redundant paths and can route around any broken links. However, each node must have a link capability for every other node. The complexity increases as number of nodes increases. For radio frequency connections there could be spectrum and interference issues.

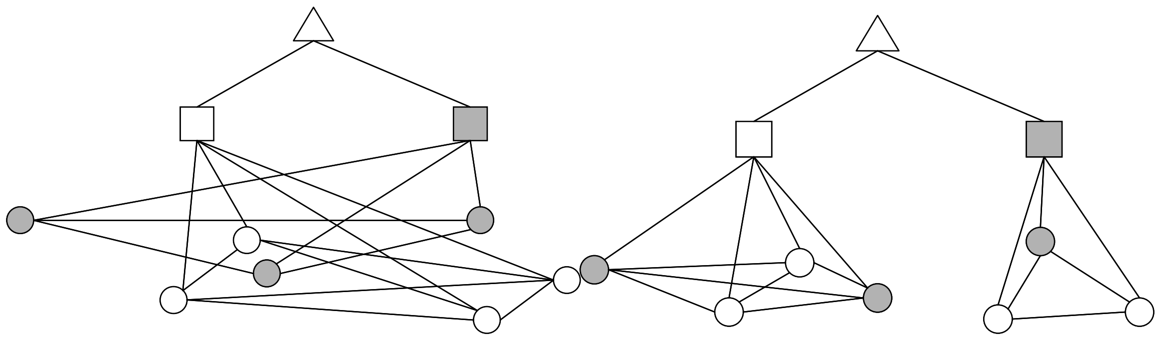

Figure 37: Interwoven and Interconnected Mesh Link Topologies

Hybrid Approaches: It is probably desirable to mix network structures in a hybrid topology approach. For example, it may make sense to vary the network strategy depending upon data rate or latency need. Partial mesh redundancy is a common approach to balancing link overhead against risk. In addition, as discussed above, sensorweb nodes may serve more than one function and be of more than one "type." Also, different data types may take different paths, with a separate path for commands, a rapid path for high value alerts (possibly a direct peer pass through at low data rates), a slow and less direct path for "bulk mail," and a dedicated direct link for high data rate source nodes. Finally, some paths may be two-way, and some one-way only. This variety is depicted notionally in the following figure.

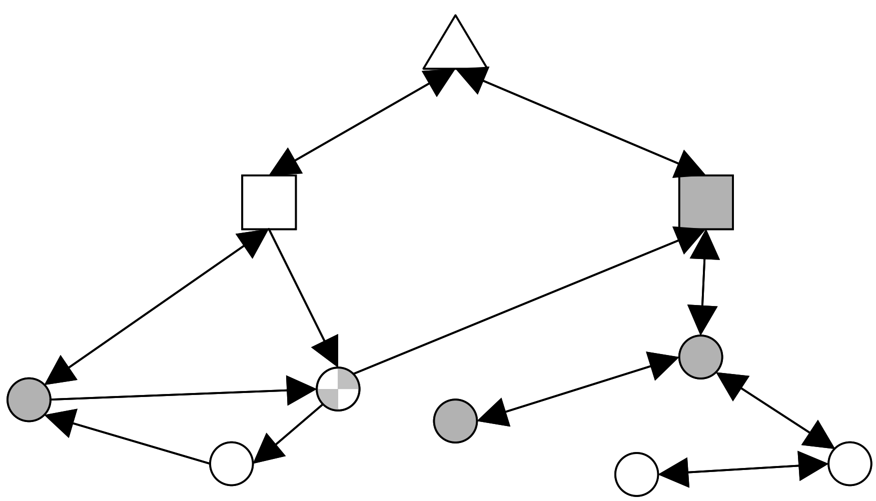

Figure 38: Hybrid Link Topologies

Concepts for autonomous coordination and adaptation of distributed space- and Earth-based observation systems require a real-time network structure that is robust and adaptable as configurations shift at orbital velocities. The design of such a network is complex and the optimum approach is not obvious. NASA needs to develop models and metrics to refine and evaluate sensorweb mission link approaches. These models and metrics can increase understanding of the nature of the problem, as well as allow simulations and performance trades.

NASA and its National and International partners are currently developing missions that will be operating a decade from now. Also, NASA has begun to link together missions that were conceived and designed separately, creating satellite trains. These missions have no space-to-space communications capability to support autonomous interaction or coordination of these trains, but could benefit from this ability. In addition, a concept for recovering from a failed instrument on a multi-instrument mission is to fly a replacement instrument in formation on a single-instrument spacecraft. This could also benefit from space-to-space coordination.

