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Envisioning a 21st Century, National, Spacecraft Servicing and Protection Infrastructure and Demand Potential: A Logical Development of the Earth Orbit Economy

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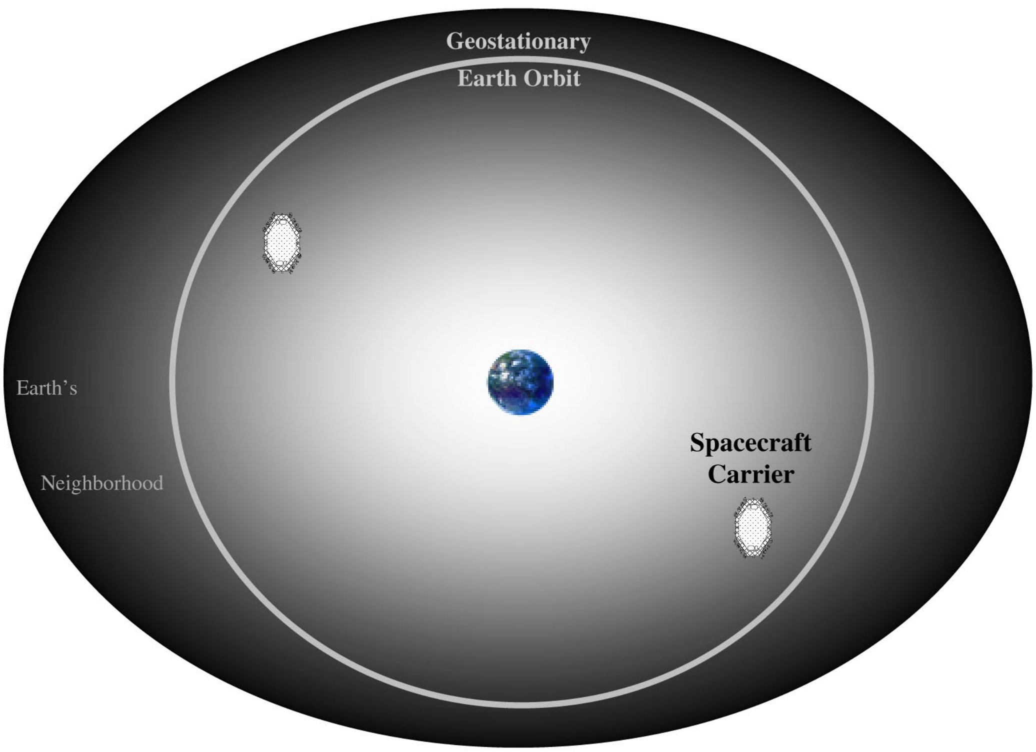

July 2003

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Space Administration

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1.0 Abstract

The modern world is extremely dependent on thin strings of several hundred civil, military, and commercial spacecraft/satellites currently stationed in space. They provide a steady stream of commerce, defense, and knowledge data. This dependency will in all likelihood increase significantly during this century. A major disruption of any kind in these essential systems and networks could be socially, economically, and politically catastrophic, on a global scale. The development of a space-based, robotic services economy could be useful in mitigating this growing risk, from an efficiency and security standpoint. This paper attempts to suggest what makes sense to invest in next for the logical, economic development of Earth orbit—i.e., after ISS completion. It expands on the results of an advanced market research and analysis study that sampled the opinions of several satellite industry executives and presents these results within a broad policy context. The concept of a "spacecraft carrier" that serves as the nucleus of a national, space-based or on-orbit, robotic services infrastructure is introduced as the next logical step for United States leadership in space. This is viewed as a reasonable and appropriate follow-on to the development of ELVs and satellites in the 1950s and 1960s, the Space Shuttle/PRLV in the 1970s and 1980s, and the International Space Station (ISS) in the 1980s, 1990s and 2000s. Large-scale experience in LEO-to-GEO spacecraft/satellite servicing and protection by robotic means is assumed to be an indispensable prerequisite or "stepping-stone" toward the development and preservation of the large scientific exploration facilities that are envisioned by NASA for operation beyond GEO. A balanced, return on national investment (RONI) strategy for space, focused on the provision of enhanced national/homeland security for increased protection, national economic/industrial expansion for increased revenue, and national scientific exploration for increased knowledge is recommended as the next strong, irrepressible goal toward realizing and achieving the official NASA vision and mission.

2.0 Introduction

It will probably remain the responsibility of the United States to continue its leadership of the world in space throughout most of the 21st century. European and Asian countries are rapidly integrating and/or transforming their respective economies and thus might assume a significant share of space leadership and power later in this century. However, given current political and economic realities, it is becoming increasingly apparent that every step we propose to take in

* Mr. Horsham has contributed to NASA's advanced planning, development, and technology transfer activities for over eighteen years. The opinions presented in this paper are those of the author and do not reflect any NASA policies or plans.

space, whether for exploration or development, must minimize and simultaneously reduce dependence on taxpayer dollars.

The United States National Aeronautics and Space Administration's present space vision is *to Improve life here, to Extend life there, and to Find life beyond* (*NASA 2003 Strategic Plan*). A complementary vision crafted by the Commission on the Future of the United States Aerospace Industry is *Anyone, Anything, Anywhere, Anytime*. In Recommendation #3, the Commission stated: "*The Commission recommends that the United States create a space imperative. The DoD, NASA, and industry must partner in innovative aerospace technologies, especially in the areas of propulsion and power. These innovations will enhance our national security, provide major spin-offs to our economy, accelerate the exploration of the near and distant universe with both human and robotic missions, and open up new opportunities for public space travel and commercial space endeavors in the 21st century."*

Behind these visions stand the National Aeronautics and Space Act of 1958. Section 102 (b) states that *"The Congress declares that the general welfare and security of the United States require that adequate provision be made for aeronautical and space activities. The Congress further declares that such activities shall be the responsibility of, and shall be directed by, a civilian agency exercising control over aeronautical and space activities sponsored by the United States, except that activities peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States (including the research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and shall be directed by, the Department of Defense; and that determination as to which such agency has responsibility for and direction of any such activity shall be made by the President in conformity with section 201(e)."* Section 102 (c), requires NASA to *"seek and encourage to the maximum extent possible, the fullest commercial use of space."* This is followed by Section 102 (d) (1), which requires NASA to contribute materially to *"the expansion of human knowledge of the Earth and of phenomena in the atmosphere and in space."*

In relation to the above statutory requirements, NASA primarily responds and seeks to collaborate and support various matters of overlapping interest regarding high-priority U.S. national defense and security activities and policies. For example, a new military focus on the utility of space as a "high-ground" was ushered in with the release the Report of the Commission to Assess United States National Security, with key enabling technologies and mission areas strategically defined in the Department of Defense - Space Technology Guide. Also, on September 11, 2001, the United States entered a new age in which potential threats to critical national assets cannot be underestimated. A key part of NASA's stated mission is *"to understand and protect our home planet."* This resonates with the Department of Homeland Security's mission to protect the nation's homeland (*The White House, 2003*). In this regard, it should encompass the hundreds of spacecraft and satellites that operate in space and provide national defense, commerce, and knowledge.

Over the last 45 years, since its inception, NASA has attempted to realize the visions mentioned above and meet its statutory obligations. The agency has steadfastly transitioned, developed and/or introduced various systems and technologies into civil and commercial use. This began with the transitioning of military expendable launch vehicle technologies during the late 1950s and early 1960s, which culminated in the Apollo/Moon program success. NASA then graduated to reusable launch vehicle technology in the form of an ambitious shuttle STS program in the 1970s. Throughout the shuttle program thus far, the agency has amassed an impressive record of accomplishments by pushing back the boundaries of knowledge in the material sciences, life sciences, and biomedical and bioengineering disciplines.[1] Much more remains to be accomplished, and with the advent of the International Space Station (ISS), the civil infrastructure development of LEO will continue to progress onward.

In meeting its obligations under Section 102 (c), NASA also created the spacecraft or satellite industry. This industry has become one of the most critical capabilities of paramount, strategic military and economic importance to the purposes and objectives of modern, global civilization. In addition to several high-value scientific spacecraft such as the Hubble Space Telescope (HST) in LEO, there are presently around 250 commercial communications satellites in GEO. There are also several military reconnaissance and GPS satellites operating in MEO. Planning is underway in all sectors, civil, military, commercial and industrial, to establish new satellite networks in the future. In addition, NASA has plans for an ambitious exploration program that will require the installation of large scientific platforms throughout Earth-Moon space and beyond. It is becoming increasingly apparent that the total value of assets to be installed and operated in space during the 21st century, by either government or private interests, could be in the hundreds of billions of dollars. The magnitude of this potential investment implies that the capability to service spacecraft and satellites by robotic means will become increasingly economical, from a cost-effectiveness, asset value, revenue potential, and human safety or risk minimization standpoint.

