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# Transformational Systems Concepts and Technologies for Our Future in Space

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Proceedings of a workshop sponsored
by the National Aeronautics and Space
Administration held in Huntsville, Alabama,
June 17–19, 2003

**June 2004**

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# EXECUTIVE SUMMARY

The Transformational Systems Concepts and Technologies for Our Future in Space workshop, held June 17–19, 2003, in Huntsville, AL, brought together invitees from NASA, the Department of Defense (DOD), universities, and industry to conceptually formulate notional "road maps" that could lead to an accelerated, ongoing transformation of space infrastructure, beginning in the middle years of the next decade.

National space strategies call for technical innovation with programmatic realism. The increasing importance of space is reflected in national-level guidance from within key agencies and from independent blue-ribbon advisory panels, as well as the President's recent commitment to space exploration.

NASA's Vision for Space Exploration, released in 2004, and NASA's Strategic Plan, released in 2003, both spoke of the benefits of space for the prosperity and security of future generations of Americans. In the Strategic Plan, NASA Administrator Sean O'Keefe pointed to the potential of NASA's work to enable fundamental advances in science, improve homeland security, counter threats to Earth's ecosystem, and strengthen young people's interest in math and science. He also emphasized that in today's environment of new changes, challenges, and opportunities, NASA must transform the way it plans and operates its programs.

NASA's Advanced Systems Office (ASO) offers a workable approach in transforming space systems. The ASO is exploring modular design combined with stepping-stone development as a promising new approach to achieve transformation in space in service of its explicit responsibility to support NASA's strategic goal: "Enable revolutionary capabilities through new technology." The ASO's proposed approach to innovation can transform space systems in the future. Such an approach can, it appears, achieve up to five times as much with the same resources if each new space system or component is not treated as a unique and discrete design and development challenge. New space systems instead can be designed and planned so that each builds on previous systems and provides capabilities to support future systems. Subsystems can be designed to use common modular components, achieving economies of scale in production and operation. Standards, interoperability, and "plug and play" capabilities, if they are implemented vigorously and consistently, will result in systems that can efficiently be upgraded with new technologies.

The initial benefits of such an approach can be dramatic. Since the first generation of space technology, space infrastructure and systems have seen periodic evolution but have not seen the same transformational change. Today's expendable launch vehicle's, upper stages, spacecraft busses, and components are relatively similar to those used for the last 30 yr. Yet, in that period, new technologies and techniques in dozens of relevant disciplines have been emerging and maturing. The Transformational Space Systems approach formulated by the ASO will draw on those advances, and future advances that build on them are poised to help achieve revolutionary innovation in space.

At the heart of this ambitious target is the notion that transformative innovation in space is overdue. Since the last big change in space infrastructure—the decision 20 yr ago to build the Space Station, space technology has not advanced dramatically.

Transformation can be realized through modular design and stepping-stone development. The approach to transformation that NASA is exploring consists of a shared framework for planning and a set of design and development principles.

The disciplined planning process incorporates integrated development and demonstration cycles, frequent new starts, and clear go/no-go decision points. It relies heavily on a technology planning work breakdown structure (WBS) and technology roadmaps, and employs systems analysis models and technical interchange workshops.

Transformational design and development yield revolutionary advances by using modular designs and a planned, stepping-stone development process. A modular approach to space systems can offer many improvements over traditional one-of-a-kind space systems comprised of different subsystem elements with little standardization in interfaces or functionality. Modular systems are more flexible, scaleable, reconfigurable, and evolvable. They can reduce costs through learning-curve effects and economies of scale, or by enabling servicing and repair that would not otherwise be feasible.

NASA's progress to date in embracing modular design has been modest. However, the Agency's strategic commitment to using a building-block approach to create stepping stones to the future has poised the Agency to move toward transformation of space systems.

Modular technology for space systems is real. Technologies that have the potential to address some of the chief near-term challenges; e.g., self-assembling structures, modular spacecraft and propulsion, and modular space infrastructure elements, have been demonstrated in the laboratory. Reaping the benefits of these technologies and of new technologies that will emerge in the future requires additional research and development (R&D), and the opportunity for frequent flight demonstrations and experiments.

The Transformational Systems Concepts and Technologies for Our Future in Space workshop helped chart NASA's path. The workshop consisted of an alternating series of plenary sessions and working sessions. Working groups developed recommendations on the transformation process and provided technical inputs on technology roadmaps, conceptual designs, and technology development plans on the following topics:

- Systems Integration, Analysis, Concepts, and Modeling: The working group's recommendations were that NASA should support interface and data standards, hybrid modeling approaches that accommodate both single-user applications and multiuser environments and interchange between them, open architecture and data standards, and architecture assessment models.

- Architectures, Mission Applications, and Benefits: The working group's first finding was that past failures and limitations should not be allowed to inappropriately constrain future options. The group felt it would be necessary to change NASA's scientific mission strategy from a debate; e.g., like the current debate over Mars programs, to a thoughtful, analysis-based process. It offered suggestions to make systems analysis the norm, such as a better understanding by NASA and the DOD of how well predictive tools performed for on-orbit systems. The group advocated an evolutionary approach that would dovetail high-level, lower fidelity studies with higher fidelity studies. The group called for a process for integrating the studies from different groups (NASA, DOD, industry, etc.) and a central repository for sharing information. Finally, the group strongly encouraged that the advanced systems, technologies, research, and analysis modeling teams open communication immediately with the space architect team members and work with them to identify which models to use in higher level studies.

- Space Assembly, Maintenance, and Servicing: The working group suggested that future mission opportunities for space assembly, maintenance, and servicing could include Jupiter Icy Moons orbiter-class missions. The group suggested these missions include assembly support and onboard maintenance capability. The group also identified postlaunch verification capability for deep-space missions as a related opportunity. The group felt that the process of technology roadmapping required inputs to roadmaps from a much broader community than NASA space assembly, maintenance, and servicing experts. The group also found that the domain as a whole needs better, more formalized studies to focus future investment more strategically. The working group also recommended undertaking a series of tasks to demonstrate that the ability currently exists to build an optical-quality telescope with multiple assembly approaches.

- High-Energy Space Systems: The working group recommended that a range of promising power-rich technologies be pursued, in recognition of the fact that different technologies have different attributes and limitations. The group specifically recommended R&D occur in four areas—novel photovoltaics, nuclear propulsion, beamed power, and chemical and mechanical propulsion. The objective of this R&D should be the development of a “power toolbox” that provides alternative technologies to meet different needs. The group emphasized the importance of an “assembly line” for technology that moved technologies up through maturity levels. Finally, the group emphasized that competition drives innovation, and recommended that competition among firms be encouraged and competition between technologies be promoted. However, they recommended government agencies should work together.

- Revolutionary Space Systems: The working group found that the development of revolutionary systems needs seed money to keep planning and technology activities alive, with funding applied to both existing and new initiatives as needed. The group recommended setting a series of integrated milestones to set goals and track progress. It also urged that decision makers make a clear connection between NASA and the DOD. Finally, the group felt that it was important to involve industry access and recommended assessing the related policy issues.

- Technology Flight Demonstrations: A specific recommendation of the working group was that leads of the technology-development WBS elements in support of transformation should collect technology flight demonstration and technology flight experiment candidates into an accessible resource. Broader recommendations were that, for technology flight demonstrations to be most useful, NASA would have to change the thinking about success and failure when dealing with technology, to recognize the value and legitimacy of a negative result. Finally, the group suggested that NASA investigate how the DOD conducts technology experiments and demos.

NASA will continue to explore the potential for transformation through workshops with diverse stakeholders. Future workshops will address flight demonstrations and experiments, leading-edge research in academia, principles of modular design and development, and other topics. Future workshops will be based on what NASA learns from its ongoing interactions with engineers, scientists, mathematicians, business people, academics, and many others. These insights from these events will aid NASA in its quest to understand and act on the potential for transforming space infrastructure and advancing NASA's vision to improve life here, to extend life to there, and to find life beyond.

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# LIST OF ACRONYMS

| | |
|---|---|
| ASO | Advanced Systems Office |
| ASTRA | advanced systems, technologies, research, and analysis |
| CL | collaborative |
| DB | database |
| DE | discrete events |
| DOD | Department of Defense |
| ELV | expendable launch vehicle |
| EVA | extravehicular activity |
| GEO | geosynchronous Earth orbit |
| GRC | Glenn Research Center |
| GSFC | Goddard Space Flight Center |
| HIL | human in the loop |
| HQ | Headquarters |
| IRC | intelligent and reconfigurable component |
| *ISS* | *International Space Station* |
| JPL | Jet Propulsion Laboratory |
| JSC | Johnson Space Center |
| LaRC | Langley Research Center |
| LEO | low-Earth orbit |
| MDA | multiple discipline areas |

## LIST OF ACRONYMS (Continued)

| | |
|---|---|
| ML | multiple locations |
| MMS | multimission modular spacecraft |
| MP | multiple projects |
| MSFC | Marshall Space Flight Center |
| MTD | microspacecraft technology development |
| NSI | Nuclear Systems Initiative |
| NSSA | National Security Space Architect |
| OSF | Office of Space Flight |
| PMAD | power management and distribution |
| RASC | Revolutionary Aerospace Systems Concept |
| R&D | research and development |
| TFD | technology flight demonstration |
| TFE | technology flight experiment |
| TRL | technology readiness level |
| TSCT | transformational space concepts and technologies |
| TSI | transformational space infrastructure |
| WBS | work breakdown structure |

CONFERENCE PUBLICATION

# TRANSFORMATIONAL SYSTEMS CONCEPTS AND TECHNOLOGIES FOR OUR FUTURE IN SPACE

## 1. NATIONAL SPACE STRATEGIES CALL FOR TECHNICAL INNOVATION WITH PROGRAMMATIC REALISM

The increasing importance of space is reflected in national-level guidance from within key agencies and from independent blue-ribbon advisory panels, as well as the President's recent commitment to space exploration.