A near-term goal should be to seek a low-impact space-to-space communications interface (evaluating both hardware systems and information standards) that could be included with future missions to increase the likelihood that they are compatible with future sensorweb concepts. Using current and likely future satellite trains, virtual platform missions, and instrument replacement scenarios as case studies, NASA should evaluate the desirable functionality and cost trade-offs of a space-to-space interface to determine if there is a flexible, low cost subsystem that could be added to missions to enable this capability. The interface for co-orbiting assets does not face the challenge of rapid reconfiguration due to differential orbital motions, and therefore may be easier to define in the near term.

5.4.5 Standard Space/*In Situ* Components

Previous chapters have also discussed this aspect of the multi-mission system form, briefly summarized here. The previous concept chapter discussed the efforts of the Rapid Spacecraft Development Office (RSDO) to develop a standard catalog of spacecraft busses. The previous chapter also discussed NASA’s structure for new concepts and technology development. As a general rule, the current technology programs tend to emphasize component and subsystem developments, and tend towards supporting technologies related to instrument and information system capabilities.

This reflects the assessment that much of the progress in platform components and capabilities for space missions is being driven by the needs of other stakeholders. These are mainly the commercial communications industry. The NASA Earth Science Enterprise investments in technology are weighted towards the areas where the needs are unique. These are mainly in instrument and data system technologies.

Also, the Earth Science Enterprise has the opportunity to influence NASA-wide technology investment programs, such as the Small Business Innovation Research (SBIR) program, which is targeted to the small companies that are often the suppliers of key components.

Similarly, the concept chapter mentioned the efforts to develop new unmanned air vehicle (UAV) capabilities under the Environmental Research And Sensor Technology (ERAST) program. NASA is the world's leader in the *in situ* exploration of other planets, and this provides NASA with unique capabilities that can be applied to the *in situ* exploration of Earth.

5.4.6 Development Capabilities

As mentioned before, for readability and consistency the discussion of the multi-mission development system is consolidated in chapter 4.

Chapter 6: Integrated Earth and Space-Based Observation System Implementation Timing and Operation

6.1 Chapter Summary

This chapter examines the level 2 Earth- and Space-based Observation System timing and operation to identify unique issues provided by this view that were not captured from other views of the system. The timing and operations of the individual missions is not discussed here, but is reflected in the development of system function, concept, and form.

The major stakeholders and partners have differing timeframes of interest. Missions with short development times to allow flexibility to infuse the latest technology and adapt to emerging research results. Similarly, the timeframes of graduate students and career academics seeking to use space-based data indicate the desirability of mission development times on the order of two or three years.

Operational agencies require assured capability. They often have considerable spare assets either in development or on orbit. There is almost always a long delay between when an operational agency agrees to take over a sustained, long-term measurement and when that agency actually launches the capability. Often NASA must develop an additional mission to “bridge” this coverage gap.

Commercial communications satellites may have as little as six months between order and launch of a satellite. NASA has studied “quick-ride” flights of opportunity using excess capacity on these satellites for scientific research. Currently NASA has difficult matching this short cycle time.

These different timeframes suggested a further examination of strategies for increasing the flexibility of the mission development process. For conciseness and readability, the detailed discussion of concepts and improvements for the development system has been consolidated into chapter 4.

Other timing and operational constraints addressed include the time required to phase-in multi-mission measurement capabilities requiring multiple launch or deployments and orbital debris constraints and mitigation approaches for multi-satellite constellations.

6.2 Research and Partnership Timeframes

The major stakeholders and partners in the Integrated Earth- and Space-based Observation System have differing timeframes of interest. These timeframes reflect influences such as the pace of academic discovery, the academic and graduate student career cycle, operational agencies' need for assured capability, and the cycle time of commercial space missions.

Freeman Dyson wrote that in scientific research "new discoveries and new ideas often turn whole fields of science upside down in a few years."* He argues that "quick is beautiful" and that science is best served by missions with short development times. This allows greater flexibility to infuse the latest technology and adapt to emerging research results. Similarly, the timeframes of graduate students and career academics seeking to use space-based data indicate the desirability of mission development times on the order of two or three years. As discussed in the concept chapter, the original NASA Earth Observation System (EOS) concept was to fly identical instruments to obtain consistent observations for 15 years. The key problem with the concept was the lack of flexibility and adaptability.

In contrast, operational missions such as the weather satellites of NOAA and the Department of Defense have substantially longer timeframes. Operational needs involving defense and protection of life and property demand assured capabilities. These agencies frequently maintain spare capability, both on the ground and in orbit, such as the two spare GOES weather satellites currently in geostationary orbit.