This paper presents a discussion of the prospects for spacecraft/satellite servicing and protection[2] by robotic means (i.e., by tele-operated remote control and/or full-autonomy) as a common government/industry strategy for the development of space. Fundamentally, the paper envisions the full-fledged development of a space-based/on-orbit infrastructure that can support the creation of a robust, on-orbit, robotic satellite services enterprise. This capability could significantly benefit NASA's science-driven exploration plans both technologically and economically. A balanced, return on national investment (RONI) strategy for space, focused on the provision of enhanced national/homeland security for increased protection, national economic/industrial expansion for increased revenue, and national scientific exploration for increase knowledge, is recommended as the next strong, irrepressible goal toward realizing and achieving the official NASA vision and mission.

Six sections follow this introduction. The first, section 3.0, summarizes the paper by highlighting several key statements for enhanced comprehension and ease of reference. Section 4.0 presents the approach, results and interpretation of an advanced market research and analysis study that involved several interviews with industry leaders. Section 5.0 introduces a national infrastructure concept and a high-level roadmap by which this could be achieved. Section 6.0 discusses the rationale for LEO-to-GEO investment and attempts to realistically extrapolate the future economic or market context. This section is subdivided into four subsections: (6.1) Present

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[1] During this period, Russia (the former Soviet Union) was the only other nation in the world contributing to the development of similar types of knowledge and understanding of the utility of the space environment through its Salyut and Mir programs.
[2] In addition to unintentional orbital debris and meteorite threats, the newly established U.S. Department of Homeland Security (DHS) mission indicates that U.S. national space assets may become increasingly vulnerable to intentional, terrorist threats during the 21st century. In this respect, NASA, DoD, and commercial space-based infrastructure/asset protection interests overlap.

Status and Condition of the Satellite Industry, (6.2) Emergence and Future Growth of the On-orbit, Robotic Services Economy, (6.2.1) Assessment of Potential, Early-to-Mid-21st Century Demand, and, (6.2.2) Assessment of Potential, Mid-to-Late 21st Century Demand. Sections 7.0 and 8.0 offer several conclusions and recommendations, respectively. Finally, Section 9.0 includes a list of acronyms for the reader's convenience.

3.0 Summary

A listing of twenty-two key statements made throughout the paper are extracted and highlighted below:

1. For long-term viability, the 20th century build, launch, operate, and replace (BLOR) business model should probably be upgraded to a 21st century build, launch, operate, service and maintain/protect (BLOSM/BLOSP) strategy. (Section 4.0)
2. Potential economic viability exists in various market segments such as: satellite/spacecraft refueling, upgrade, repair, and perhaps also relocation, removal and threat interception/neutralization. (Section 4.0)
3. An affordable or cost-effective, robust, reliable, on-orbit infrastructure is required for efficient and ready access to the above market segments. (Section 4.0)
4. Tele- or semi-autonomous robotic systems would offer the best means by which to provide services in the LEO-to-GEO domain supported by either ground or space-based operators. (Section 4.0)
5. Industry would probably aggressively pursue the on-orbit robotic services markets by building standardized satellites and servicer spacecraft if government assumed responsibility for development and construction of the high-risk, on-orbit infrastructure. (Section 4.0)
6. A NASA, DoD, DHS, and industry collaboration might be established, within which NASA assumes its "traditional" and essential role of a defense-to-commercial (D2C) transition agent (as it did in the 1960s in converting missile launch technology to civil and commercial application). (Section 4.0)
7. The LEO-to-GEO region is currently the only accessible, extraterrestrial region with both near- and far-term civil, military, and commercial development potential (Section 5.0)
8. In the opinion of several industry leaders, it would be rational for U.S. space strategy to focus on establishing an infrastructure for space-based or on-orbit servicing. (Section 6.0)
9. Satellite technology is mature, however, the perceived high risk and accompanying high insurance premiums have combined to negatively impact this sector's market power. (Section 6.1)
10. The existence of a thriving satellite industry offers government an excellent opportunity for effective implementation of a space-based, economic growth and capital infrastructure expansion strategy. (Section 6.1)
11. Satellite and cable technologies will complement each other and co-exist synergistically in the future. (Section 6.2)
12. United States space policy should focus on the development of a LEO-to-GEO-and-beyond, robotics-centered space program. The satellite industry offers an excellent showcasing opportunity and should be the first beneficiary of such a policy. (Section 6.2)
13. A robust, on-orbit, services industry sector should be developed and established through a government-led initiative. (Section 6.2)

14. It is in the long-term interest of NASA, DoD, and other governmental entities, to build and sustain a healthy commercial space/satellite industry. (Section 6.2.1)
15. There is a growing interest within both the defense, commercial, and industrial sectors in the development of a robotic, servicing sector, along with various high-risk satellite technologies—such as laser/optical systems. (Section 6.2.1)
16. Commercial, space-based robotic servicing is expected to find an initial foothold or market in GEO. (Section 6.2.1)
17. Outside the United States there is a strong and growing interest in the establishment of satellite information networks to provide a variety of services ranging from global positioning to remote sensing. (Section 6.2.1)
18. The 21st century holds the promise of the potential emergence of a large international market for robotic, space-based servicing that would effectively dwarf the present global satellite industry. (Section 6.2.1)
19. North America, Europe, and Asia are well positioned to competitively or cooperatively control the agenda for global space investment throughout the 21st century. (Section 6.2.1)
20. It is reasonable to expect that the market for a future development of a robust, on-orbit, robotic servicing infrastructure will rest not only on the formation of a strong collaboration between U.S. civil, military, commercial, and industrial concerns, but also on strong international cooperative interests. (Section 6.2.1)
21. The use of space exploration as a technology catalyst, spurred by the expansion of human civilization into outer space, continues to be an underlying theme and rationale in U.S. space policy and planning. In order to achieve this goal, the development of a robust, satellite/spacecraft servicing industrial capability seems to be a logical prerequisite. (Section 6.2.2)
22. It is reasonable to project that by the end of this century, the Earth-centered, space based servicing infrastructure model discussed in this paper will replicate and expand. In other words, all inner solar system, planetary and interplanetary locations (libration points) of scientific interest will be connected by an integrated, serviceable, satellite and spacecraft communications network. (Section 6.2.2)

4.0 Examination of Prospects for Satellite Servicing

The advanced market research and analysis study described in this section was performed between May and July 2002. It provides a core framework around which the conceptual interpolations and extrapolations presented in this paper were subsequently formulated. A five-step approach was used (*Appendix A, slide 4*):

1. Develop Interview Questions
2. Identify Interviewees
3. Conduct Interviews
4. Analyze Responses
5. Formulate Space Infrastructure Vision

The study was based on the following premises (*Appendix A, slide 6*):

- Satellite industry established by governments during the 1960s.

- Government (NASA–"NEXT/RASC," OSD/DoD/DARPA–"Orbital Express/ASTRO," etc.) at cross-roads considering 21st century space investments.
- Satellite industry at cross-roads considering 2000s growth prospects.
  – Viability weakening (unfavorable regulatory and competitive environment – terrestrial fiber, foreign encroachments, etc.)
- A robust, 21st century satellite servicing industry sector is a potential emerging prospect.

Twenty-five (25) open-ended questions were formulated in order to collectively answer one governing question: *What are the core beliefs of current industry leaders regarding the technological feasibility and economic prospects for space-based, satellite servicing?* These twenty-five questions were subdivided into five categories: Business, Technology, Government, On-Orbit Infrastructure, and Satellite Servicing. The five categories were further divided into twenty-two sub-categories (*Appendix A, slides 15 and 16*). Target respondents consisted of ten executives and senior managers from the operator, manufacturing, academic, and government sectors of the satellite industry (*Appendix A, slides 12 and 14*). Finally, responses to the questions (primary data) were gathered through a series of individual, in-person interviews conducted at the respective business location of each respondent.