NASA's Vision for Space Exploration, released in 2004, and NASA's Strategic Plan, released in 2003, both spoke to the benefits of space for the prosperity and security of future generations of Americans.

### 1.1 The Nation Relies on Space and Will in the Future

NASA's Strategic Plan contained a message from NASA Administrator Sean O'Keefe, emphasizing the benefits of space for the prosperity and security of future generations of Americans. O'Keefe pointed to the potential of NASA's work to enable fundamental advances in science, to improve homeland security, to counter threats to the Earth's ecosystem, and to enhance the connection of young people to math and science. He also said that, in today's environment of new changes, challenges, and opportunities, NASA must transform the way it plans and operates its programs.

The Commission to Assess National Security Space Management and Organization, established by Congress, reported that space capabilities support the Nation's domestic, economic, diplomatic, and national security objectives. It characterized threats to space assets as threats to national security. The Commission's concerns and findings were compelling enough that the U.S. Department of Defense (DOD) has reorganized its management of its space systems, making sweeping changes in response to the report. These changes, advocated in the January 2001 report, continue to reverberate through the DOD as the Nation's space policy and doctrine evolve to reflect new realities.

The President's Commission on the Future of the U.S. Aerospace Industry, in its final report issued in November 2002, found that a healthy aerospace industry is a national imperativeness. The report said that strong aerospace industry was important to the United States in the defense arena, in global market, and in workforce development.

These and other studies identified promising future technologies, systems, and capabilities that they urged the Nation to pursue to help achieve national security, economic health, and scientific objectives. While some are mission-unique to NASA, the DOD, or industry, many are of interest across space sectors.

The planning framework created by these findings and recommendations is one of an enhanced commitment to space through more research and development (R&D), new and better space systems, and improved management. Innovation in space can be regarded as a national mandate.

## 1.2 Future Space Benefits Must be Realized with Constrained Resources

This hunger for innovation and enhancement of space capabilities does not, however, translate into a proportionally growing resource base. Particularly in the area of civil space, it is likely that today's budget constraints will also be tomorrow's. Decisions about space funding and programs are shaped by the political context. Large, expensive systems that require many years of investment before they yield even preliminary results require the ongoing support of many different decision makers and success in changing political environments over time. Moreover, even the occasional failure of such systems is highly visible and difficult to recover from, both in terms of program funding and in terms of political commitment. Alternatively, if Government-funded space activities can achieve results within political cycles, they become more meaningful to and more robustly supported by any given set of decision makers.

As a result, the Nation faces a profound challenge—to achieve dramatic, transformational results on an evolutionary budget. To realize the extraordinary potential of space, there must be a new path to innovation and achievement.

# 2. NASA'S ADVANCED SYSTEMS OFFICE OFFERS A WORKABLE APPROACH TO TRANSFORMING SPACE SYSTEMS

NASA's Advanced Systems Office (ASO) is exploring a promising approach to achieve transformation in space.

One of the ten overarching goals in the 2003 NASA Strategic Plan is "Enable revolutionary capabilities through new technology." Responsibility for this goal vests in four organizations, one of which is the ASO. The ASO was created in spring 2002 within the Office of Space Flight (OSF). The OSF encompasses the Space Shuttle, the *International Space Station* (*ISS*), and Space and Flight Support (called "enabling themes" in the Strategic Plan). The ASO is the future-looking element of the Space and Flight Support enabling theme within the OSF.

The ASO works with other Enterprises and with the NASA Space Architect's Office, created in September 2002, to help create and enable shared long-term vision for human and robotic exploration and development of space. The ASO assesses strategic technology investments, analyzes advanced concepts, and fosters innovative approaches.

The ASO has drawn on a knowledge base created through research and trade studies, evaluations of technology investments, targeted seed funding portfolio, and collaboration with other organizations to formulate an approach to realizing transformational space concepts, technologies, and systems. The ASO's findings suggest that such an approach might realize twofold to fivefold improvements in important metrics that drive what can be done in space. Improvements of that magnitude can make an extraordinary contribution to achieving the innovation and enhanced space capabilities that the Nation seeks.

## 2.1 Transformational Innovation in Space is Overdue

The ASO seeks to use a new approach to innovation to transform space systems in the future, achieving two to five times as much with the same resources. At the heart of this ambitious target is the notion that transformative innovation in space is overdue. Since the last big change in space infrastructure—the decision 20 yr ago to build the Space Station, space technology has not advanced dramatically.

The first generation of space technology innovation saw the creation of launch facilities, the deep-space network, ground networks, expendable launch vehicles (ELVs), spacecraft busses that enabled communication satellites, weather satellites, sensing satellites, and a robust national security space infrastructure. And all of this innovation happened in a decade.

Since that time, space infrastructure and systems have seen periodic evolution; e.g., the global positioning system and the shuttle program, but have not seen the same transformational change since the early 1960s. Today's ELVs, upper stages, spacecraft busses, and so on are relatively similar to those used for the last 30 yr. Yet, in that period, new technologies and techniques in dozens of relevant disciplines have been emerging and maturing.

The foundation of the transformational approach formulated by ASO is that those advances and future advances that build on them are poised to help achieve revolutionary innovation in space.

## 3. REALIZING TRANSFORMATION THROUGH MODULAR DESIGN, STEPPING-STONE DEVELOPMENT

The approach to transformation that NASA is exploring consists of a shared framework for planning and a set of design and development principles.

### 3.1 Disciplined, Analytic Planning

The disciplined planning process incorporates integrated development and demonstration cycles, frequent new starts, and clear go/no-go decision points. It relies heavily on a technology planning work breakdown structure (WBS) and technology roadmaps. The modular infrastructures transformational roadmap is shown in figure 1. The planning process also incorporates systems analysis models and technical interchange workshops.

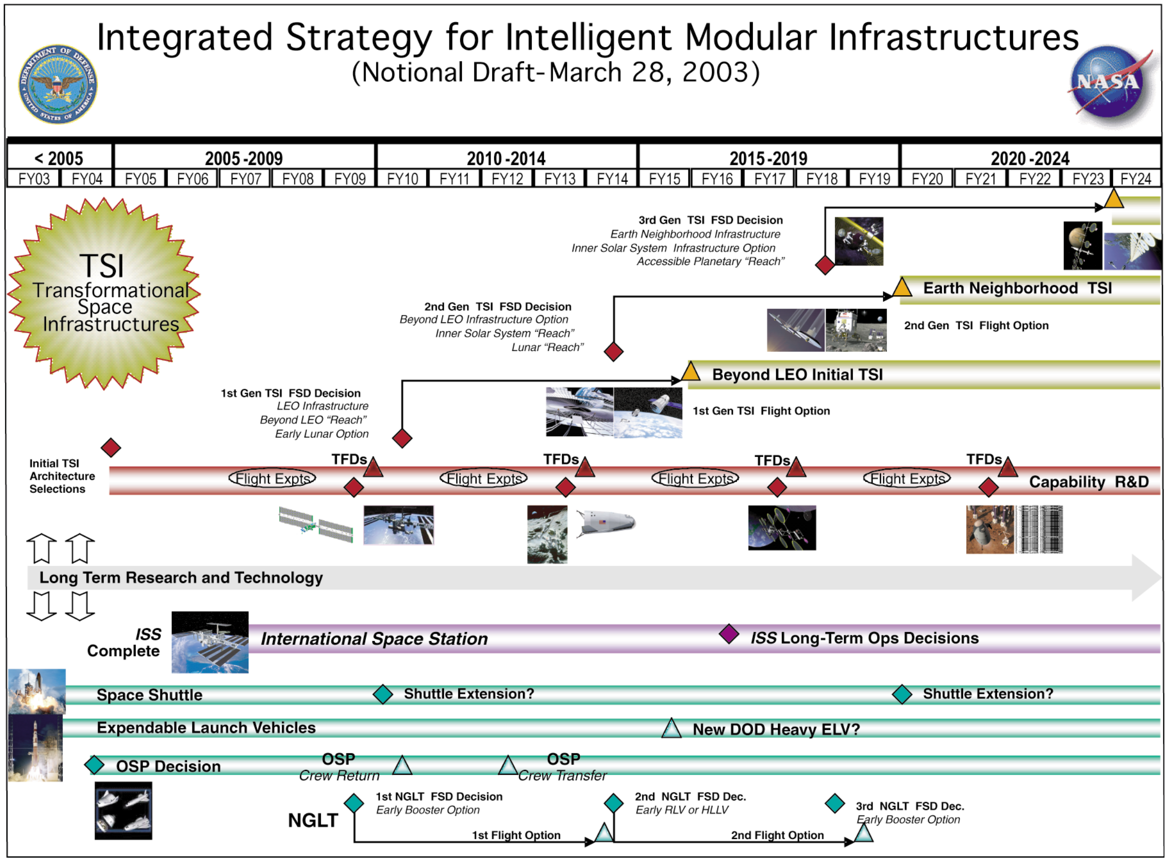


Figure 1. Transformational roadmap for modular infrastructures.

### 3.1.1 Cyclical Process

Integrated technology R&D and demonstration cycles form the structure of the ASO planning process to achieve transformational space systems. Three-year design and development phases overlap one another with 6-yr demonstration phases. Decisions to continue or abandon a line of inquiry or development are made for each cycle. Relatively frequent and predictable launch demonstration opportunities reduce the impact of slips in development schedules. Program managers can postpone demos, taking a launch demo in the next cycle, which they trust will be available, rather than conducting a premature demonstration or holding up their launch and creating downstream delays for others.

### 3.1.2 Roadmaps and Work Breakdown Structure

Technology roadmaps reflect the pace and decision nodes of this process. They are developed with input from experts in a wide range of technology. This dispersed data collection is mapped by a WBS. The WBS and technology roadmaps that the ASO has developed are referred to by the acronym ASTRA (advanced systems, technologies, research, and analysis) for future space flight capabilities.