For example, NASA is actively engaged with NOAA and the DOD in developing a merged polar orbiting satellite system supporting Civil and Defense weather forecasting needs, as well as some systematic measurement needs of NASA. However the schedule for this system, the National Polar Orbiting Environmental Satellite System (NPOESS), will not provide NASA continuity with recently launched missions. This is due to the inventory of capability already in development or available for the current weather satellite systems of these agencies. This schedule mis-match requires NASA to cooperatively develop a mission, called the NPOESS Preparatory Project (NPP), to bridge the gap between the agreement by these operational agencies to continue long-term research observations and the timeframe in which these agencies can actually provide these observations.

On the other extreme, communications companies typically order satellites from the manufacturer six months before launch. The commercial communications industry has significantly shortened the cycle time for the development of missions. Some of these missions may have excess capacity to support scientific instruments. NASA has studied such "quick ride" opportunities, but the timeframe tends to be too short to effectively identify and develop instruments. Taking advantage of partnership opportunities for these missions requires either

* Dyson, F., "Space Butterflies and Other Speculations," Science, November 1985, pages 127-130.

introducing innovations to radically shorten the development cycle or building instruments "on speculation" for flights of opportunity.

6.3 Constellation Build-up and the Interdependence of Missions

Operational timing implications of observation concepts that rely upon large numbers of separated spacecraft and Earth-based missions include the time to build the full capability and the increased risk of loss or delay of some elements. Wertz provides a good discussion of these issues for global constellations.*

A number of timing-related factors need to be considered in the design of a distributed observation system. These include:

- The time required for launching or deploying the full the constellation.
- The likelihood of partial loss of the constellation due to either programmatic or technical problems.
- The impact of such a loss on the value of the remaining constellation.

If at all possible, systems should be designed to provide value even when partially deployed. This provides value during the constellation build-up phase, and allows for graceful degradation in the event that part of the system is lost.

This highlights the overall system performance risk as an aspect of distributed multiple missions. Multiple missions can reduce risk and allow for graceful degradation. However, this is only true if the reduced fleet can meet an acceptable level of performance. Reliance on multiple missions can actually increase risk if all constellation elements are needed to meet minimum performance. For example, four missions, each with a 95% independent probability of individual mission success, have only an 81% probability of success. Eight missions with this individual level of mission reliability would have only a 66% probability of success. The following figure and table show these relationships for different levels of individual mission probabilities of success.

* Wertz, J., "Orbit and Constellation Design," chapter 7, section 7.6 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

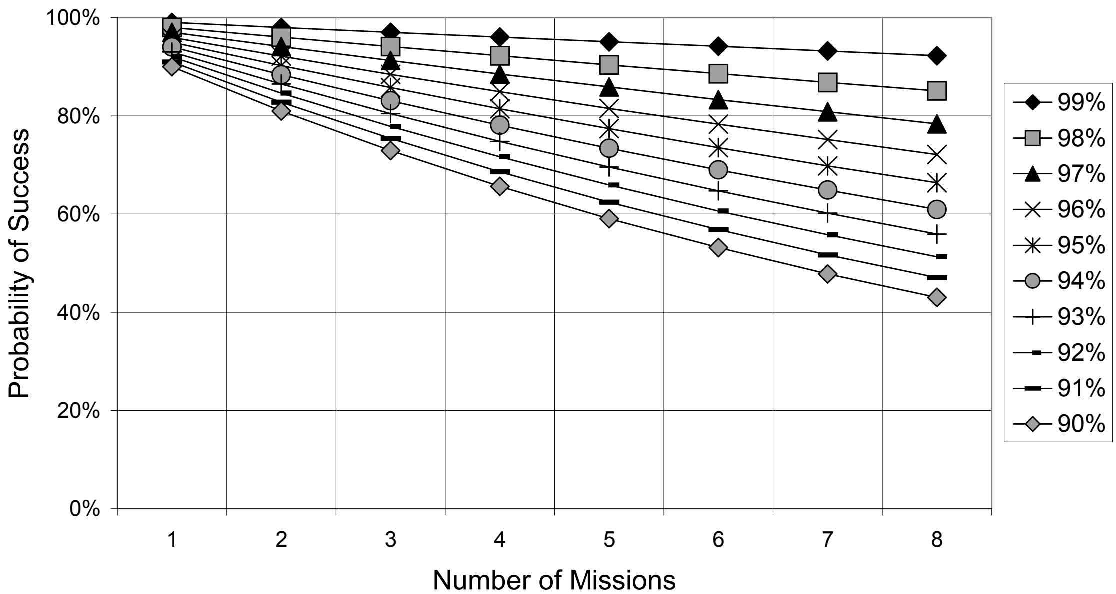

Figure 39: Probability of Full Multi-Mission Success for Different Levels of Individual Mission Reliability

Table 22: Probability of Full Multi-Mission Success for Different Levels of Individual Mission Reliability