The results of the study were packaged and presented as shown in appendix A. Appendix A contains a 53-slide (PowerPoint) presentation[3] entitled: *Examination of the Prospects of Satellite Servicing – A Common Government/Industry Strategy for the Future Development of Space*. This presentation is subdivided into five sections: (1) List of Acronyms, (2) Approach, (3) Introductory Framework, (4) Satellite Industry Interviews, and (5) Summary of Findings. Four charts from appendix A are explained below for proper interpretation:

- (Slide 8)*: Stepping Stones:* This chart describes the stepping-stone strategy adopted by the NASA Exploration Team. It implies a cost-effective, buy-by-the-yard approach to exploration.
- (Slide 9): *Stepping Stones - Satellite Servicing - The Next Step:* This chart shows a copy of the chart from page 8 above, but with an "Economic Foundation" stepping-stone inserted. The chart suggests that along with being "Science-Driven" and "Technology Enabled," exploration also needs to be "Economics Supported." The economic foundation stepping-stone would add a government/industry partnership and establishment of a LEO-to-GEO satellite servicing industry infrastructure.
- (Slide 10): *Satellite Servicing - LEO-to-GEO Infrastructure Concept:* This chart proposes a concept for the "Economic Foundation" mentioned above (see Figure 1). It consists of "Space Harbors," (renamed "Spacecraft Carriers" in this paper) specialized (e.g., refueling servicer, repair servicer, etc.) "Satellite Servicer" spacecraft stationed at each space harbor; a tri-satellite system for command, communications and control; a fuel station; and a parts station (space harbors are assembled at an assembly orbit and then relocated to their operations orbit).

[3] This presentation was delivered to the Assistant Associate Administrator, NASA Headquarters, Office of Space Flight, Advanced Systems, in August 2002. Several other attendees were present from the Office of Space Flight, Office of Space Science, and NASA Goddard Space Flight Center.

- (Slide 11): *Satellite Servicing – Investment Profile:* This chart presents a qualitative interpretation of past satellite servicing investment and suggests a future upturn driven by the NEXT exploration agenda. Four stages are portrayed: “Introductory,” 1970 to 1980; “Growth,” 1980 to 1990; “Dormancy,” 1990 to 2000; and “Forward & Beyond,” 2000 to 2020.

Appendix B presents a 38-page detailed companion supplement to appendix A. Appendix B contains the complete repository of all responses gathered from each interview, and shows the unique qualitative analytical technique that was applied. A quantitative summary of all responses based on a weighted average characterization is shown on slide 17 of appendix A. This analysis indicated that the interviewees in this study were all *(1) very “encouraging” about the technological, orbital infrastructure, and future business and market potential for satellite servicing; while being, (2) very concerned about the current and near-term business and industry weaknesses, and the lethargic government response to date.*

The most direct advice to the government came in response to a question on “NASA roles and responsibilities” (*Appendix A, Question 11, slide 31 and Appendix B, pages B19 and B20*): *What could NASA be doing to help the satellite industry achieve greater levels of market/economic performance in the future?* The industry interviewees generally believe that NASA should invest in high risk, high payoff systems and technologies as follows:

- Establish laser/optical communications program
- Eliminate categorization of spectrum bands
- Initiate development of TDRS replacement
- Develop infrastructure with commercial potential
- Develop one reliable launcher for the future while supporting current Atlas/Delta launch systems
- Serve as military-DARPA/commercial transition agent
- Address cost drivers for human systems

This paper responds to the challenge to develop infrastructure with commercial potential and to serve as a military-DARPA/commercial transition agent. In this regard, the following six statements provide a reasonable basis and rough outline for the approach that is developed and presented in this paper.

1. For long-term viability, the 20th century build, launch, operate, and replace (BLOR) business model should probably be upgraded to a 21st century build, launch, operate, service and maintain/protect (BLOSP[4]) strategy.

[4] A BLOSP (or BLOSM) strategy would contribute efficiencies in the industry’s insurance and operating costs by reducing BOL risk, opening up secondary markets near EOL, reducing orbital debris, etc.

2. Potential economic viability exists in various market segments[5] such as: satellite/spacecraft refueling, upgrade, repair, and perhaps also relocation and removal, in addition to threat interception and/or neutralization.
3. An affordable or cost-effective, robust, reliable, on-orbit infrastructure is required for efficient and ready access to the above market segments.
4. Tele- or semi-autonomous robotic systems would offer the best means by which to provide space-based services in the LEO-to-GEO domain supported by either ground or space-based operators.
5. Industry would probably aggressively pursue the robotic servicing market by building standardized satellites and servicer spacecraft if government assumed responsibility for development and construction of the high-risk, on-orbit infrastructure.
6. A NASA, DoD, DHS, and industry collaboration might be established, within which NASA assumes its "traditional" and essential role of a defense-to-commercial (D2C) transition agent (as it did in the 1960s in converting missile launch technology to civil and commercial application).

5.0 National Spacecraft Servicing and Protection Infrastructure Concept

The LEO-to-GEO region is currently the only accessible, extraterrestrial region with both near- and far-term civil, military, and commercial development potential (*Appendix A, slides 41 to 46 and Appendix B, pages B26 to B38*). The initial exploitation of this potential began with the 20th century installation of numerous communications satellites and other spacecraft in orbits throughout the region. The Van Allen radiation belts[6] dominate the region and produce a very harsh environment that challenges the survivability of both humans and machines. Current technology research and development activities (conducted respectively by the U.S. BMDO and Britain's DERA,[7] GRC, GSFC, JSC, DARPA, and UMD, etc.), involving radiation tolerant electronics, laser/optical communications, and space robotics, etc., can be expected to mature early in this century and open up this military/economic high-ground. In this regard, the LEO-to-GEO domain is perhaps also the only accessible region in space with any reasonable potential for achieving increasing relevance and value to the economy of the United States and the world during the 21st century.

[5] The threat of "Orbital Debris" was mentioned as an area of grave concern to satellite operators. Part of their operating cost goes toward guarding against and avoiding potential debris impact damage. The development of a capability that can substantially reduce or eliminate this threat would be of high value to the industry. A characterization of the orbital debris problem can be found in the U.S. Office of Technology Assessment background paper entitled: *Orbital Debris: A Space Environment Problem; OTA–BP–ISC–72; October 1990 (NTIS order #PB91–114272).* Also the threat of terrorist attack on space-based infrastructure/ assets is possible during the 21st century.
[6] Formed by lines of flux from the Earth's magnetic field that trap and contain energetic particles – protons, neutrons and electrons, emitted by the solar wind.
[7] Space Technology Research Vehicles (STRVs) launched into the Van Allen radiation belts in 2000. (http://www.spacedaily.com/2000/001116020340.s36jbhwb.html)

Figure 1 depicts the stepwise progression of space systems and capabilities development from ELVs and satellites in the 1950s and 1960s, to the shuttle/PRLV in the 1970s and 1980s, then to the ISS in the 1980s, 1990s and 2000s. The next logical step in early 21st century U.S. [and international] space strategy should perhaps focus on establishing a “spacecraft carrier”-centered, national infrastructure. Progress in this systematic manner would establish a strong economic and experiential[8] foundation upon which the planned scientific exploration strategy beyond GEO (*NASA 2003 Strategic Plan, page 4*) can be built.

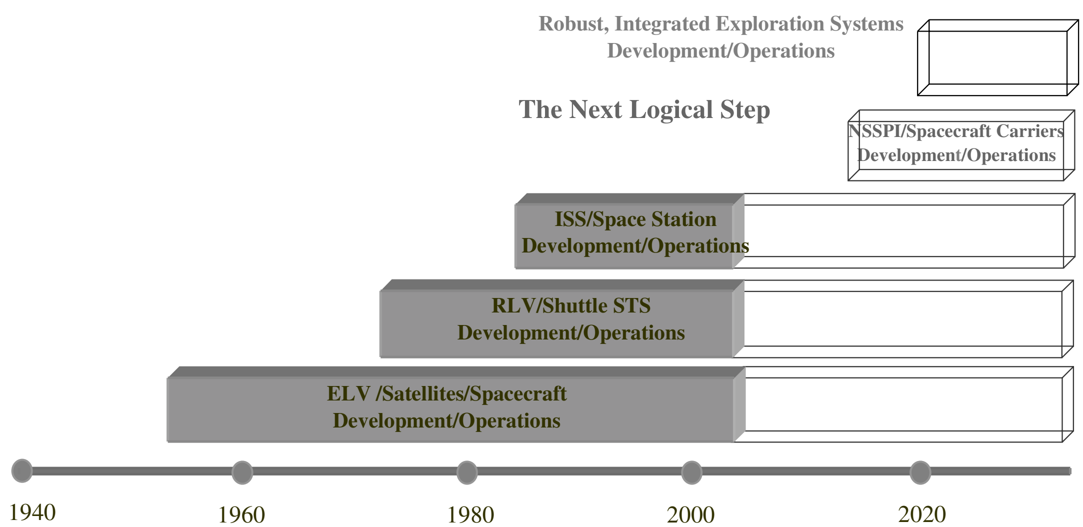

Figure 1. The next logical step in early 21st century US (and international) space strategy should perhaps focus on establishing a “spacecraft carrier”-centered, national infrastructure following the NASA STS and ISS investments.