### 3.1.3 Systems Analysis

The ASO conducts systems analyses that consider trades and interrelationships among performance, cost, schedule, and risk at the technology, system, mission, architecture, scenario, and market levels. The ASO tries to coordinate its work with other organizations conducting related analysis. An important tool in ASO's analytic arsenal is a systems analysis model that is a cooperative technology modeling effort among different NASA organizations and other researchers. The overarching model integrates separate models of advanced space systems into a planning tool that enables trades and sensitivity analyses among technology development strategies, space systems, architectures, and even multiscenario visions.

### 3.1.4 Workshops

Workshops such as the June 2003 Transformational Systems Concepts and Technologies (TSCT) workshop are vital to this planning process. Technical interchange workshops provide the opportunity for expert technologists to help refine the transformational space approach and supporting analytic tools. The ASTRA WBS and technology roadmaps are continually refined through the inputs of experts at workshops and through the ongoing interest of the community of stakeholders that workshops help create.

## 3.2 Design and Development Stepping Stones

The ASO's approach to transformation emphasizes design and development that reflect programmatic realism, meaning that if it will cost $4 billion to $7 billion for each trip to the Moon, and nearly $100 billion to get started, there will be no program. Revolutionary advances are a fundamental necessity to achieving the Nation's ambitions in space.

Transformational design and development principles achieve revolutionary advances by using modular designs and a planned, stepping-stone development process. (The ASO's approach also encompasses other widely applicable strategies for cost reduction, such as reducing Earth-to-orbit transportation costs and increasing the data intensiveness and knowledge yield of missions. However, these strategies were ground-ruled out of the June 2003 TSCT workshop to focus efforts on space infrastructure.)

### 3.2.1 Modular Systems

The concept of modularity in engineering design is widely applied. A modular system employs components that are standardized in form or function to enable flexibility. Modularization is a life-cycle strategy, with potential for improving design; manufacture; production; deployment, including assembly and checkout; operation and maintenance, including servicing or repair; and disposal or recycling.

A modular approach to space systems can offer many improvements over what may be called traditional space missions: unique collections of purpose-built systems, often one of a kind, comprised of different subsystem elements with little standardization in interfaces or functionality.

Modular systems are more flexible, scaleable, reconfigurable, and evolvable. They can reduce costs through learning-curve effects and economies of scale, or by enabling servicing and repair that would not otherwise be feasible. Consider the three major drivers of the cost of space activities—hardware, launch, and operations. (On average, across a wide range of types of space activity, mission hardware tends to cost ≈\$100,000 per kilogram. By comparison, launch costs, often regarded as the worst economic barrier to space development, are ≈\$10,000 per kilogram.)

Space hardware costs are typically high because just one system is manufactured. By comparison, auto manufacturing costs are very low relative to space systems, in large part because of mass production. It would be very expensive to build just one Mustang automobile. Modular systems that have many similar components rather than a few unique components will create manufacturing economies of scale.

Modular systems will affect both nonrecurring and recurring launch costs. There are many scenarios in which these benefits would occur. For example, large modular systems that can be deployed in smaller chunks and then be assembled robotically on orbit would enable in-space advances without massive investment in developing new heavy-lift launch capability. The on-orbit infrastructure created this way would permit taking advantage of the efficient on-orbit transportation instead of relying entirely on systems that have to launch out of Earth's gravity well. Smaller payloads would translate into a higher launch rate, enabling further economies of scale.

Flexible, reconfigurable, serviceable modular systems would likely need fewer operations personnel than large, unique systems. In addition, because of greater efficiency in the use of the standing work force, operations costs per launch would decline as the launch rate increased.

Moreover, at least some of the multiple, modular building blocks used for space systems are also likely proven useful for other applications and purposes. For example, modular systems will also drive innovation in robotics. On-orbit robotic capabilities for assembly, repair, and servicing are needed to realize the benefits of modularity in-space systems. (It is important to note that success in robotics does not imply a decrease in human presence; in fact, the reality is quite the opposite. The cost reductions and technology benefits of robotics will be the precursors that will clear the path to new environments and applications for human ventures. Ultimately, a revolution in machinery will enable humans to go to the Moon again.)

NASA is not completely without experience in modular space systems. In the 1970s, NASA designed and built the multimission modular spacecraft (MMS), used by NASA and the U.S. Air Force as the bus for a number of missions. Modularity for the MMS was conceived as a cost reducer for integration and testing; serviceability fell out as a secondary benefit. Ultimately, the usefulness of the MMS was ended by technological obsolescence; there was little provision for continuing evolution of its subsystems. Moreover, the program appears to have had no linkages to the technology programs in NASA and industry that could have provided innovative improvements. NASA's experience also includes building serviceability into the Hubble Space Telescope. Some future projects—proposed for timeframes around 15 yr from now—use concepts of modularity.

NASA's progress to date in embracing modular design has been modest. However, the Agency's strategic commitment to using a building-block approach to create stepping stones to the future has poised the Agency to move toward transformation of space systems.

### 3.2.2 Stepping Stones

The NASA Strategic Plan charts its path to the future as a series of building blocks, each expanding on its predecessors and on new discoveries (fig. 2). The Strategic Plan identifies potential building blocks of many different types. There is a program to create a body of knowledge for humans in space, another to create the technology basis for optical communication, the nuclear propulsion program Prometheus, and many others. Some are large system projects, others are technology development activities, and still others are intended to create a body of knowledge.

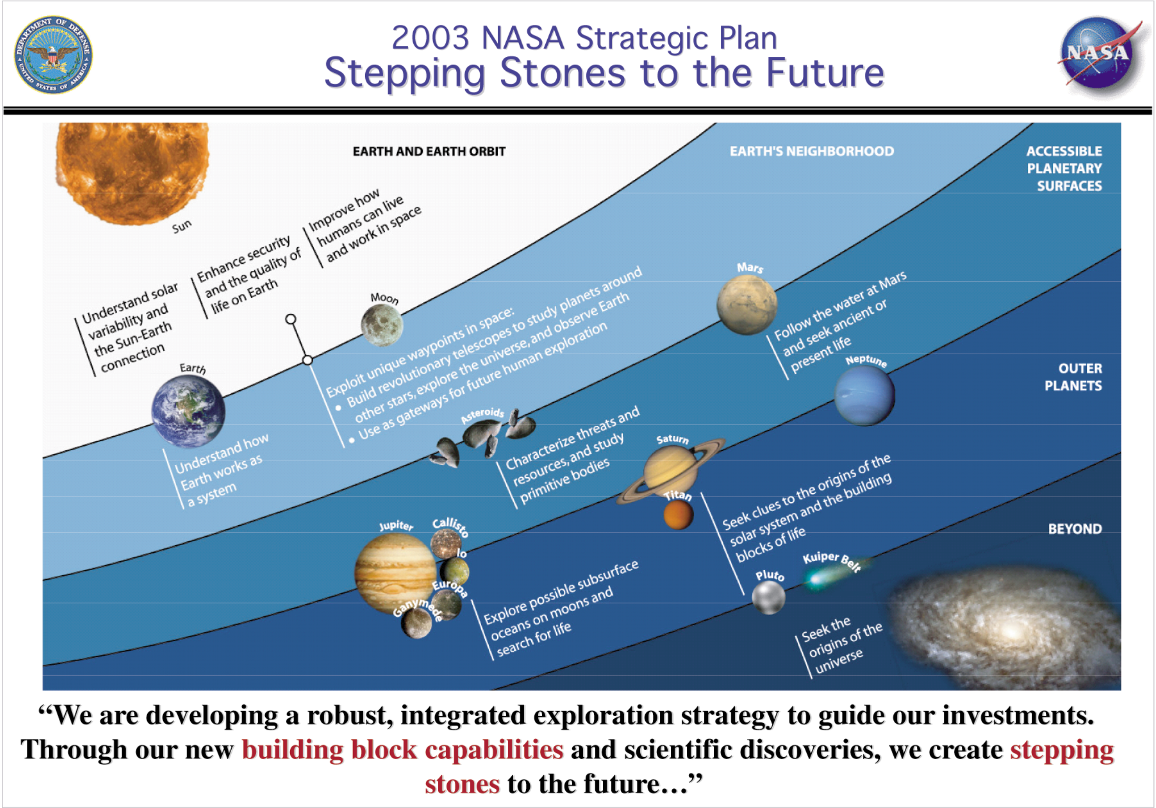
The Transformational Space Systems concept is an articulation and expansion of NASA's strategic stepping-stone concept. Its careful planning and use of modularization will create unexpected synergies with NASA's building-block programs and help them to achieve results faster.

## 3.3 Laboratory-Proven Transformational Technologies

Modular technology for space systems is real. Technologies that have the potential to address some of the chief near-term challenges; e.g., self-assembling structures, modular spacecraft and propulsion, and modular space infrastructure elements, have been demonstrated in the laboratory. Reaping the benefits of these and future technologies requires additional R&D, and the opportunity for frequent flight demonstrations and experiments. The June 2003 TSCT workshop featured three presentations that highlighted the state of the art of several important technologies.

### 3.3.1 Self-Assembling Structures

An interdisciplinary team of researchers from the NASA Jet Propulsion Laboratory (JPL) and the University of Southern California has developed modular robots that can self-assemble with each other into different configurations. These intelligent and reconfigurable components (IRCs) consist of



2003 NASA Strategic Plan
Stepping Stones to the Future

**"We are developing a robust, integrated exploration strategy to guide our investments. Through our new building block capabilities and scientific discoveries, we create stepping stones to the future…"**

Figure 2. Stepping stones to the future.

(1) a controller, (2) a set of named connectors, (3) wireless communication, (4) a self-locating system, and (5) short-range sensors for docking guidance (fig. 3). The robots have the intelligence to activate themselves when receiving a call for their identifier or type. They can call other robots like themselves or other types of robots to assist them, and they can activate other connectors. The robots were designed to be able to free-float and dock on orbit as part of a system to achieve space self-assembly. This self-assembling capability could save thousands of astronaut hours when constructing large-scale space structures. The JPL continues its research on IRCs and on the other elements of the system: free-flying robots that can search, navigate, and bring together IRCs and a process controller that can plan self-assembly in a distributed manner and recover from unexpected situations. Figure 4 shows IRCs in action.