	Number of Independent Missions							
	1	2	3	4	5	6	7	8
Probability of Full Success	99%	98%	97%	96%	95%	94%	93%	92%
	98%	96%	94%	92%	90%	89%	87%	85%
	97%	94%	91%	89%	86%	83%	81%	78%
	96%	92%	88%	85%	82%	78%	75%	72%
	95%	90%	86%	81%	77%	74%	70%	66%
	94%	88%	83%	78%	73%	69%	65%	61%
	93%	86%	80%	75%	70%	65%	60%	56%
	92%	85%	78%	72%	66%	61%	56%	51%
	91%	83%	75%	69%	62%	57%	52%	47%
	90%	81%	73%	66%	59%	53%	48%	43%

The current NASA mission evaluation process tends to assess the risk of individual missions. As we move towards reliance on the fusion of data from multiple missions, we must either be ready to accept the occasional loss of individual missions, or make the investments to raise the overall reliability of the individual missions to a level that results in acceptable risk for the multi-mission system.

6.4 Orbital Debris Constraints on Multiple Spacecraft Systems

Wertz provides a discussion of the effect a satellite explosion or collision could have on a constellation orbit.* Such an event would potentially create thousands of debris particles that are co-orbiting with the remainder of constellation. These co-orbiting debris increase the likelihood of additional impacts with other members of the constellation. The kinetic energy of debris at orbital velocities (7 km/sec) makes damage likely. A secondary impact would create more co-orbiting debris, further increasing likelihood of impacts. Such a chain of events could potentially make the orbit "uninhabitable. "

The above scenario may be a consideration even for individual spacecraft missions. Spacecraft operators may face liability issues if they loose control of their satellite and pass through someone else's constellation. This could force the constellation operator to take temporary evasive maneuvers, resulting in loss of revenue. In the worst case, it could destroy, damage, or force constellation relocation.

The sources the author has found concerning the risk of debris on constellation design are qualified discussions and not quantified studies. Several web sources discuss this issue in a general way, emphasizing the need for more detailed modeling, and in some cases offering services to provide this modeling. The author sees a benefit from conducting a worse case analysis to scope what size constellation begins to raise concern.

Based upon the author's experience, the worst case would probably be a moderately high Low Earth orbit. This orbit would be high enough to reduce the differential in drag between the spacecraft and small particles. Small particles tend to have higher cross-section to mass ratios, making them relatively more affected by drag. This causes them to clear from orbit faster when at lower altitudes. The worst case would most likely be a circular orbit. The debris orbit would precess at different rate due to solar pressure and drag. Circular orbit paths intersect wherever the orbit planes cross. This increases the likelihood of impact at the intersections. These conditions, higher altitude and circular orbits, would mean that spacecraft and debris remain in orbits that intersect for longer periods of time. Calculating spatial density of the debris and using the kinetic theory of gasses would be an approach to estimate the risk. Madler and McKnight describe this method.†

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* Wertz, J., "Orbit and Constellation Design," chapter 7 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999, see section 7.6, pages 198 and 200.

† Madler, R., and McKnight, D., "Orbital Debris – A Space Hazard," Section 21.2 of *Space Mission Analysis and Design*, 3rd Ed., Wertz, J., & Larson, W. (editors), Microcosm Press and Kluwer Academic Publishers, 1999.

There are a number of ways to mitigate the debris risk for constellations and co-orbiting spacecraft. Wertz as referenced above describes approaches for satellite constellations. For satellites co-orbiting in close proximity, one approach is to consider the relative ballistic coefficients in determining the order of the spacecraft. These could be selected so that drag separates the formation, providing a “fail-safe” mechanism in case of loss of control of a satellite or the entire fleet. Finally, if there is the potential for an orbit to become “uninhabitable,” a mitigation approach would be to design for alternate orbit options as back-up configurations. This would involve moving the fleet of satellites to a clearer plane, altitude, or orbit space if a collision or explosion creates a debris cloud.

Chapter 7: Thesis Summary, Guidance, and Recommendations

7.1 Chapter Summary

As stated in the beginning of this document, the goal of this thesis was to develop guidance and recommendations for the NASA Earth Science Enterprise by assessing and refining strategic architecture options for an integrated Earth and space-based observation network for Earth science, evaluating upstream and downstream trends and influences that may affect the architecture and the Enterprise. In doing so the author intended to develop a deeper understanding of these issues for use in future policy and implementation discussions. As a result of this effort, the author has gained this deeper understanding. The three main areas where the author sees uncertainty in the future development of the system are:

- The various "Sensorweb" related concepts and the approaches for multi-mission interaction.
- The potential for changes in the underlying architectural drivers and the ability of the Earth Science Enterprise to recognize and adapt to these changes.
- The many stakeholder relationships and the potential influence they will have on the future of the Earth- and space-based observation network.