[8] In particular, large-scale, on-orbit, remote control and/or fully autonomous robotic development and operations.

Figure 2 offers a high-level roadmap that could lead to a logical expansion of the Earth orbit economy through the realization of a future national infrastructure. Figure 3 presents a high-level, LEO-to-GEO, robotic services system architecture concept.[9] At the heart of this concept is a "Spacecraft Carrier"[10] that provides a "transport" facility for a fleet of market specialized robotic servicing and protection spacecraft (SRSPS). This fleet could consist of several spacecraft, each one specially built to provide service in one services (i.e., servicing or protection) market segment such as: refuel, upgrade, repair, inspection, relocation, removal, threat interception, threat neutralization, etc. With autonomous rendezvous and docking interface and other standards accepted internationally, these servicer spacecraft could conceivably be built, owned and/or operated by numerous private companies from any country in the world—somewhat similar to today's commercial satellites model. The goal of this logic would be to build a strong "economic foundation" (*graphically portrayed in Appendix A (slides 8 to 11) as a logical enhancement to NASA's stepping-stone, exploration strategy*) with the aim of achieving economic ROI for NASA's beyond-GEO, science-driven, exploration strategy.

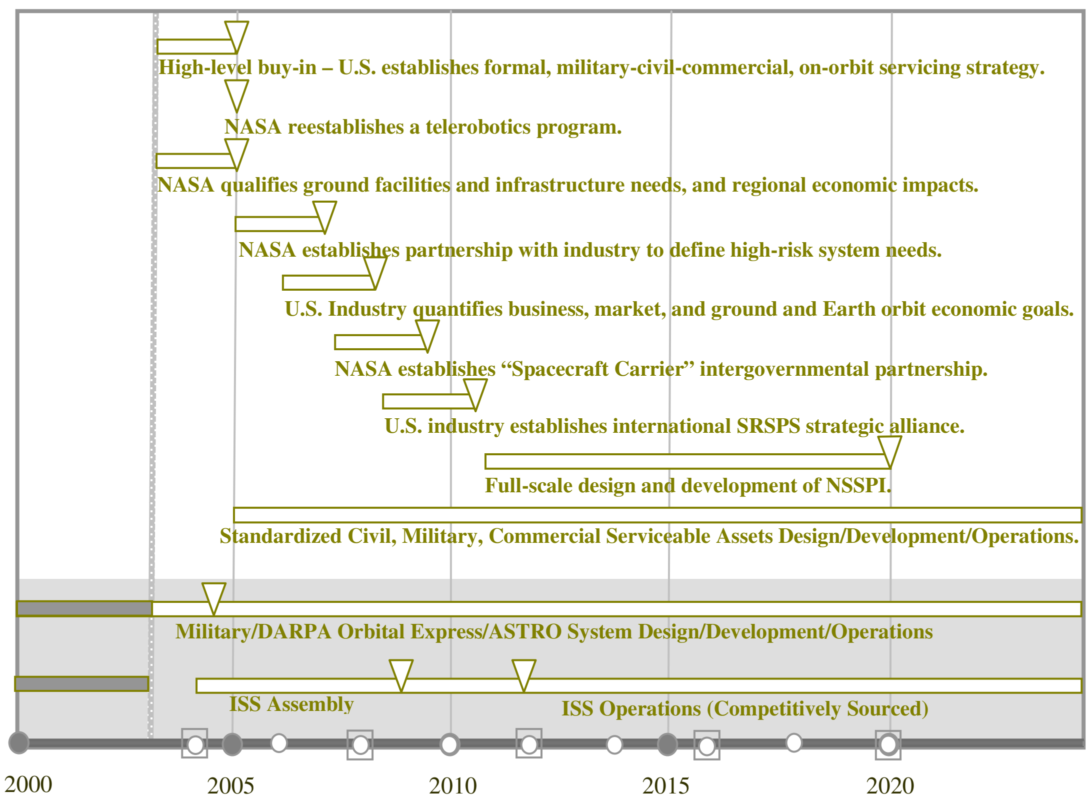

Figure 2. A possible, high-level roadmap for the systematic realization of a LEO-to-GEO NSSPI by 2020. This outlines a civil-to-commercial transition strategy in relation to the military/DARPA Orbital Express/ASTRO program framework, and other related and significantly funded NASA programs. (Federal leadership transition cycles shown—presidential (rectangles), congressional (circles))

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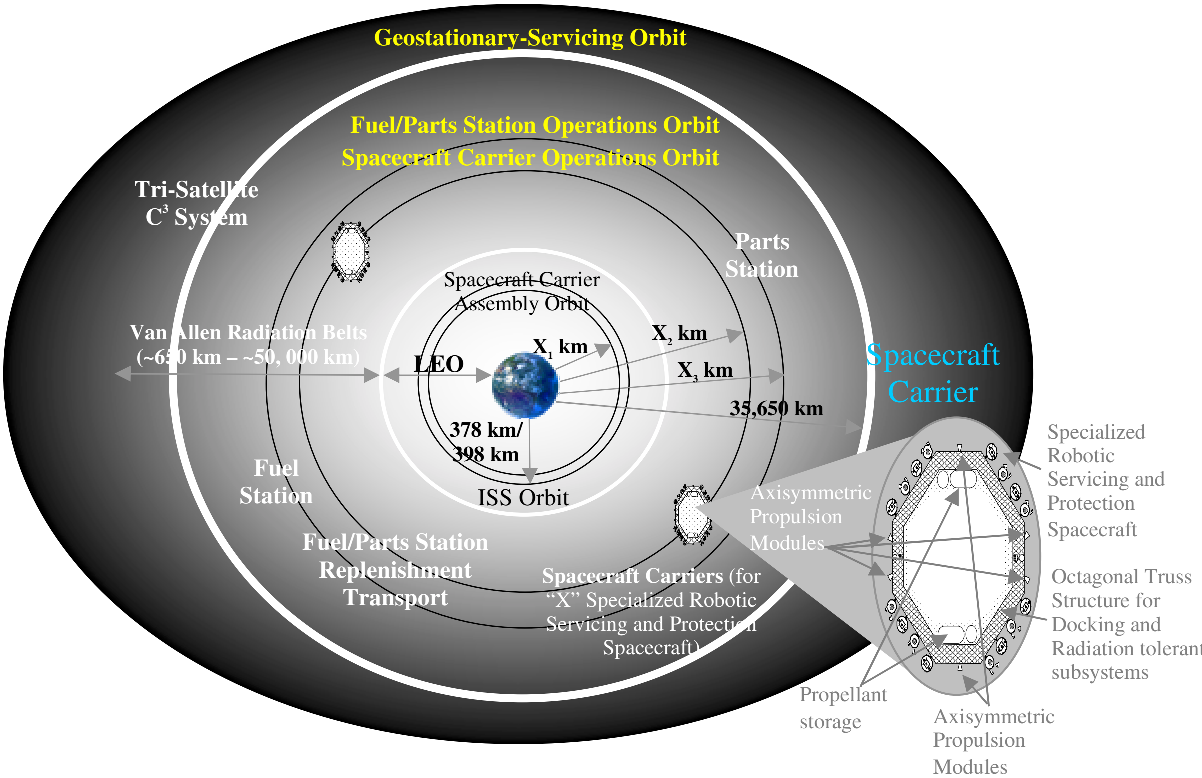
[9] The origination of this concept was based on an interpretation of the results of an earlier NASA GRC managed market assessment study performed by SAIC (SAIC; NAS3-26565; Final Report, 2000). The subsequent advanced market research and analysis study described in Section 3.0 of this paper was broader in scope and explored the prospects at the executive level.
[10] The term "Space Harbor" was conceived as an appropriate, functional metaphor for the concept being introduced in this paper. Subsequent research revealed that the early 1980s Space Station Task Force, Concept Definition Team, had originally applied this metaphor to the LEO, human-tended, space station concept. Further details on the earlier usage of this term can be found at http://www.abo.fi/~mlindroo/Station/Slides (Slides 6, 24, 26).