### 3.3.2 Modular Micropropulsion and Microspacecraft

Propulsion researchers at JPL have built tiny spacecraft and thrusters that would serve as one of hundreds or thousands of similar components in a modular system. Utilizing a "fleet" of microspacecraft would allow for economies of scale in production and reduce the risk of developing a single, large spacecraft.

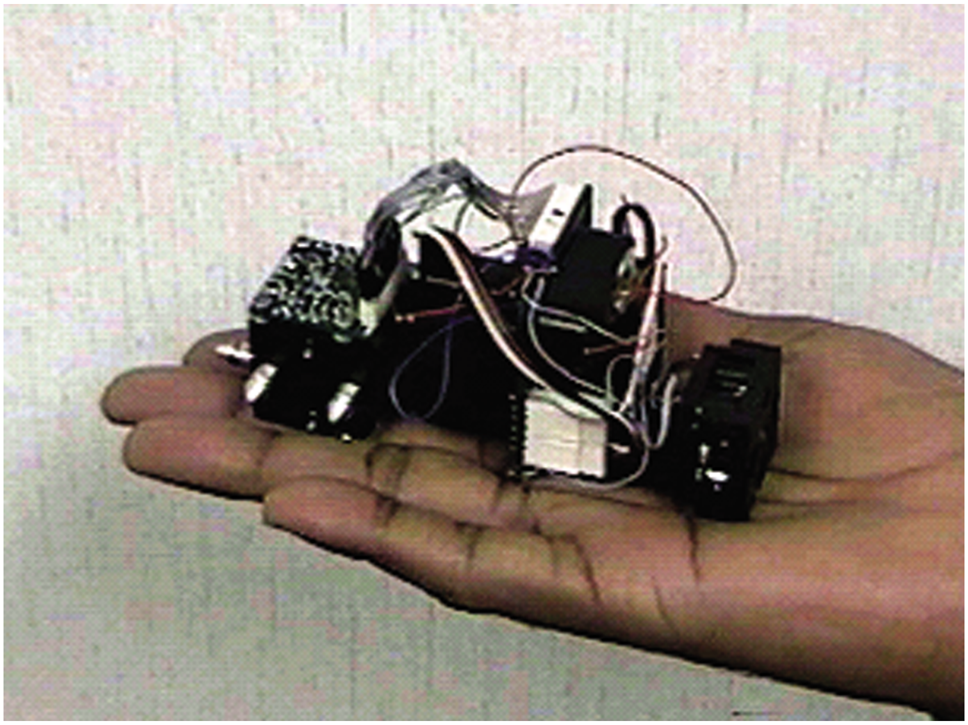


Figure 3. An IRC.

Figure 4. IRCs in action.

JPL's fully functioning microspacecraft prototype, the Microspacecraft Technology Development Task phase II (MTD II), weighs ≈7 kg and is roughly the size of a shoebox (fig. 5(a)). The prototype comes complete with a camera, solar array for power generation, avionics, and attitude control system.

Microelectromechanical systems-based phase change thruster concepts are currently under investigation for class 1 and 2 microspacecraft; i.e., spacecraft ranging from a basketball to a baseball in size. Among the concepts considered are subliming solid microthrusters (fig. 5 (b)) and vaporizing liquid microthrusters, currently under development at JPL. In the case of the subliming solid microthruster, a solid propellant (ammonia salts) is sublimated by heating the tank until a suitable tank pressure is reached; then, a microvalve is opened and the gaseous phase of the propellant is vented to produce thrust. In the case of

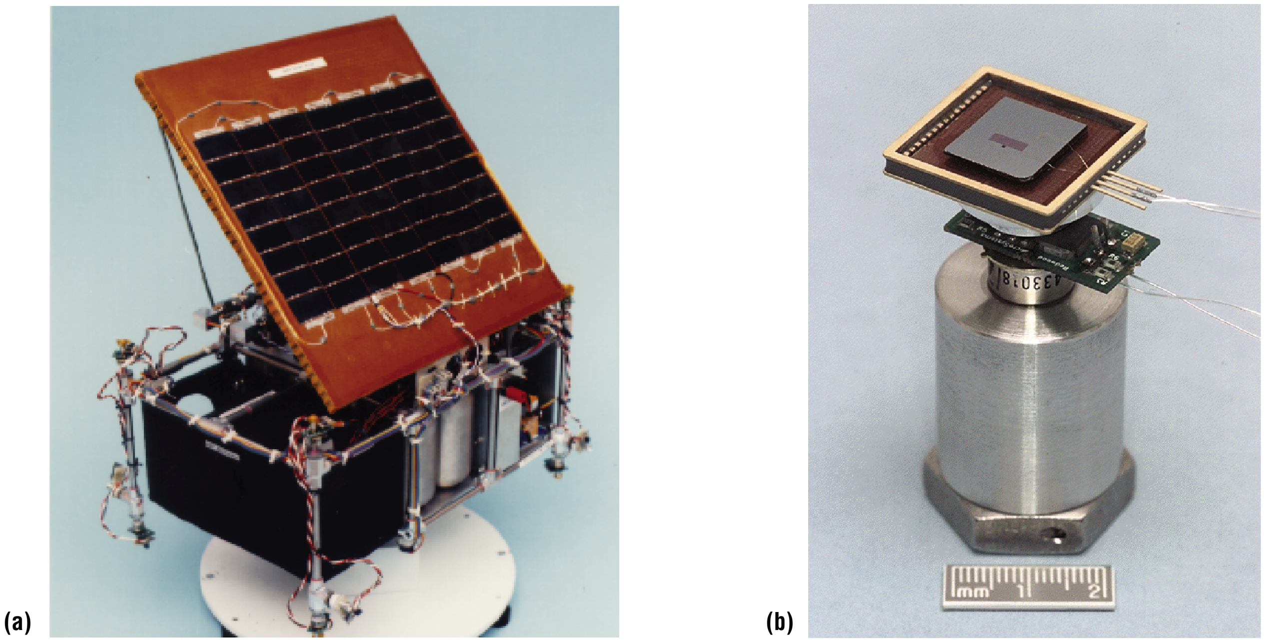
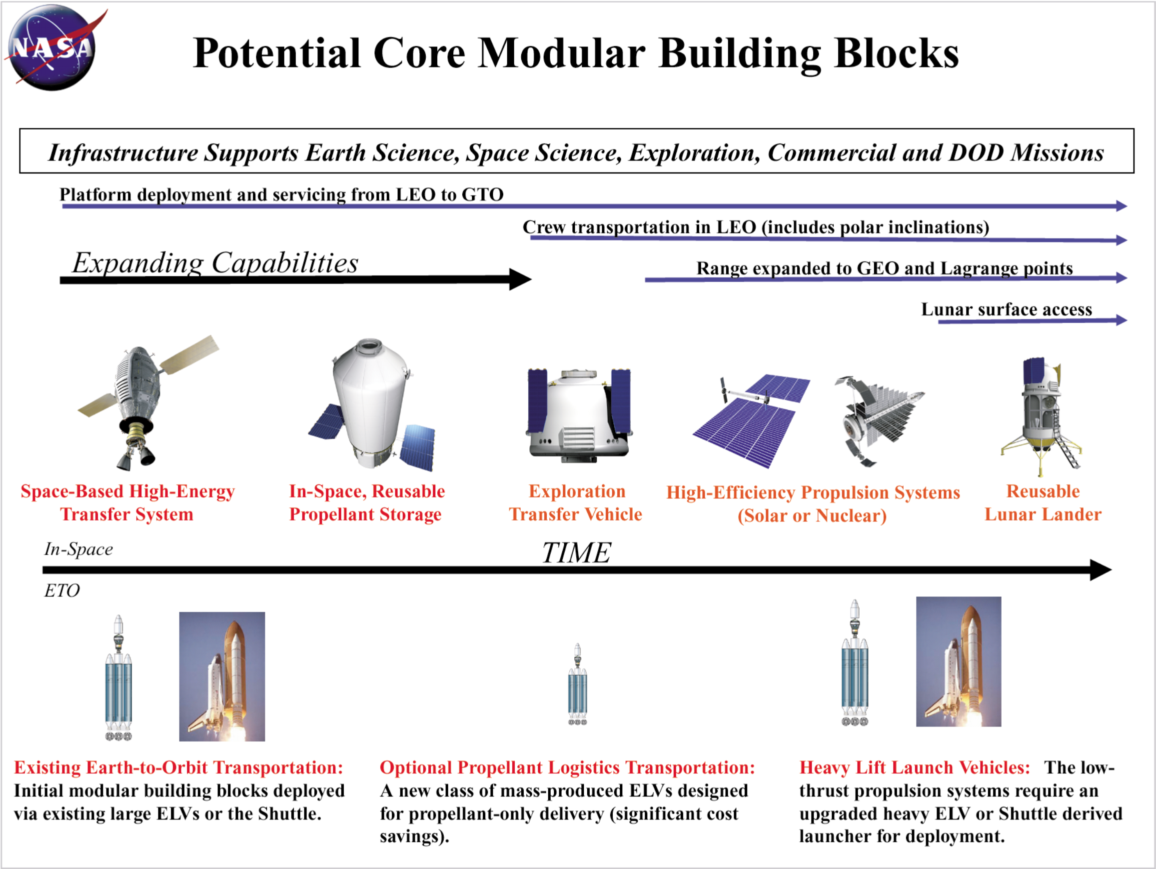


Figure 5. JPL MTD II (a) deep-space microspacecraft functional model and (b) subliming solid microthruster.

the vaporizing liquid thruster, a suitable liquid propellant; e.g., water, ammonia, hydrazine, is fed into a microthin film heater assembly that vaporizes the propellant just prior to exiting the nozzle.