This chapter provides guidance concerning these three areas of concern, identifies additional recommendations derived from this work, and summarizes the thesis.

7.2 Guidance and Recommendations

It should be no surprise that the current Earth- and space-based systems to observe the Earth are working extremely well. This reflects decades of thoughtful design and hard work on the part of many people worldwide. NASA has begun the Earth Observing System (EOS) era. Satellites today observe the Earth across the electromagnetic spectrum, as well using other phenomena such as gravity to probe the Earth. The measurement requirements for the Earth Science Enterprise are well defined and widely agreed upon. International mechanisms allow space agencies to exchange information and coordinate mission strategies. Technology programs are developing and demonstrating new instruments and technologies. The infrastructure is in place to launch, navigate, communicate, and operate most missions. Much of this can now be done autonomously.

The author sees three general areas of concern and uncertainty in the future evolution of the integrated Earth- and space-based observation system for Earth science. These three areas are:

- **Multi-Mission Interaction**: The promise of the sensorweb concept is compelling. If implemented properly, this concept should enable the emergence of synergistic system capabilities that are only beginning to be conceived. However, the author sees a great deal of ambiguity concerning what a sensorweb is and uncertainty on how this concept should be implemented.
- **Changes in Architectural Drivers**: The approach to global Earth observations has evolved over the last fifteen years to the current system of relatively small missions with short development times. This approach appears well matched to the current environment, and the author does not expect any near-term changes other than an increased emphasis on improving the mission development process. However, the transition from the large EOS-A and -B platforms to the current approach was extremely painful. The author is concerned that the Earth Science Enterprise does not have in place the ability to forecast shifts in the underlying influences and drivers that led to the current approach. In addition, the author is concerned that the mission implementation system may lack the flexibility to adapt, if and when these influences and drivers impose a new architectural approach.
- **Multiple Stakeholder Complexity**: Other stakeholders will develop much of the capability of future Earth- and space-based observation systems. Without interaction, these stakeholders may develop capabilities without consideration of the interests of NASA or the Earth Science Enterprise. In addition, these stakeholders may exert direct influence (political and otherwise) over the future development of NASA systems. The author sees the potential for a great deal of uncertainty due to these stakeholder influences and relationships.

7.2.1 Multi-Mission Interaction Guidance

The following discusses some high level guidance on autonomous multiple mission interaction and the implementation of sensorweb-related concepts. Concepts for autonomous coordination and adaptation of distributed space- and Earth-based measurement systems require real-time network structures that are robust and adaptable as configurations shift at orbital velocities. The design of such a network is complex and the optimum approach is not obvious. The NASA Earth Science Enterprise needs to develop models and metrics to refine and evaluate sensorweb mission link approaches. These models and metrics can increase understanding of the nature of the problem, as well as allow simulations and performance trades.

NASA and its National and International partners are currently developing missions that will be operating a decade from now. Also, NASA has begun to link together missions that were conceived and designed separately, creating satellite trains. These missions have no space-to-space communications capability to support autonomous interaction or coordination of these trains, but could benefit from this ability. In addition, a concept for recovering from a failed instrument on a multi-instrument mission is to fly a replacement instrument in formation on a single-instrument spacecraft. This could also benefit from space-to-space coordination.

A near-term goal should be to seek a low-impact space-to-space communications interface (evaluating both hardware systems and information standards) that could be included with future missions to increase the likelihood that they are compatible with future sensorweb concepts. Using current and likely future satellite trains, virtual platform missions, and instrument replacement scenarios as case studies, NASA should evaluate the desirable functionality and cost trade-offs of a space-to-space interface to determine if there is a flexible, low cost subsystem that could be added to missions to enable this capability. The interface for co-orbiting assets does not face the challenge of rapid reconfiguration due to differential orbital motions, and therefore may be easier to define in the near term.

7.2.2 Architectural Drivers and Mission Implementation Guidance

The following discusses some high level guidance on the architectural drivers the Earth observation system and the processes to implement missions within this system.

Mission and Multi-Mission System Complexity

The current Earth- and space-based observation system has evolved in response to the past drivers and assumptions underlying current missions and capabilities. However, these drivers and assumptions will change and will need to be periodically reassessed. Guiding the future evolution of the Earth- and space-based observation network for Earth observation requires a broad, strategic view. This strategic view requires forecasting the trends and influences, and understanding the consequences of key policy and implementation decisions. This understanding requires both analysis and insight.

This thesis begins the systematic assessment of the drivers and assumptions underlying current and planned NASA Earth Science Enterprise missions and capabilities, establishing views, frameworks and approaches to perform analysis and develop insight. However, the system will continue to evolve, and this will be a never-ending task.