National Spacecraft Servicing and Protection Infrastructure Concept



Proposed System Composition (TBD)

1. Two Space Harbors each equipped with several, specialized servicer spacecraft.
2. A tri-satellite command, communication, and control (C^3) system
3. Parts Station
4. Fuel/Parts Replenishment Transport

Some Top Level Assessments (TBD)

- Orbital Parameters: X_1, X_2, X_3, Co-planar, Circular, Elliptical
- 3D Simulation
- Mass Estimations
- Delta V Estimations
- Electric/Chemical Life Span Comparison
- Parts/Repair Identification
- Satellite Design
- ISS Evolution
- Logistics

Some Required Technologies (TBD)

1. Telerobotics (e.g. Highly Dexterous Robotic Manipulation)
2. On-Orbit Assembly/Disassembly
3. Inter and Intra-Orbital Transfer and Insertion
4. Autonomous Rendezvous and Docking
5. Low Thrust Electric/Chemical Propulsion
6. Power/Energy Storage
7. Low Temperature/Radiation Hardened Electronics
8. High Data Rate Communications
9. Broadband Satellite Communications
10. Cryogenics
11. In-Space Fuel Transfer and Storage
12. GSE for Systems Integration and Testing

Some Preliminary Studies and Analyses (TBD)

- Feasibility Studies
- Architectural Definition Studies
- Systems Analyses
- Cost Analyses

Figure 3. A LEO-to-GEO robotic servicing architecture concept can be a logical follow-on to the ISS. It would require a government-led initiative, preferably spearheaded by a transformational, civil-military-commercial partnership. This would help build a sturdy economic foundation or building block for space development and exploration. ("X" indicates an unknown quantity. Figure not to scale.)

6.0 Rationale for LEO-to-GEO Investment

As discussed in section 4.0, an investigation into the feasibility and prospects for satellite servicing was conducted in 2002. The results suggested that in the opinion of several industry leaders, it would indeed be rational for early 21st century U.S. space strategy to focus on establishing an infrastructure for space-based satellite servicing[11] (*Appendix A, slides 17, and 32 to 36 and Appendix B, pages B20 to B25*). A flow of private capital investments in commercial servicing (and/or protection) spacecraft and other systems, made cost-effective by standardization, could then be encouraged. These industry leaders all generally believe that the development of space "telerobotics" technologies, spacecraft manufacturing standardization, government tax-breaks, and/or incentive-driven premiums from the space insurance industry would constitute the keys to realizing this potential future (*Appendix A, slides 32 to 46 and Appendix B, pages B20 to B38*). In addition, the building of a market based on a civil-military-commercial collaboration (perhaps involving NASA, DoD, DHS, and industry, as indicated earlier) is considered vital. Also, international cooperative involvement would be important for long-term, economic viability.

6.1 Present Status and Condition of the Satellite Industry

From a commercial point of view, the development of LEO-to-GEO has been underway since the early 1960s. The satellite industry presently consists of a mix of integrated services and applications sectors that include: Communications, Remote Sensing, GPS/Navigation, Broadband, DBS/DARS. The industry's production sectors include: Launch Vehicles, Ground Equipment, Insurance, and Manufacturing. World satellite revenues in 2002 amounted to $86.8 billion,[12] which represented a 10% increase over 2001. As indicated earlier, the satellite industry is presently at a cross-roads. Revenues peaked at $97.6 billion in 1998. This has resulted in a large amount of chronic, intractable overcapacity in manufacturing, launch services, transponder services, etc. As a consequence, this serious overcapacity has precipitated consolidation of the industry with an accompanying loss of thousands of jobs and tax revenues. This has resulted in serious concerns about present and future business prospects that the industry believes require some degree of government attention and action. (*Appendix A, slides 17 to 31 and Appendix B, pages B5 to B20*)

The practicality of a satellite in geostationary orbit was first envisioned in the 1940s (Arthur C. Clark). The satellite industry (in particular the "communications" segment) has contributed positively to international trade, and has become indispensable to the national and global security and economic infrastructure. The satellite industry was effectively born in the early 1960s and became dominant during its "introductory" stage in the 1960s and 70s when copper wire cable technology (a nineteenth century technology that enabled long distance and transoceanic,

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[11] The Futron Corporation identified various segments of satellite servicing as "evolving" and "emerging" market sectors in a recent, robust, launch vehicle market research study (ASCENT Study, Futron, 2003).

[12] According to the SIA Director's Report (April 14, 2003), as in the last several years, satellite industry revenues were driven primarily by Direct-To-Home (DTH) services, which accounted for $42.5 billion, roughly 49% of the entire industry's revenues. By comparison, at just $7.3 billion, transponder-leasing revenues experienced zero growth in 2002 after a decline in 2001. Global satellite manufacturing revenues were $12.1 billion, a 27% increase over 2001 revenues. Overall launch industry revenues increased 23% to $3.7 billion in 2002, while U.S. launch revenues declined by 9% to a seven year low of $1 billion. The satellite ground equipment sector accounted for $21.2 billion in revenue—an 8% increase over 2001. The largest revenue growth in this sector has been observed is in end-user equipment sales for VSAT, satellite television, high-speed Internet, and satellite radio services.

telegraph communications entered its decline.) Now in its "mature" stage, satellite technology (i.e., transponders) is threatened by the 1980s and 90s emergence of challengers in the form of optical fiber cable and terrestrial wireless technologies. In addition to the challenging export control environment,[13] the emergence of serious challengers during maturity is preventing the industry from reaping healthy returns on its investment. Most importantly though, perceived high risk and the accompanying high insurance premiums[14] have combined to negatively impact this sector's market power.[15]

Within the last decade, there were several high-profile, beginning of life (BOL) satellite failures *(Sullivan, 2001)*, which may have been salvageable if the nation and the world were in possession of a robust, space-based servicing capability. It is imperative therefore, that government and industry join forces and define a common, BLOSP-based strategy that expands this important industrial capability while opening up the development of space. The creation of a satellite or spacecraft servicing industry sector could be that initial, common strategy.

The existence of a thriving satellite industry offers government(s) an excellent opportunity for effective implementation of a space-based, economic growth and capital infrastructure expansion strategy. Standardization, however, appears to be the key to any economic expansion of this industry due to its inherent cost-effectiveness. If standardization were to become an industry practice, new markets and private capital investment could ignite and propel the integrated, civil, military, and commercial development of LEO-to-GEO, and beyond. Another cost-effectiveness factor is international cooperation for cost sharing, especially where common goals and objectives are found.

6.2 Emergence and Future Growth of the Space-Based Services Economy

Figure 4 depicts the evolution[16] of the global market presence.[17] This represents a rough approximation of the evolutionary, substitute/complementary[18] telecommunications, technology life cycle market context within which on-orbit robotic servicing emerged and could establish its niche. It is suggested that satellite and cable technologies will complement each other and co-exist synergistically in the future.

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[13] SIA News Release, February 6, 2001.

[14] Satellite Insurance Rates on the Rise – Market Correction or overreaction; Futron Corporation, July 10, 2002.

[15] The seriousness of this situation is further underscored when one considers that if the communications satellite sector meets an "early" 21st century demise, the industry's supporting commercial launch vehicle sub-sector will probably also suffer a similar fate as well.

[16] Not based on actual statistical data.

[17] Global market presence provides a qualitative picture of the relative impact, influence, and dominance a complementary or substitute technology/system has had in the global marketplace over time. Market presence can perhaps be quantified by determining the actual industry capitalization of each respective technology. Further quantitative analyses of this sort would increase the fidelity and accuracy of this qualitative picture. That was beyond the scope of this study.