### 3.3.3 Modular In-Space Infrastructure

NASA's Revolutionary Aerospace Systems Concepts (RASC) program at Langley Research Center (LaRC) has defined modular building blocks that would support ambitious future space architectures and mission sets. RASC seeks modularity, reusability, and commonality of elements across many missions, enterprises, and organizations. Modular building blocks are envisioned for activities ranging from propellant delivery and refueling to crew and vehicle transfers. RASC's objective is to create infrastructure such that the overall cost per mission is reduced the more the infrastructure is used. RASC has identified potential core modular building blocks (fig. 6). Systematically identifying and roadmapping these technologies through system studies of various architectures will help drive out their potential benefits.



**Potential Core Modular Building Blocks**

*Infrastructure Supports Earth Science, Space Science, Exploration, Commercial and DOD Missions*

Platform deployment and servicing from LEO to GTO

Crew transportation in LEO (includes polar inclinations)

*Expanding Capabilities*

Range expanded to GEO and Lagrange points

Lunar surface access

**Space-Based High-Energy Transfer System**

**In-Space, Reusable Propellant Storage**

**Exploration Transfer Vehicle**

**High-Efficiency Propulsion Systems (Solar or Nuclear)**

**Reusable Lunar Lander**

*In-Space*

*TIME*

*ETO*

**Existing Earth-to-Orbit Transportation:** Initial modular building blocks deployed via existing large ELVs or the Shuttle.

**Optional Propellant Logistics Transportation:** A new class of mass-produced ELVs designed for propellant-only delivery (significant cost savings).

**Heavy Lift Launch Vehicles:** The low-thrust propulsion systems require an upgraded heavy ELV or Shuttle derived launcher for deployment.

Figure 6. Potential core modular building blocks.

# 4. TRANSFORMATIONAL SPACE SYSTEMS CONCEPTS AND TECHNOLOGIES INSPIRE AMBITIOUS VISIONS OF THE FUTURE

The ASO has developed a progression of possible scenarios for the future in space (fig. 7). This vision, meant to be one representative of many possible future development paths, uses the building-block approach to achieve exciting results in a decade and to continually build on them.

In this vision of the future, transformational design and development over the next decade produce reconfigurable, evolvable modular spacecraft that are routinely produced and deployed. These systems usher in a decade that sees enhanced geosynchronous Earth orbit (GEO) operations and the introduction of a high-energy space infrastructure that increases orbital life and enhances system performance for many missions, including human and robotic sorties beyond low-Earth orbit (LEO). (Eventually, this leads to a large-scale space utilities system.) Beginning sometime in the middle of that decade, the vision also sees 10 yr of achievement in modular space stations, platforms, and gateways and the placement of a permanent on-orbit laser communication grid. Within three decades of today, the vision leads to a better understanding of this and other planets through dramatically enhanced scientific instruments on orbit and ultimately through robotic and human exploration of Mars.

The value of this vision of the future is not that it is a blueprint of what should or will be done. The vision of the future informs technology planning by providing one set of overarching objectives that can be used in conjunction with other visions and other sets of objectives to inform technology roadmapping and R&D investments. Its value as a tool is to help envision a possible future, and to understand what is needed to get there. It is a thought experiment conducted within the boundary conditions of the Transformational Space Concepts approach; it formulates a progressive series of innovative and high-yield advanced concepts that could be conducted within today's budget constraints.

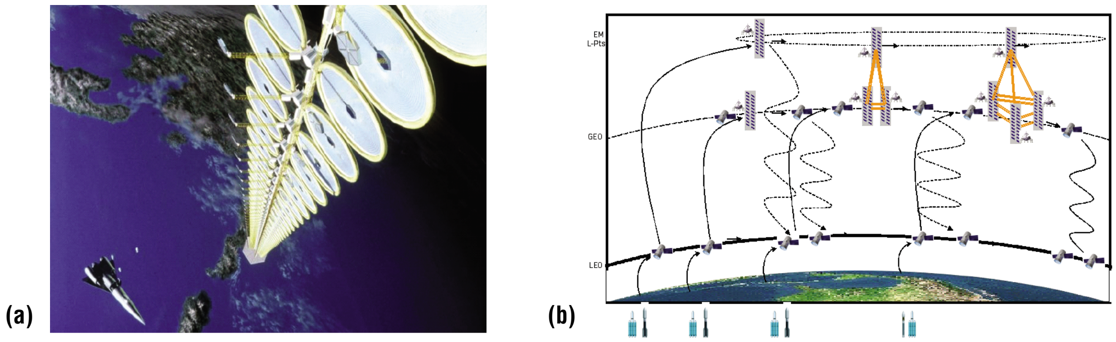


Figure 7. Examples of possible future transformational space concepts: (a) Suntower configuration and (b) deployment scenarios.

# 5. WORKSHOPS HELP NASA CHART A PATH TO SPACE TRANSFORMATION

The Transformational Systems Concepts and Technologies for Our Future in Space workshop, June 2003, was one in a planned series of meetings extending over 2 yr—2003 and 2004—that is examining the subject of transformational systems for our future in space. The first meeting was held at the California Institute of Technology in January 2003 with particular emphasis on topics related to machine intelligence, computing, and robotics.

The June 2003 workshop reported here examined a broader scope of prospective topics. The general focus of the workshop was on transformational space infrastructures of broad applicability to NASA, other agencies, and industry, rather than on specific missions or instruments. The goal of the workshop was to aid NASA in its planning and analysis process by refining technology roadmaps that could lead to the accelerated and ongoing realization of transformational space systems, beginning in the middle years of the next decade.

## 5.1 Objectives

The TSCT workshop brought together invitees from NASA, the DOD, universities, and industry. The workshop was designed to engage these experts in discussion and analysis, with the goal of conceptually formulating notional "road maps" that could lead to the accelerated and ongoing realization of a transformation of space infrastructure, beginning in the middle years of the next decade.

## 5.2 Structure and Products

The workshop consisted of an alternating series of plenary sessions and working sessions. There were two overall chairs for the workshop, representing sponsoring organizations: Patrick George, Project Manager, Power and Propulsion Office, NASA Glenn Research Center (GRC) and Joe Howell, Manager, Advanced Projects Office, Flight Project Directorate, Marshall Space Flight Center (MSFC).

A series of invited overview/background presentations was given in the plenary sessions. The concept of Transformational Space Systems was laid out in conjunction with the state of the current ASTRA strategic road maps. Workshop participants were asked to formulate revisions to existing road maps, and asked to consider new features such as the revised "3, 3, 6" timeframe for accelerating and better synchronizing the pace of progress in space. They were asked to identify and incorporate innovative technologies and key technology metrics. Participants were also asked to provide and comment on conceptual designs and analysis of innovative architectures and advanced systems for the development of space.

Participants worked in five groups covering six topics:

(1) Systems Integration, Analysis, Concepts, and Modeling (day 1).

(2) Space Assembly, Maintenance, and Servicing.

(3) High-Energy Space Systems.

(4) Revolutionary Space Systems.

(5) Technology Flight Demonstrations.

(6) Architectures, Mission Applications, and Benefits (day 2).

Extensive background material on NASA programs, future concepts, and the concept of Transformational Space Infrastructure was provided to all of the working groups. Working group final presentations, including recommendations and technology roadmap inputs, were given at the plenary sessions. Reports from each working group included a summary viewgraph presentation of the group's findings and additional information such as technology roadmaps, conceptual designs, and technology development plans.

In addition to the catalytic and plenary presentations given at the workshop, the workshop produced this Conference Publication.

## 5.3 Workshop Findings

### 5.3.1 Systems Integration, Analysis, Concepts, and Modeling

Effectively guiding the accelerated development and validation of new space concepts and technologies will depend on ongoing modeling and analysis to better identify and understand the possibilities and weaknesses associated with various "transformational" systems concepts. The working group on systems integration, analysis, concepts, and modeling reviewed both current and planned practices and activities in this area, with an eye toward identifying challenges and approaches to solving them.

**5.3.1.1 Current and Planned Activity**. The working group identified nine important questions to characterize the attributes of models of technology decisions as follows:

(1) What is the type of model; i.e., overall, what is the function or environment being modeled?

(2) Does the model use an expert system as its knowledge expert, or are there humans in the loop providing that expertise?

(3) To what degree does it reflect collaborative engineering; e.g., across single and multiple locations, or in multiple discipline areas?

(4) Are activities being modeled concurrent or asynchronous? What time/space constraints does the model consider?

(5) What is the level of detail of the model?

(6) Does the model cover a single project or multiple projects?

(7) Does it model discrete events or a continuous process?

(8) What is the engineering process associated with the model? What is the model's state of maturity, reusability, automation?

(9) What engineering standards related to modeling; e.g., interfaces, does it incorporate?

The working group characterized models, or in some cases, families or types of models, that are used in technology decision making in terms of these attributes. The working group characterized a spectrum of models (table 1). The spectrum ran from single-user, probabilistic, integrated models of high-level problems that are defined early in a decision process through to multiuser, loosely integrated models that are likely to be defined during a process to consider a greater level of detail.