Often in government, immediate problems can draw most of the attention, making it difficult to sustain this long view. Key leaders have the vision but may not always have the analysis to support and develop continued insight. The Earth Science Enterprise needs to maintain mechanisms that help focus on the long view. These mechanisms need adequate resources to develop methods, tools, and techniques to periodically reassess the overall architecture of the system. These reassessments should characterize and help the Earth Science Enterprise to understand the basic influences and assumptions underlying the current approach and predict major shifts in these drivers. This will support the timely prediction of when the Earth Science Enterprise will need to make major changes in the basic architectural approach.

Process Improvement Guidance

The one trend that the author has identified that has the potential to influence the mission development approach is the potential shift from technology "product" innovation towards increased mission development "process" innovation.

Both research and experience with the evolution of other industries suggests that as industries mature the uncertainties in requirements and in technologies are resolved and a "dominant design" tends to emerge. When this occurs, technical innovation tends to shift from product feature improvements to development and manufacturing process improvements. This leads ultimately to a "lean" enterprise where each step in the development adds value at minimum cost and delay. In the past 40 years the world has developed over 5,000 space objects. There are currently about 650 operational spacecraft, about 420 in the commercial communications segment alone. A dominant architecture and design has emerged for space missions.

Implementing a lean enterprise includes developing long-term relationships with suppliers that provide all partners with incentives and rewards for identifying and implementing technical and development improvements without fear of loosing competitive advantage, regardless of specific responsibilities. Research indicates that the traditional "lowest bid wins" approach used in mass manufacturing provides the wrong incentives, encouraging participants to hide cost information and protect proprietary insight in order to gain competitive advantage.

NASA needs to investigate and develop mechanisms consistent with Government procurement regulations that allow NASA to establish collaborative long-term relationships with space mission suppliers. These need to give all parties incentives to improve the mission development process and rewards for cooperation and knowledge sharing.

In addition, NASA's technology program has mainly focused on innovative components and subsystems, which correspond to product improvements. NASA has begun to consider collaborative engineering environments and other approaches to improve the mission development process. NASA needs to devote more attention to mission development process improvement and innovation. The NASA Earth Science Enterprise should seek ways to complement its current technology programs, focused on the development of mission components and instrument systems, with efforts to develop innovations in the mission development process.

7.2.3 Multiple Stakeholder Complexity Guidance

The following discusses some high level guidance concerning the complexity of relationships with multiple stakeholders. The task of observing and understanding the Earth is challenging. In addition to the engineering task of building Earth- and space-based global systems, the fact that it is useful to many people makes it more complex than many other space-based research activities. It is not easy to resolve the complexity and manage the evolution of such a system.

Other stakeholders will make many of the critical investments. For example, two thirds of the world's active satellites are for commercial communications. National security investments in space have had and will continue to have a major impact on the architecture options for future space missions. The US National Security community is likely to spend four to six times what NASA does for Earth observation systems over the next decade.

The NASA Earth Science Enterprise needs to maintain close ties to these stakeholders. In particular, the ESE should establish closer relationships and coordinate plans with the Office of the National Security Space Architect, especially in the areas of real-time, adaptive multi-mission communications, navigation, and control.

7.2.4 Specific Recommendations

The following summarizes the more narrowly focused and specific recommendations that have arisen as a result of this thesis effort.

- Competition for radio frequency spectrum allocation is increasing, driven mainly by the growth in commercial communications and wireless applications. NASA uses radio frequency spectrum allocations for passive and active remote sensing as well as for communications. Optical links are an option for communications. Some measurement applications have no alternative. The Earth Science Enterprise should continue to actively engage with the International Telecommunications Union on issues of radio frequency allocation for passive and active remote sensing, as well as for communications. This includes continue to register all uses of the radio spectrum including passive uses so that international users are aware of potential conflicts if they operate in these regions.

- Current navigation systems such as the GPS are designed for terrestrial use and the signal strength tends to drop off with altitude. Although some work has been done on using the signal that "spills over" the Earth's limb for geostationary orbit locations, mission designers cannot assume that current satellite navigation systems would work in orbits other than low Earth orbit. Similarly, the NASA Tracking and Data Relay Satellite System (TDRSS) is designed for satellites in LEO and does not support GEO satellites. Future navigation and relay infrastructure investments studies should consider the costs and benefits of including other orbits and make deliberate design decisions about the types of orbits that these systems will support.

- NASA is currently upgrading its networks of ground-based satellite laser ranging stations, and has the opportunity to add optical communications capabilities. The Earth

Science Enterprise needs to evaluate adding laser communications capability to all or some stations, assessing the "option value" of enabling future communications alternatives.