[18] "The synergy between satellite transponders and optical fiber is starting to emerge this year. Intelsat has built a hybrid network that uses optical fiber between the hubs in London and New York. Traffic from central Asia can be routed to London via a satellite then to U.S. via optical fiber. Therefore the "substitute/complements" starts to converge in 2003." (B. Chang, Intelsat)

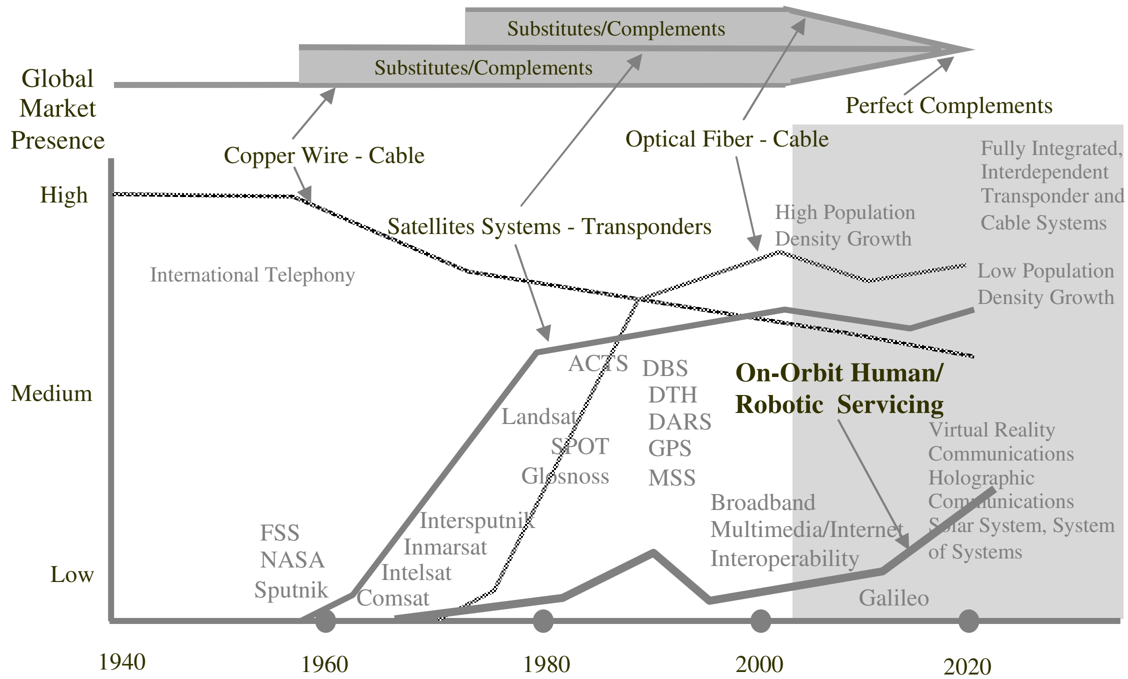

Figure 4. Rough approximation of the evolutionary, telecommunications, technology life cycle market context within which on-orbit robotic servicing emerged and could establish its niche.

Space-based, robotic servicing (or protection) through a large-scale, on-orbit infrastructure is considered as a potentially viable industry or economic technology activity. Such activity might effectively and efficiently connect future space enterprise and space exploration with real economic growth contributions. Most importantly, economic growth contributions from the space sector are necessary to increase the relevance of space in the public's eye. In the latter half of the 20th century the feasibility of a LEO humans-in-space-centered space operations program was tested. The results indicate that the real and perceived benefits of having people in space need to heavily outweigh the risks inherent in transporting, keeping them there, and returning them to the Earth. Space, in terms of the LEO-to-GEO economic operations zone, or the beyond GEO exploration zone, appears to be the domain of semi- (i.e., tele-operated) and fully-autonomous (i.e., artificially intelligent) robots. It is suggested that United Stated space policy should focus on the development of a LEO-to-GEO-and-beyond, robotics-centered[19] space program, for the integrated, civil, military, and commercial development of space. The satellite industry offers an excellent showcasing opportunity and should be the first beneficiary of the implementation of such a policy.

Spacecraft or satellite servicing is defined in this paper as the offering of services to owners or operators that involve the direct manipulation of on-orbit hardware or assets for the purposes of refueling, upgrade, repair, inspection, relocation, removal, etc. (*Appendix A, slide 7)* (*see also, Hackel, 1989, p 254; Messinger, 1987, Section 1*). The capability to service satellites began with the demonstration of the first U.S. extravehicular activity (EVA) on the Gemini 4 mission in June 1965. The technological development of human/robotic satellite servicing has been pursued

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[19] That includes humans peripherally for ground-or space-based support.

since the 1970s and came to a high point with a series of capability demonstrations (see Figure 4). With the advent of the space shuttle space transportation system (STS) in 1981, satellite servicing, as a discipline, formally entered the public's consciousness.

In April 1984, the term "satellite servicing" was introduced with the retrieval, repair, and redeployment of the Solar Maximum Mission (SMM) satellite. The STS 41-D SMM satellite servicing mission was very successful. Shortly after, in October that same year, astronaut, on-orbit refueling was demonstrated *(Chenard, 1990)*. In November 1984, the Westar and Palapa communications satellites were captured and returned to Earth. Space robotics, a key enabling technology for satellite/spacecraft servicing received considerable international and U.S. government investment during the 1980s, from the Canadian robotic manipulator system (RMS) for the STS and ISS, to a formal NASA space telerobotics program *(Anders, 1994; Stephenson, 1989; Rice, 1986; Spencer, 1982)*. The European Space Agency (ESA), led by the DLR German Space Center, has continued significant development of telerobotic/satellite servicing technologies *(SpaceRef.com, 2002; De Peuter, 1994; Vandenkerchove, 1981)*.

Between 1984 and 1990, NASA's attention was focused on the development of a "commercial" satellite servicing facility (SSF) and a flight telerobotics servicer[20] (FTS) as major business components of the core space station system *(Stephenson, 1989; Hackel, 1989; Lavigna, 1987; Middleton, 1984; Holt, 1983; Forsberg, 1983)*. The SSF was abandoned, however, for three apparent reasons: (1) inherent incompatibilities with the space station's microgravity (i.e., 10^{-7}, 10^{-8}g) environment requirements; (2) the lack of a compelling business case; and, (3) severe space station program budgetary shortfall problems. Nonetheless, it has been recognized that there exists a need for the creation of a robust, servicing infrastructure in space *(Aronovitch, 1985)*. The military has initiated a focused effort in this area led by DARPA and its Orbital Express/ASTRO program (*http://www.darpa.mil/tto/programs/astro.html)* – aimed at correcting continuous satellite reconnaissance weaknesses *(National Security Space Report, 2001)*. Although NASA's telerobotics program[21] was shut down in 1997, the agency continues to work jointly with DARPA on the low-level development of "Robonaut" *(NASA Tech Briefs, October 2002)*. For all practical purposes though, NASA's investment in space telerobotics and space-based servicing technology has remained marginal and limited to Hubble Space Telescope (HST) and ISS continuing support needs.[22]

Compared to 1980s spending levels, the development of U.S.-led, robotic, space-based servicing technology development entered a period of virtual dormancy throughout the 1990s (*see Figure 4 and Appendix A, slide 11*). This was perhaps largely attributable to downsizing of the space station program and the general restructuring of the entire United States space program and aerospace industry *(Aerospace Commission, 2002)*. NASA has now articulated a compelling

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[20] NASA decided to develop a $288-million Flight Telerobotic Servicer in 1987 after Congress voiced concern about American competitiveness in the field of robotics. The FTS would also help astronauts assemble the Space Station, which was growing bigger and more complex with each redesign. Martin Marietta and Grumman received $1.5-million study contracts in November 1987. Martin Marietta received a $297-million contract in May 1989 to develop a vehicle by 1993. The Bush Administration briefly tried to commercialize the FTS project in early 1989. The contractors objected since the FTS had no commercial customers. The FTS was then combined with the Orbital Maneuvering Vehicle into the Robotic Satellite Servicer concept. (Source: http://www.astronautix.com/craft/flivicer.htm)

[21] http://ranier.hq.nasa.gov/telerobotics_page/telerobotics.shtm

[22] From a civil needs standpoint, if it is determined that tile damage was the cause of the STS 107 accident, NASA would probably be encouraged to develop a surface-to-orbit telerobotics servicing capability to inspect and perhaps repair thermal heat shield damage on orbit – if feasible. This might also provide a good, strong rationale for reestablishing a formal telerobotics program.

vision and commitment to science-driven exploration (discussed later). The large-scale systems required to make this exploration vision a reality clearly underscore the long-range need for development of a space-based servicing infrastructure. Furthermore, over the next 20-plus years, the inevitable shift to a BLOSP philosophy for future civil-military-commercial space systems might be justified on the basis of establishing a robust, cost-effective, space-based servicing infrastructure[23] for 21st century spacecraft. Toward this end, entrepreneurial investment activity[24] in this area has continued at a low level.