Table 1. Technology planning models by attribute.

| | **AEE** | **IMDC** | **ISAT** | **TEAM-X** | **GLIDE** | **TITAN (In Develop)** | **FASTPACK** | **JSCDT** | **Wargames** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Trans | Biological/ Physical, Satellites, Modular Spacecraft | ETO | Autonomous Satellites | Comsats, In Space Transportation | Trans, Satellite, Planetary, Phasers | ETO | Planetary, Exploration | Weapons, Logistics |
| 2 | DB, HIL | DB, HIL | DB, HIL | DB, HIL | DB, HIL | DB | DB | DB, HIL | DB, HIL |
| 3 | CL, ML, MDA | CL, ML, MDA | CL, MDA | CL, ML In Development | CL, MDA, ML In Development | Single User, MDA | Single User, MDA | CL, ML, MDA | CL, MDA |
| 4 | Synch, Async | Async, Synch | Synch | Synch | Synch, Async | Async | Async | Synch, Async | Synch |
| 5 | Component | Component | Subsystem | Component | Component | System, Subsystem | Subsystem | Subsystem | Component → System |
| 6 | MP | MP | MP | MP | MP | MP | MP | MP | MP |
| 7 | DE | DE | DE | DE | DE | DE | DE | DE | Continuous |
| 8 | In Development | Help Desk Established | Support Contractor, Some Document | Well Documented | In Development | In Development | Proprietary | Documented Spiral Evolution | Well Documented |
| 9 | Some Commercially Accept, Oracle, Phoenix, Legacy Codes & Commercial | Excel, Oracle | Homegrown Environment, Legacy Codes | Homegrown, Excel Publish & Subscribe | Excel, Legacy, Homegrown, Integration, Glue Ware | Homegrown, Excel, VBA | Excel, Phoenix, Model Center | Legacy, Commercial | Homegrown, MIL Spec |

**5.3.1.2 Findings**. The working group also considered the advantages and disadvantages of single-user models and multiuser models. They noted that while a single-user model can provide quick answers, and can support many types of analyses, it is hard to get decision-maker buy-in based on a single-user model. In addition, such a model typically requires significant problem definition upfront. By contract, modeling in a multiuser environment can provide built-in buy-in. It can serve as an educational tool. Multiuser model results are likely to be higher fidelity and the initial problem definition can be looser than for a single-user model. However, a more loosely defined problem can be a disadvantage as well. In addition, a multiuser model is likely to be slower, more expensive to develop and to maintain, and more likely—because of the complexity and high cost as well as the revenue potential associated with multiple users—to be proprietary to the developer.

**5.3.1.3 Recommendations**. The working group's recommendations were that NASA should support the following:

- Interface and data standards.
- Hybrid modeling approaches, both single-user applications and multiuser environments.
- Processes for generating curves from multiuser environments for single-user environments.
- Encourage/enforce open architecture and data standards.
- Establish management policies and ensure interchange between multiuser and single-user environments.
- Develop models for multiuser and single-user environments to enable architecture analysis.

### 5.3.2 Space Assembly, Maintenance, and Servicing

The ability to assemble, inspect, maintain, service, refuel, reconfigure, and/or evolve future space systems throughout the Earth's neighborhood and beyond is a critical capability needed to realize the goals of Transformational Space Infrastructures. This working session reviewed current and planned approaches and activities in this area, including all-robotic systems, self-assembling systems, and extravehicular activity (EVA) system-based approaches—with an eye toward identifying challenges and approaches to solving them.

**5.3.2.1 Current and Planned Activity**. The working group found that today's investment profile in support of space assembly, maintenance, and servicing is very limited. There is no viable EVA development program, nor an organized robotics program or active assembly program at the Agency level.

Today, on-orbit servicing activities are limited to *ISS* support and to one remaining Hubble flight of the Shuttle. On the other hand, there is a fairly healthy program in support of systems autonomy. DOD/Defense Advanced Research Projects Agency is investing in this domain on multiple levels, but not in many programs oriented towards space systems. DOD programs that are oriented toward space systems include Orbital Express (intended to develop and demonstrate autonomous techniques for on-orbit refueling and reconfiguration of satellites), Experimental Small Satellite microsatellite (XSS–11), and joint projects with NASA.

The limited investment in the area of space assembly, maintenance, and servicing is reflected in the list of active programs compiled by the working group. NASA's current programs in space assembly, maintenance, and servicing are as follows:

- Robonaut.

- Mini-AERCam.

- Personal satellite assistant.

- Elements of Mars technology.

- Station assembly and servicing.

- Hubble servicing.

- Miscellaneous structures programs—very limited.

- Tile repair and inspection.

The working group members were also aware of programs in academia at Carnegie Mellon, the University of Maryland, Massachusetts Institute of Technology, and very small programs at other institutions.

The working group's view was that there was little work going on in industry that was relevant to this topic.

**5.3.2.2 Findings**. The working group articulated the major technology development challenges in the area of space assembly, maintenance, and servicing. The group discussed the need for robotic systems with increased autonomy/intelligence, achievable in the group's view through an approach of layered autonomy. Layered autonomy is a strategy of building up primitive robots to allow more complex behavior.

The group advocated increased environmental awareness for both robots and humans in supporting space assembly, maintenance, and servicing. The group particularly noted the need of robots for enhanced force-feedback data.

The culture in which design for assembly, maintenance, and servicing occurs needs to change to allow and encourage more consistent, standardized approaches.

Finally, the group noted that space assembly, maintenance, and servicing decisions must fundamentally be made based on a trade analysis of the cost of repairing or maintaining an existing system versus the cost of putting a new system in space.

**5.3.2.3 Recommendations**. The working group offered general recommendations. It suggested that future mission opportunities for space assembly, maintenance, and servicing could include Jupiter Icy Moons orbiter-class missions. The group suggested these missions include assembly support and onboard maintenance capability. The group also identified postlaunch verification capability for deep-space missions as a related opportunity.

The group felt that the process of technology roadmapping in support of space assembly, maintenance, and servicing required inputs to roadmaps from a much broader community than NASA space assembly, maintenance, and servicing experts. Narrowly targeted workshops and requests for information could capture inputs specific to a given roadmap.

The domain as a whole needs better, more formalized studies that help define needs and that can focus future investment more strategically. It would benefit from state-of-the-art projections, architectures, and deeper characterization of mission profiles to derive capability needs and map to technology options. Agencies should coordinate similar road-mapping activities.

The working group also recommended undertaking a series of tasks to demonstrate that the ability currently exists to build an optical quality telescope with multiple assembly approaches. The working group defined the following three tasks:

- Task No. 1: Optical quality demonstrator. Build an optical “bench” to learn if an optical quality instrument can be built and maintained onorbit. Approach: Start with a design process that plans for assembly and maintenance onorbit and allows for either human or robot assembly. Do a ground demonstration in assembly jigs that show alignment accuracy and maintainability. Move to a neutral buoyancy demonstration that shows full-scale assembly process, assembly and alignment infrastructure, maintenance activities, and task choreography. Task assessment metrics are that optical alignment objectives are met.

- Task No. 2: Optimize assembly and maintenance process. Use the optical “bench” developed in task No. 1 to learn about assembly process. Approach: Start with the design and hardware from task No. 1 and select multiple approaches toward assembly; i.e., different combinations/types of robots, humans, etc. Conduct multiple ground demonstrations in assembly jigs and capture data on assembly times, work loads, etc., that are relevant to future cost models. Pick two or three approaches and move to neutral buoyancy demonstration that shows full-scale assembly process, assembly and alignment infrastructure, and task choreography.

- Task No. 3: Demonstrate capability on orbit. Approach: Select an approach from task No. 2 for a flight demonstration with the optical bench flown into space, assembled, and maintained to optical quality. Execute a defined series of maintenance procedures over some timespan. Measure performance characteristics and maintenance costs.

### 5.3.3 High-Energy Space Systems

A fundamental requirement to achieve transformational capabilities in space is the realization of future "energy rich" infrastructures and systems, rather than "energy poor" systems possible today. This concept involves onboard power generation; high-energy and high-efficiency propulsion systems; innovative means of power storage or distribution, particularly in light of modular systems approaches; and other areas. This working session reviewed both current and planned developments in this area, with an eye toward identifying challenges and approaches to solving them.

**5.3.3.1 Current and Planned Activity**. This discussion of spacecraft power systems encompassed power, onboard propulsion, storage, and distribution. The working group noted that current power systems are often unique designs for a single mission. The group also raised the concern that new technology is not getting into flight.

The group noted that one activity underway today is the Nuclear Systems Initiative (NSI), currently funded and making progress. However, NSI is being mission driven. The working group felt that NSI would be improved if it embraced the transformational approach to technology development. The transformational program should address constraints on the use of new power technology, such as perceptions of risk and inconsistent interfaces.

**5.3.3.2 Findings**. The working group characterized the primary high-energy space system challenges as falling within the areas of solar power generation and related power management and distribution (PMAD), advanced propulsion options, cryogenics, and revolutionary energy transfer and storage. The group noted that there are, of course, other important areas.

**5.3.3.3 Recommendations**. The working group recommended that a range of promising power-rich technologies be pursued in recognition of the fact that different technologies have different attributes and limitations. The group specifically recommended R&D occur in four areas—novel photovoltaics, inherently modular; nuclear propulsion, recognizing that this may be affected by United Nations' restrictions; beamed power; and chemical, including in situ resource utilization and mechanical propulsion.

The objective of this R&D should be the development of a "power toolbox" that provides alternative technologies to meet different needs. The desired characteristics of the contents of the toolbox are:

- Complies with standards, provides standard interfaces.
- Modular.
- Scalable.
- Well-defined reliability—cost-effective, predictable reliability may solve problems that would otherwise call for extremely high reliability.
- Ready availability.
- Cost effectiveness.

To achieve the group's objectives, the group advocated an assembly line for technology. Activities at a low level of technology maturity, such as those conducted by code R, need to continue. Table 2 shows the NASA technology readiness level (TRL) scale used to measure technology maturity. However, while getting from TRL 1 to 4 happens, getting from TRL 3 to 6 does not currently happen. The proposed transformational change in development from TRL 4 to 7 will also influence new TRL 1 to 3 activities; e.g., in encouraging modularity.

Table 2. TRL scale.

| TRL | Description |
|---|---|
| 1 | Basic principles observed and reported |
| 2 | Technology concept and/or application formulated |
| 3 | Analytical and experimental critical function and/or characteristic proof of concept |
| 4 | Component and/or breadboard validation in laboratory environment |
| 5 | Component and/or breadboard validation in relevant environment |
| 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| 7 | System prototype demonstration in a space environment |
| 8 | Actual system completed and "flight qualified" through test and demonstration (ground or flight) |
| 9 | Actual system "flight proven" through successful mission operations |

Finally, the group emphasized that competition drives innovation, and recommended that competition among firms be encouraged and competition between technologies be promoted. However, they recommended Government agencies should work together.