- For multi-satellite constellations, several sources discuss the potential for an impact between orbital debris and a constellation member to generate more debris, increasing the likelihood of impacts with additional constellation members in a chain reaction that can render an orbit uninhabitable. Within the time available, this thesis was not able to quantify this concern. The Earth Science Enterprise should further investigate potential orbital debris restrictions on satellite constellations. This should include a worst-case analysis to determine the minimum constellation size that should raise a concern under different general obit conditions.

- Recent launch data show a trend towards larger launch payloads, driven by a trend in commercial communications satellites towards larger missions. This runs counter to NASA's trend towards smaller space missions. The Earth Science Enterprise in partnership with the other Enterprises of NASA should monitor trends in the commercial launch industry.

7.3 Summary and Concluding Remarks

The key intellectual progression in the study of any complex system (after recognizing that it is a system) is (1) to characterize the system, (2) use this characterization to develop an understanding of the system, and (3) to test this understanding by predicting the behavior of the system. This is in effect the scientific method, to recognize a problem, gather data, analyze, and test hypotheses. As discussed in chapter 3, the Earth Science Enterprise is following this progression (characterize, understand, and predict) in the study of the Earth as a system. This is also the progression that this thesis follows in studying the integrated Earth- and space-based observation network for Earth science.

This thesis has developed specific approaches for **characterizing** the integrated Earth- and space-based observation network for Earth science. It establishes a functional intent framework for systematically organizing current and proposed concepts for the implementation of the system. For example:

- This thesis proposes specific, consistent terminology for categorizing and describing arrangements of multiple, distributed observation missions.
- This thesis examines the major methods and infrastructure currently in place for providing multi-mission services, such as for returning science data from missions, for navigating missions, for launching missions, and for developing new missions.

This thesis provides analysis to **understand** aspects of the system. It develops a framework based on system form for examining implementation issues. For example:

- This thesis applies a consistent approach to categorize spacecraft mission orbits. Analysis of this categorization identified a class of potentially useful orbits. The thesis verifies the feasibility of these orbits through modeling reflecting the dominant orbit perturbations.
- This thesis identifies common network topology options for interconnected missions ("sensorweb" concepts). The thesis discusses the issues and general metrics that are important for evaluating these interconnected mission options. It determines that further analysis requires additional refinement of implementation requirements and more detailed modeling.
- This thesis looks at aspects of mission implementation timing and operation that affect the value of the multi-mission system.

This thesis examines the trends and influences that are important for **predicting** the future evolution of the system. For example this thesis makes it clear that much of the future evolution of space-based system capabilities will be driven by the needs and investments of other stakeholders. This thesis only begins the progression to prediction. In addition, the system is dynamic; the characterization, understanding, and prediction will have to be updated as the future unfolds. More remains to be done.

As required for an academic thesis this has been an individual activity. The work performed to write this thesis is the author's, and is original. However, the future of the integrated Earth- and space-based observation network will depend upon the coordinated activities of many. These include the stakeholders in Earth-based observation in particular and the stakeholders in space-based activities in general. This effort has increased the author's appreciation for the importance of on-going interaction with the broad community of stakeholders. A next step in the development of this architecture is to expand participation and seek additional input to, agreement with, and ownership of the frameworks and tools used to understand, analyze, and predict the evolution of the integrated Earth- and space-based observation network for Earth science. This system will provide future generations with the comprehensive and long-term observations of the Earth they will need for the sustainable development of our planet.

Appendix A: Mapping of Functional Goals (Intent, Process, Operand) to Concepts and Elements of Form

The following two tables summarize the mapping between functional goals, concepts and form, as used in this thesis.

Table 23: Mapping of Functional Goals to Concepts and Elements of Form

Intent	Process	Operand	Concepts	Related Form Elements
To Enhance the Synergistic Benefits of Multiple Measurement Capabilities	by Coordinating Nationally and Internationally	The Identification, Selection, and Development of New Missions	Mechanisms to Define and Broadly Communicate Measurement Requirements Mechanisms to Identify and Broadly Communicate Current/ Approved Mission Plans	Observation Subjects
	by Enabling	The Operational Coordination of Mission Observations	Integrated Multi-Instrument Platforms (Initial EOS Concept) Classes of Multiple Distributed Spacecraft Concepts	Observation Subjects Supported Orbits/ Vantage Points Command/ Control/ Communications/ Navigation Infrastructure
To Maintain and Upgrade the Multi-Mission Measurement System	by Developing	New Observation Techniques, Instruments, and Components	NASA ESE Instrument Incubator Program (IIP), Instrument Component Development Programs, etc.	Observation Subjects Standard Space/ *In Situ* Components
	by Developing	New Mission Platform Technologies for: Guidance (Position Control) Attitude (Orientation) Determination and Control Observation Physical Support (Power, Heating/Cooling, etc.)	NASA Technology Programs: ERAST UAV Development, ESE Platform Technology, NASA SBIR, etc. Autonomous Guidance Concepts GPS for Attitude Determination Speculative Concepts for Beamed Power and Control	Standard Space/ *In Situ* Components
	by Improving	The Mission Development Process	Better, Faster, Cheaper as a Process Improvement Concept Procedures Standards Training, Skill Development, and Knowledge Sharing	Development Capabilities
	by Developing	Servicing/Repair or Partial Replacement of Mission Capabilities	Reprogrammable Systems Robotic Servicing/Docking/ Formation Concepts	Standard Space/ *In Situ* Components
	by Safely Disposing of	Mission Assets at Their End of Life	Reposition to Safe Location Return Disposal (e.g., Satellite Reentry)	Standard Space/ *In Situ* Components