Basically, it is suggested that a robust, on-orbit, robotic services industry sector should be developed and established through a government-led initiative. This would stimulate commercial activity and evolve into a potentially strong economic foundation for space development and exploration, with perhaps numerous, unforeseeable, serendipitous economic development offshoots in space. In other words, this may be the way to achieve an economic, self-sufficient, space enterprise that can be used to minimize dependence on the public/tax-based component of investment in space development and exploration.

6.2.1 Assessment of Potential, Early-to-Mid 21st Century Demand

Past studies on the economic viability of servicing for GEO, MEO, and/or LEO spacecraft have largely endorsed the prospects through analyses of its cost effectiveness compared to expendable satellites (*Space Systems/Loral, December 1990*). Several studies and articles have focused on assessing the viability of discrete market segments (repair, refueling, etc.) *(Sullivan, 2001; Madison, 1999; Levin, 1993; Higginbotham, 1987; Space Systems Loral, 1990; Chenard, 1990).* Commercial and other economic, social, and defense activities grew and expanded around the world as a result of highway and various, public and/or private capital infrastructure investments. Likewise, on-orbit servicing and other market/business activities can be expected to emerge and thrive when the required, cost-effective, government-built, commercially managed infrastructure is established. That being said, it would be quite an achievement if start-up companies in this sector were able to effectively serve their target market.

It is in the long-term interest of NASA, DoD, and other governmental entities, to build and sustain a healthy commercial space/satellite industry. The U.S. and global economies will remain heavily dependent on a ring of roughly 250 geo-stationary commercial satellites. In the future, military reconnaissance, Global Positioning/Locating Systems (GP/LS), and other multi-satellite, “down-looking” systems or networks (such as the conceptual Transformational Communications System (TCS), and Communications, Navigation, and Surveillance/Air Traffic Management (CNS/ATM) applications systems) will probably increasingly populate medium and low Earth orbits. As indicated in the introduction, planning is underway in all sectors, civil, military,

[23] Driven by a similar rationale to that involved with creating the 20th century intermodal [i.e., road, rail, sea, and air] transportation and vehicle service and maintenance system (for automobiles, trains, ships and airplanes).
[24] Orbital Recovery Corporation is a private venture that seeks to develop a new type of spacecraft that will rendezvous with aging communications satellites in GEO that are running out of station-keeping fuel. The DLR German Aerospace Center’s robotic capture tool concept is to be incorporated into ORC’s Geosynch Spacecraft Life Extension System (SLES). (www.Spaceref.com/news/viewpr.html?pid=9944)

commercial, and industrial to coordinate a “transformational” strategy for the future.[25] There is a growing interest within both the defense[26] and commercial sectors[27] in the development of a robotic, satellite servicing sector, along with various high-risk satellite technologies - such as laser/optical systems. This prospect appears ideal as both a necessary capability and a potential economic foundation (a possible “prerequisite”) to support NASA’s long-range, science-driven, space exploration objectives.”[28]

Commercial, robotic, on-orbit servicing is expected to find an initial foothold or market in GEO. The key to this and any space market was identified as standardization (*Appendix A, slide 49; Appendix B, pages B24 and B27*). If satellite/spacecraft manufacturing were standardized (i.e., component interfaces, dimensions, etc.), as a result of market forces or government regulation, then it is conceivable that the (Earth orbit) market for spacecraft/satellite servicing (and protection) could rapidly grow into the hundreds of billions of dollars. This could become a thriving industry with no real limits to the growth-stage, given the potential for development and deployment of serviceable (Earth-Moon or -Sun libration points) exploration and other spacecraft.

Figure 5 shows the relative GDP and GDP per capita[29] purchasing power parity for ten significant space-investing nations. It is unlikely that the relative GDP and GDP per capita distributions shown will change significantly during the first half of this century. Given this condition therefore, from an economic power standpoint, North America, Europe, and Asia are well positioned to competitively and/or cooperatively control the agenda for global space investment throughout the 21st century. In other words, leadership in space development can be expected to germinate and spring from either of these economically developed regions.

Outside the United States there is a strong and growing interest in the establishment of satellite information networks to provide a variety of services ranging from global positioning to remote sensing. There is growing concern in the U.S. space industry that it is loosing market share in the satellite manufacturing and launch vehicle services sectors. This is primarily being blamed on

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[25] Civil: The NASA Advisory Council endorsed the NASA Exploration Team on September 11, 2002, thereby establishing the new philosophy of science-driven (Space Science, Earth Science, and Biological and Physical Research) “destination” driven programs enabled by technology. This was followed almost immediately by the October 11, 2002 establishment of the “Future Technology/Space Architect” function as an “Official in Charge” within the Office of the Deputy Administrator at NASA Headquarters—a strong indication of the course NASA will follow.
Military: NASA and DoD (U.S. Strategic Command, the National Reconnaissance Office, the Air Force Space Command, and the Defense Research and Engineering Agency) signed a Memorandum of Agreement at a regular meeting of the “Space Partnership Council” on October 8, 2002. This significantly expanded the interactions between the nation’s civil and military space programs.
Commercial: The Satellite Industry Association (SIA) (at a September 18, 2002 meeting at NASA Headquarters) indicated that the industry is looking to government to invest in revolutionary or high-risk systems and/or technologies. This is because the satellite manufacturing and launch vehicle sectors experienced a massive and severe 47% (i.e., $6.3 billion) contraction in their combined revenue streams between 1999 and 2001. Over-capacity, market erosion and economic survival are now grave and growing concerns for the U.S. satellite industry, and their (commercial/ international competitive) outlook remains very bleak. The Space Enterprise Council of the U.S. Chamber of Commerce has also called government attention to this situation in a recent (2002) policy paper.
[26] The defense community is already investing in the development of a satellite servicing system through its “Orbital Express/ASTRO” program.
[27] Satellite Industry Association (SIA) interpretations gathered from the International Satellite Communications exchange (ISCe) Conference and Exposition, Long Beach, CA, August 2002.
[28] Presentation at NASA Headquarters entitled: Prospects for Satellite Servicing – A Common Government/Industry Strategy for the Development of Space presentation at NASA Headquarters, August 2002.
[29] The World Fact Book 2002: Central Intelligence Agency.

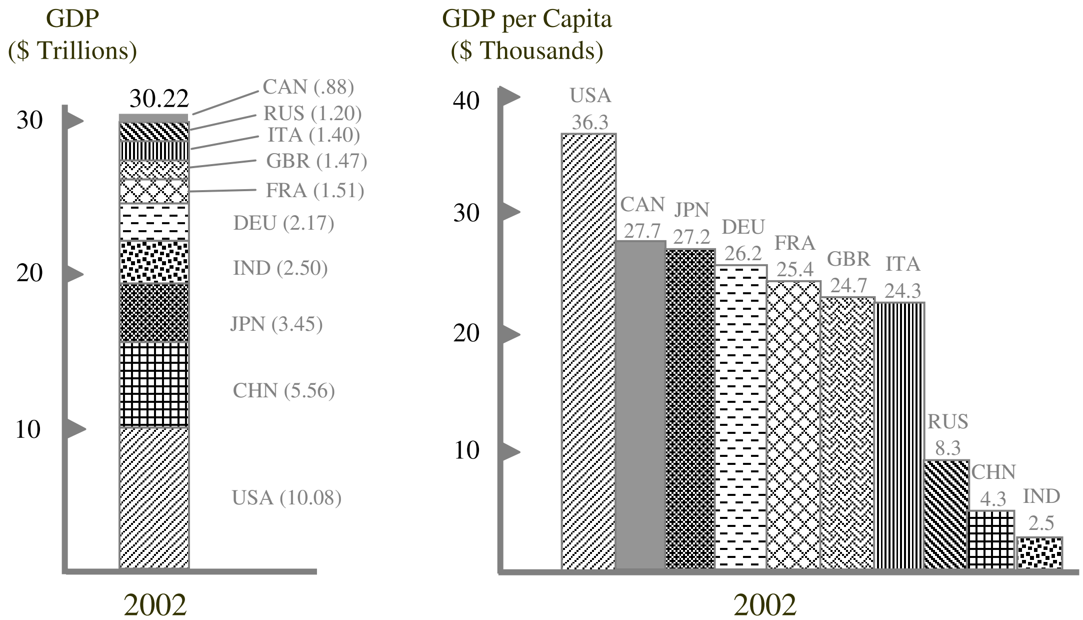

Figure 5. Relative GDP and GDP per capita for ten significant space-investing nations.

other countries' subsidies to their nascent space industries (*Appendix B, page B7*). That being said, it is clear that the 21st century holds the promise of the potential emergence of a large international market for robotic, on-orbit servicing that would effectively dwarf the present global satellite industry. A few indicators of this impending future are discussed in the next paragraph.