### 5.3.4 Revolutionary Space Systems

In order to undertake very ambitious missions in the future—and to do so in a way that is safe, effective, affordable, and sustainable—a revolutionary new generation of space systems will be needed. The advances needed will revolve around concepts that allow large, highly capable systems to be deployed that are substantially larger than the capacity of any single launcher. In addition, increasing levels of self-sufficiency will be important to reduce the cost of operations while continuing to extend activities. This working session reviewed both current and planned programs and activities in this area with an eye toward identifying challenges and approaches to solving them.

**5.3.4.1 Current and Planned Activity**. The working group considered today's state of the art and what is needed for the future in the areas it felt were most likely to contribute to revolutionary space systems. They addressed self-sufficient space systems, habitation and bioastronautics, and surface exploration systems that working group members viewed as important. They also identified work in the area of modular, reconfigurable, evolvable, and rapid response system architectures. Finally, they considered other areas where work is needed.

Current activity in the area of self-sufficient space systems include today's semi-autonomous spacecraft, communications satellites, and other systems. Planned activity is aimed at developing systems that can operate in closed loop, but that are also capable of using outside input and then compensating and reconfiguring in response. This capability will include learning and decision making.

The Space Station and the Shuttle today provide for ongoing, but short-term habitation; i.e., from a few days to several months in duration, with high resupply requirements. Test facilities on the ground and in space that can support long-term habitation are needed in order to develop revolutionary habitation and bioastronautics capabilities. These facilities must include orbital variable-gravity facilities, with the ability to support years of habitation and limited resupply requirements.

Today, surface exploration relies on remote sensing satellites and short-range, short-duration rovers. Planned systems will enable long-range, on-going surface and subsurface exploration. While there are laboratory examples today of modular, reconfigurable, evolvable and rapid response system architectures, there are no operational flight systems with these attributes. In the future, infrastructure to support on-orbit systems ranging from microsatellites to large spacecraft will be needed.

Finally, additional investment and development of infrastructure—by both industry and Government—are needed in the areas of access to space, ground habitation tests, and other related areas.

**5.3.4.2 Findings**. The working group found that self-sufficient space systems will require autonomy, the ability to capture, learn, and make decisions. They also need effective health management, analysis, and the ability to be repaired, replaced, or reconfigured as needed. To develop self-sufficient space systems, the working group recommended first developing model-based diagnostic tools at the component, subsystem, and systems levels, then conducting ground and in-space demonstrations.

Revolutionary systems in the areas of habitation and bioastronautics will entail advanced life support development that includes technology to:

- Reduce resources needed; e.g., mass, consumables, power, and increase reliability.

- Provide 30 $m^2$ per person for food production.

- Develop orbital zero to one-third variable-gravity engineering test facility.

The group recommended developing integrated modular components for various applications.

Another challenge is getting access to operational zero-gravity platforms that enable important aspects of technology and engineering development for space systems. Typically, priority for access goes to science instead of technology and engineering. This is a concern for technologists working in the area of habitation and bioastronautics, but it is also a general problem that affects other technology areas. The approach recommended by the working group was to rely more on capable Earth-based facilities with focused access-to-space facilities. The group also recommended developing artificial-gravity space vehicles.

**5.3.4.3 Recommendations**. The working group found that the development of revolutionary systems needs seed money to keep planning and technology activities alive, with funding applied to both existing and new initiatives as needed. The group recommended setting a series of integrated milestones to set goals and track progress. It also urged that decision makers make a clear connection between NASA and DOD—agreements, policy, etc.

The group recommended funding small investigative teams to explore the areas discussed here in depth: self-sufficient space systems; habitation and bioastronautics, particularly artificial-gravity environments; surface exploration systems; and modular, reconfigurable, evolvable, and rapid-response system architectures.

Finally, the group felt that it was important to involve industry access and recommended assessing the related policy issues.

### 5.3.5 Technology Flight Demonstrations

The timely validation of new technologies and systems concepts is critical, and it must be conducted in a venue of sufficiently high fidelity to adequately inform future decisions related to full-scale development of derived systems. Succeeding in the accelerated development and validation of new space concepts and technologies will depend on timely and coordinated definition and implementation of technology flight experiments and technology flight demonstrations across a broad front of technologies and systems concepts. This working session reviewed both current and planned practices and activities in this area, with an eye toward identifying challenges and approaches to solving them. Particular emphasis was placed on approaches that might best be used to utilize the *ISS* for these purposes.

**5.3.5.1 Current and Planned Activity**. The working group felt that ASTRA flight demonstrations and experiments would require some additional coordination and integration but mainly would fall within the current process for demonstrations and experiments. The specific focus on ASTRA added the following functions:

- Identify and catalog relevant experiments and demos.
- Take responsibility for developing the technology flight demonstration (TFD) segment of the ASTRA WBS.
- Coordinate demos and their input into ASTRA.
- Identify opportunities for flight.
- Coordinate TFD activities between NASA and external entities.
- Track and assess other programs, both U.S. and international, to identify partnering opportunities and to identify common technologies
- Provide advocacy of accommodations and carriers
- Support budget formulation and advocacy.

**5.3.5.2 Findings**. Criteria for technology flight experiments (TFEs) and TFDs were developed by the working group. Recommendation was made that technology flight experiments and TFDs be traceable to ASTRA WBS elements as well as to NASA’s strategic goals and charter. TFEs and TFDs should be critical to accomplishing ASTRA objectives, should be modular in nature, and should be anticipated to make an impact on the infrastructure (table 3).

Table 3. ASTRA TFE/TFD accommodations.

- Parabolic trajectory aircraft
- Sounding rockets
- Expendable launch vehicle “piggyback”
- Space Shuttle (or other reusable launch vehicles)
  - Mid-deck lockers (“laboratory” accommodations)
  - Shuttle bay (“external” accommodations
- *International Space Station*
  - “Laboratory” accommodations
  - “External” accommodations
  - “Unique” accommodations
  - “Supported” activities
- Free flyers
  - Technology development missions
- Space science mission engineering payloads

Immediate emphasis

Nearer term emphasis

The working group recommended a peer review process for selection of demos and experiments, and noted that questions remain about what the process will be and who will participate. Also noted was that it was not clear at what point a coordinating group should take responsibility for particular activities.

The group found a need for a capability to fly small payloads at a cheaper price. Solutions the group recommended were to buy an ELV once a year that flies 15 to 30 experiments. This process moves many technologies per year to TRL 6 or 7. For some demonstrations, a retrieval capability is needed, so they must use facilities such as the *ISS*, a return capsule, or the Shuttle.

Different options for TFDs and the associated challenges were discussed. The group characterized existing capabilities to fly small payloads as platforms, ELVs, and the *ISS*. The group considered how to better utilize the existing opportunities for those capabilities, such as gas cans, sounding rockets, secondary opportunities, and multipayload launches, and advocated simplifying the ways small payloads can be flown, particularly in regard to meeting human safety requirements.

The group also noted that transformational systems that use modular construction will require robots. They found that a common modular bus for the ASTRA program that can be used to demonstrate modularity would be useful.

Ways to enhance use of the *ISS* for TFDs were explored. Discussion included the transportation issues associated with bringing ELV payloads to the *ISS*, including an overview of possible techniques; *ISS* payload accommodation using modular testbeds, including a discussion of management issues; and *ISS* operations, including crew impacts, proximity concerns, and existing NASA activities, such as Robonaut and Aercam; integration management; implementing a power and propulsion testbed; *ISS* payload logistics; and using the *ISS* as a staging ground for future assembly or exploration architectures.

**5.3.5.3 Recommendations**. A specific recommendation of the working group was that leads of the technology development WBS elements in support of transformation should collect technology flight demonstration and technology flight experiment candidates into an accessible resource using the NASA Virtual Research Center. Broader recommendations were that, for technology flight demonstrations to be most useful, NASA would have to change the thinking about success and failure when dealing with technology to recognize the value and legitimacy of a negative result. Finally, the group suggested that NASA investigate how the DOD conducts technology experiments and demos.

### 5.3.6 Architectures, Mission Applications, and Benefits

This working group considered better ways to tie system integration, analysis, and modeling to the decision-making process.

**5.3.6.1 Current and Planned Activity**. The working group felt that NASA was moving in the direction of making decisions strategically rather than tactically. The space architect and study teams, and strategic, systems, and cost analysts at NASA Headquarters code B are evidence of this.

Also noted was that if NASA and DOD are united in their support of a project, approach, system, or concept, there is a greater opportunity to influence the Office of Management and Budget (and Congress). The National Security Space Architect (NSSA) is currently an analytical arm of DOD that should be linked at the conceptual level, and where possible, the more detailed level.

**5.3.6.2 Findings**. The group identified many advantages to the improved modeling and analysis capability. The group felt that the capability to analyze and perform trades quickly would encourage use of analysis to make decisions. They noted that, in order to be effective in influencing high-level decisions, analysis output must be synched with the political budget/decision-making schedule. In addition, the analysis output must be synched with this schedule to be successful at influencing decisions/decision makers.

Group members felt that analysis of an entire architecture would be needed to convince the broader community that a proposed modular approach is more effective. However, they noted, trying to tackle all levels of analysis in a single code and team is very challenging and could get bogged down in the process. They pointed out that formation of the space architect team has taken longer than originally anticipated; the effort is proving to be an extremely large jump from today’s situation, and the teams are still forming.

The working group discussed long-term retention of the knowledge base—a fundamental element of systems analysis. The group noted that when the knowledge base resides within the workforce, retention is difficult. In many technical areas, as the technical experts have retired or left the Agency, the knowledge base has eroded. As a result, models or data that could be built upon to enable analysis of architectures or technology trades are often lost.

**5.3.6.3 Recommendations**. The working group asked, "What is required to transform?" Its first finding was that past failures and limitations should not be allowed to inappropriately constrain future options. With this, the group was reacting to the statement that was made in the plenary session: "In my seventeen years of experience, no systems analysis study has been responsible for a NASA decision to fund a program."

The group recommended changing the DOD acquisition strategy. The group also felt it would be necessary to change NASA's scientific mission strategy from a debate; e.g., like the current debate over Mars programs, to a thoughtful, analysis-based process. This will require changing the attitude of the scientific community.