Table 24: Mapping of Functional Goals to Concepts and Elements of Form (cont.)

Intent	Process	Operand		Concepts	Related Form Elements
To Leverage Multi-Mission Economies of Scale	by Ensuring	the Availability of Multi-Mission Infrastructures for:	Conveying Observation Results	Physically Convey Samples or Media Radio Frequency Communications (Ground Stations or Space Relay) Optical Communications (Ground Stations or Space Relay)	Standard Space/ *In Situ* Components Command/ Control/ Communications/ Navigation Infrastructure
			Communicating Command and Engineering Data	Combinations of: Similar Radio and Optical Concepts Multiple Distributed Spacecraft Concepts with Real-Time Autonomous Coordination	Command/ Control/ Communications/ Navigation Infrastructure Standard Space/ *In Situ* Components
			Launching and Deploying Missions	Summarize and Reference Available Sources on Worldwide Launch Capabilities	Launch Capabilities Standard Space/ *In Situ* Components
			Navigating Missions	Onboard Hardware and Software to Independently Determine and Adjust Position Ground-in-Loop Approaches Using Ground Communications Infrastructure Ground-in-Loop Approaches Using Relay Communications Infrastructure (e.g. TDRSS) Ground-in-Loop Approaches Using Dedicated Ground Infrastructure (Radio or Optical, e.g., DORIS, SLR) Autonomous Concepts Using Ground Infrastructure (e.g., DORIS) Autonomous Concepts Using Space Navigation Infrastructure (e.g., GPS, GLONASS, Galileo) Relative (to Other Missions) Using Dedicated Cross-Links	Command/ Control/ Communications/ Navigation Infrastructure
			Operating Missions	Multi-Mission Operations Centers NASA Space Operations Management Office (SOMO) On-Board Autonomy Concepts	Command/ Control/ Communications/ Navigation Infrastructure
			Mission Development and Manufacture	Rapid Spacecraft Development Office (RSDO) Catalog of Spacecraft Busses Rapid Mission Simulation and Prototyping Facilities Multi-Mission Mission Development Facilities (NASA Centers, Industry, etc.)	Development Capabilities

Appendix B: Biographical Note

Gordon Johnston is currently the Associate Director for Exploratory Missions in the Office of Earth Science at NASA headquarters. Mr. Johnston's has both a Bachelors and a Master's degree in Mathematics from the California State University at Northridge. He began his career in 1977 at the Jet Propulsion Laboratory, planning Mars imaging for the *Viking* orbiter. He next worked on the mission design for the *Galileo* mission to Jupiter, focusing on the science requirements for the remote sensing instruments. While at JPL, he also taught mathematics in the evenings at the Pasadena City College. In 1987, after the *Challenger* disaster, he moved to NASA headquarters. At NASA he has managed systems analysis programs to identify and advocate technology developments, space technology university grant programs, an advanced data system technology program, and instrument and sensing technology development programs.

In 1997 he joined the Office of Earth Science, where he helped plan the Earth Science technology program. He has led several major mission selection panels for Earth Science, including the technical panel for the first Earth System Science Pathfinder (ESSP) announcement of opportunity (AO), the Technical, Management, Cost, and Other factors (TMCO) panel for the Triana AO evaluation, the technical panel for the Lightweight Synthetic Aperture Radar (LightSAR) AO, and the overall evaluation for the second ESSP AO. He has also led the assessment of several New Millennium Program missions.

In 1999 he was competitively selected for the NASA Project Management Development Process (PMDP) Accelerating Leadership Option (ALO). This thesis represents the completion of the academic portion of this program. Before coming to MIT he help draft the University Earth System Science (UnESS) and the third ESSP announcements of opportunity.

His publications include:

- "Advanced Technologies to Support Earth Orbiting Systems," Robert Rosen, Gordon I. Johnston, paper no. IAF-92-0751, 43rd Congress of the International Astronautical Federation, August 28-September 5, 1992.
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Appendix C: References

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