Another objective, the group felt, should be to establish the desire within the NASA and DOD community to understand how well predictive tools performed for on-orbit systems; e.g., satellites. Again, this helps to make systems analysis the norm.

The group found that an evolutionary approach—one that would dovetail high-level, lower fidelity studies with higher fidelity studies—was appropriate for developing a modeling and analysis capability to support transformation. The group noted, however, that this does not mean that it is necessary to build the analysis tool that does it all. Rather, there should be communication among engineers and analysts so that subsystem and system modelers communicate with the existing higher fidelity study teams, including the space architect's team. In fact, the group suggested that a process for integrating the studies from different groups—NASA, DOD, industry—become part of program integration.

The group advocated creating a central repository of information that would be accessible to the whole Agency. It noted the value of producing analytical results on a yearly schedule synched with the budget/decision-making schedule. Finally, the group strongly encouraged that the ASTRA modeling teams open communication immediately with the space architect team members and work with them to identify which models to use in higher level studies.

The working group offered an overview of potential partnerships:

- DOD/NASA/National Oceanic and Atmospheric Administration in partnership to address weather, remote sensing, and Earth observing systems.

- NASA/industry in partnership to address LEO business parks.

- NASA/DOD/international entities to address planetary defense, navigation, and communication.

The working group also commented on the high-level characterizations of long-term mission goals that have been developed by ASO as part of the transformational infrastructure analysis and planning process. The group described a pyramid of increasing layers of detail and specificity below the level of scenario. Twenty scenarios would result in consideration of hundreds of architectures that would in turn consider thousands of concepts that would be based on tens of thousands of technologies and technology choices.

They characterized the drivers underlying the major concepts under consideration. Transformational space concepts are driven by the efforts to achieve the following:

- Large observatories for space science in the long term, which will require advances in in-space assembly and test, manufacturing of optics, and in-space transportation, such as a space tug.
- Low-cost modular instruments and satellites for Earth and space science in the near term.
- Modular in-space systems, focusing on common spacecraft with multiple applications and modular upgradeable sensors and processing.

Technologies that will drive these concepts should seek to:

- Mitigate space environmental effects, such as radiation and debris.
- Develop techniques to cope with limitations on accessible spectrum and available bandwidth.
- Make effective development and use decisions by understanding trades associated with upgrading as opposed to using cheap throwaways.
- Reduce the cost of launch and operations.
- Reduce required payload capacity, especially by reducing the volume and mass of structure concepts and components.
- Reduce risks by validating designs and predictive tools.

Finally, the group offered suggestions for improving the ASTRA WBS, including adding surveillance, reconnaissance, weapons, communication, navigation, and weather; adding enablers for Mars and lunar permanent presence; and adding planetary defense. The group also suggested developing analytical capability to model assembly at a high level.

## 6. NEXT STEPS TO SPACE TRANSFORMATION

NASA will continue to explore the potential for transformation through workshops with diverse stakeholders. Future workshops will address flight demonstrations and experiments, leading-edge research in academia, principles of modular design and development, and other topics. Future workshops will be based on what NASA learns from its ongoing interactions with engineers, scientists, mathematicians, business people, academics, and many others. The insights from these events will aid NASA in its quest to understand and act on the potential for transforming space infrastructure and advancing NASA's vision to improve life here, to extend life to there, and to find life beyond.

# APPENDIX A—PARTICIPANTS AND CATALYTIC PRESENTATIONS

Table 4 shows workshop attendees, their affiliation, and presentation topics.

Table 4. Workshop attendees, their affiliation, and presentation topics.

| Attendee | Affiliation | Presentation Topic |
|---|---|---|
| Bangham, Mike | Boeing | |
| Beach, Raymond F. | GRC | High-Power Systems (High-Energy Space Systems) |
| Borchardt, Heidi S. | LaRC | |
| Bruce, Walt | LaRC | |
| Bullman, Jack | MSFC | |
| Bushnell, Dennis | LaRC | |
| Campbell, Jonathan W. | MSFC | |
| Campos, Carlos S. | NASA / HQ | |
| Carrasquillo, Edgar J. | MSFC | |
| Carrington, Connie | MSFC | |
| Christensen, Carissa | Tauri Group | |
| Conde, Al | JSC | Infrastructure-Foundation to Expansion of Outer Space (Technology Flight Experiments and Demos) |
| Cox, Ken | JSC | Infrastructure (Revolutionary Space Systems) |
| Culbert, Christopher | JSC | Auto Tool Selection, Grasping (Space Assembly, Maintenance, and Servicing) |
| Dickinson, Richard M. | Off-Earth | |
| Dorsey, John | LaRC | Modular Space Systems (Space Assembly, Maintenance, and Servicing) |
| Dudenhoefer, James E | GRC | |
| Esper, Jaime | GSFC | A Modular, Reconfigurable, and Rapid Response Space System Architect (Architectures, Mission Applications, and Benefits) |
| Falker, Dr. John (Jay) | NASA / HQ | |
| Feden, Robert H. | NASA Liaison/ OASD | |
| Ferebee, Melvin | LaRC | |
| Fikes, John | MSFC | |
| Foidl, Jack | MITRE | |
| Fork, Richard | UAH | High-Energy Laser Gain Elements to Transport Energy (High-Energy Space Systems) |
| Frisbee, Robert H. | JPL | Innovative Concepts Space Propulsion (Architectures, Mission Applications, and Benefits) |
| Fullerton, Richard K. | JSC | ASTRA (Space Assembly, Maintenance, and Servicing) |

Table 4. Workshop attendees, their affiliation, and presentation topics (Continued).

| Attendee | Affiliation | Presentation Topic |
|---|---|---|
| George, Patrick | GRC | |
| Gill, Paul | Boeing | |
| Gross, Anthony R. | ARC | Information and Communication Technology Concepts (Revolutionary Space Systems) |
| Henley, Mark | Boeing | |
| Henninger, Donald L. | JSC | Advanced Life Support, Thermal, EVA, Other (Revolutionary Space Systems) |
| Herath, Jeff | LaRC | |
| Hoffman, Steve | SAIC | |
| Holt, Alan | JSC | |
| Howell, Joe | MSFC | |
| Jankovsky, Rob | GRC | Rocket Propulsion for the Future<br>(High-Energy Space Systems) |
| Lollar, Louis | MSFC | |
| London, John R. | MSFC | |
| Marzwell, Neville I. | JPL | Modular Systems (Architectures, Mission Applications, and Benefits) |
| Mankins, John C. | NASA / HQ | Agenda and Charge to Working Groups<br>Transformational Space Infrastructure Applications<br>ASTRA Roadmaps and Template (Plenary) |
| Mazanek, Daniel | LaRC | Modular In-Space Transportation Architecture, Near-Earth Asteroids (High-Energy Space Systems) |
| McGinnis, Richard S. | LaRC | |
| Moe, Rud | GSFC | On-Orbit Assembly Possibilities for Large Telescopes<br>(Space Assembly, Maintenance, and Servicing) |
| Moore, Chris L. | NASA / HQ | |
| Mullins, Carie | Tauri Group | |
| Nozette, Stewart, Ph.D. | DARPA | DARPA (Technology Flight Experiments and Demos) |
| Olds, Ph.D., John | Georgia Tech | Georgia Tech's Space Systems Design Lab (High-Energy Space Systems) |
| O'Neil, Daniel | MSFC | Titan System Overview<br>Titan Demo (Systems Integration, Concepts, and Modeling) |
| O'Neill, Mark | Entech, Inc., | |
| Parks, Wayne | UAT | |
| Paylor, II, Dr. Earnest D. | Pacific Disaster Center | |
| Perkinson, Don T. | Sverdrup | |
| Powell, Dr. James | Plus Ultra Technologies | |
| Raffaelle, Ryne P. | GRC | Nanomaterials for Space Power Systems<br>(High-Energy Space Systems) |
| Sackheim, Robert L. | MSFC | |
| Smitherman, David | MSFC | Space Elevator (Revolutionary Space Systems) |
| So, Maria | GSFC | |

Table 4. Workshop attendees, their affiliation, and presentation topics (Continued).

| Attendee | Affiliation | Presentation Topic |
|---|---|---|
| Spampinato, Phil | ILC Dover, Inc. | Advanced Space Suit Briefing<br>Trends in Engineered Softgoods (Technology Flight Experiments and Demos) |
| Spaulding, Omar | NASA / HQ | |
| Troutman, Pat | LaRC | RASC Vision in Support of a NASA Strategy for Exploration (Architectures, Mission Applications, and Benefits) |
| Verhey, Timothy | GRC | |
| Webbon, Bruce, W. | ARC | |
| Wegeng, Robert S. | Pacific Northwest National Laboratory | Micro Chemical and Thermal Systems (MICROCATS) (High-Energy Space Systems) |
| Welch, Sharon S. | LaRC | |
| Wellman, Bill | Tauri Group | |
| Wilcox, Brian H. | JPL | Transformational Concepts (Space Assembly, Maintenance, and Servicing) |
| Williamson, David | UTC | |

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**13. ABSTRACT** *(Maximum 200 words)*

NASA is constantly searching for new ideas and approaches yielding opportunities for assuring maximum returns on space infrastructure investments. Perhaps the idea of transformational innovation in developing space systems is long overdue. However, the concept of utilizing modular space system designs combined with stepping-stone development processes has merit and promises to return several times the original investment since each new space system or component is not treated as a unique and/or discrete design and development challenge. New space systems can be planned and designed so that each builds on the technology of previous systems and provides capabilities to support future advanced systems. Subsystems can be designed to use common modular components and achieve economies of scale, production, and operation. Standards, interoperability, and "plug and play" capabilities, when implemented vigorously and consistently, will result in systems that can be upgraded effectively with new technologies. This workshop explored many building-block approaches via way of example across a broad spectrum of technology discipline areas for potentially transforming space systems and inspiring future innovation. Details describing the workshop structure, process, and results are contained in this Conference Publication.

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