At the last European Interparliamentary Space Conference (EISC), held in London under the auspices of the UK Presidency of the EISC, space was described as "central to the evolution of the world community in the 21st century." Subsequently, the UK Minister of Science and Innovation, Lord Sainsbury, in his *"Draft Space Strategy: "2003 – 2006 and Beyond,"* specified three purposes for investments in space. These were: *(1) to expand knowledge in astronomy, planetary, Earth and life sciences; (2) to create opportunities for commercial exploitation of satellite systems; and (3) to advance key public services*. As an ESA member, UK strategy is closely aligned with European space strategy with its strong focus on "space at the service of the citizen" (*STAR21, 2002*). Europe, through the ESA is partnered with the U.S. in the construction of the ISS. ESA is also poised to expand its reliance on satellite networks in the future for emerging services such as navigation, telemedicine, high value asset tracking, etc. Like Europe, Japan has also engaged in long-range planning for 21st century space investments driven by both science-driven exploration and commerce.

There is also significant interest in space in the developing world. At the Space Summit of the 90th Session of the Indian Science Congress, the President of the Republic of India (an Aero Engineer from Madras Institute of Technology), Dr. Avul Pakir Jainulabdeen Abdul Kalam, gave a speech entitled: *Vision for the Global Space Community: Prosperous, Happy, and Secure Planet Earth.* In his speech, Dr. Kalam pointed to a clear and growing emergence of a "Knowledge Society: a future in which space technology is fully integrated with information and communications technologies for the generation of conventional and non-conventional energy, environment and ecology protection, mining and new resources from planets, telemedicine and teleeducation, infotainment." The Indian president also highlighted the need to "resolve the Man-Planet conflict created by severe pollution arising from a fossil fuel based industrial era." In addition to India as a new player in long-range space planning, the Chinese have made a strong commitment to future space investment, and plans to put its first human in space in late 2003 on Shenzhou-V. From Europe, to Japan, to China, to India therefore, it appears that during the early-to-mid 21st century, attention will increasingly be focused on significant development of satellite/spacecraft systems. Clearly, such systems will be spawned from the fertile and potent interests of nations driven by the quest for new knowledge, resources, and the fundamental need to prove the plurality of life in the universe.

Based on the above indicators, it is reasonable to expect that the market for a future development of a robust, robotic, on-orbit servicing infrastructure will rest not only on the formation of a strong collaboration between U.S. civil, military, commercial, and industrial concerns, but also on strong international cooperative interests.

6.2.2 Assessment of Potential, Mid-to-Late 21st Century Demand

Human and robotic exploration beyond GEO was initiated and led by the United States during the latter half of the 20th Century. The use of space exploration as a technology catalyst, spurred by the expansion of human civilization into outer space, continues to be an underlying theme and rationale in U.S. space policy and planning. In order to achieve this goal, the development of a robust, satellite/spacecraft servicing industrial capability seems to be a logical prerequisite. Over the last decade and a half, high-level U.S. government planning for a significant and sustained expansion beyond GEO during the 21st century has intensified. A brief review of progressive U.S. government plans and activities is presented below.

1. In July 1989, former president of the United States, George H. W. Bush, announced to the world that the United States would lead the way forward into space through the (then) "Space Exploration Initiative." This pronouncement was based on three intense years of focused study beginning with former president Ronald Reagan's *National Commission on Space (NCOS)* in 1986. The NCOS report outlined a detailed Earth-Moon-Mars human (and robotic) exploration and settlement scenario that extended 50 years into the future. NASA responded by preparing the Ride report entitled *Leadership and America's Future in Space,* which was released in 1987. Subsequently, a temporary "Office of Exploration" was established at NASA Headquarters in 1987 with a charter to study various scenario options and prepare recommendations for a presidential decision. The 1989 SEI announcement was the high-watermark of the nation's human/robotic space exploration aspirations. The words of a president, however, were insufficient to overcome the "inertia" and higher priorities of the time. In addition, NASA's initial $500 billion cost estimate was not saleable in the budget tightening, fiscally austere environment at the time. The result: the SEI vision stalled.
2. In October 2001, the Clinton Administration's National Aeronautics and Space Administration produced a report entitled *Report on the NASA Exploration Team (NEXT): Setting a Course for Space Exploration*. The NEXT described a vision "to develop an ever-expanding cascade of capabilities that brings humans and their robotic partners together first in a region called Earth's Neighborhood." This region extends from high Earth orbital locales (beyond the Van Allen radiation belts) to the Sun-Earth libration points. The vision proposed a sustained investment in deep space scientific

systems, and the opening up of the Solar System to exploration by both humans and robots by exploiting their respective strengths. The goal was to achieve the ever-expanding cascade of capabilities using a 'stepping-stone' approach."

3. In April 2002, the [current] Bush Administration's National Aeronautics and Space Administration released a new vision for America's space program to *"Improve life here, to Extend life there, and to Find life beyond."* Towards this end, the United States, through its International Space Station (ISS) venture, has hopefully established the initial stages of the permanent occupancy of space.[30] This achievement represents the first, concrete step toward actualizing the vision. NASA has continued to conceptualize and define the steps forward. The NEXT built a low-level consensus on the steps that will lead this nation and the world forward into a future of symbiotic, human/robotic space exploration. This agenda is being institutionalized within NASA.[31]
4. In a complementary exercise completed in November 2002, the Commission on the Future of the United States Aerospace Industry formulated its vision of the future encapsulated by the terms: *Anyone, Anything, Anywhere, Anytime*. The commission believes that this national vision for aerospace will help sustain U.S. leadership in the 21st century.

Market demands for space-based servicing will multiply significantly if any of these potential futures are created. For example, it is apparent that the need for communications satellite support services will increase dramatically, resulting in a large proliferation of satellite communications network throughout the inner and outer solar system. Currently, deep space communications systems design and technology issues revolve around reliability, continuity, latency (speed-of-light limitations), and data rates (seamlessly integrated, multi-satellite, broadband, giga- or tera-bits per second (gbps/tbps), networks for voice, video, and interactive multi-media, etc.). It is reasonable to project that by the end of this century, the Earth-centered, space-based servicing infrastructure model discussed in previous sections will replicate and expand. In other words, all inner solar system, planetary and interplanetary locations (the libration points) of scientific interest will be connected by an integrated, serviceable, satellite and spacecraft communications network.

7.0 Conclusions

Seven general conclusions are drawn from the overall discussion presented in this paper. Fundamentally, they extended from a characterization, interpretation and summary of various core beliefs and opinions gathered from very experienced executives and senior program managers from the satellite industry.[32]

1. Domestic civil, military, commercial, and industrial long-range interests in space will converge and become cooperatively interdependent in the 21st century. This environment could foster the development and establishment of a large-scale, robotic, spacecraft/satellite services infrastructure (as depicted in Figure 2) as a joint undertaking or collaboration.

[30] Notwithstanding the precarious space transportation problems being addressed, it unfortunately took the STS 107 accident to precipitate a high-level debate and reassessment of the U.S. mission, strategy, and plans of action - particularly where it pertained to humans in space. This timely 2003 debate came at a critical and important juncture in the U.S. space program's evolution and should mark a clear turning or inflection point.
[31] By the Office of the Space Architect.
[32] See Appendices A and B for the core rationale that underpins these conclusions.

2. National and international (i.e., North American, European, Asian) long-range interests in space military and economic development will converge and become more cooperatively and competitively interdependent in the 21st century. This environment could be used to strengthen and formulate a more mutually beneficial, cost-sharing, cooperative agenda.
3. The market for full-scale, commercially driven, robotic, on-orbit servicing lies about 25 to 50 years into the future. This market should materialize as the government and industry transform the 20th century build, launch, operate and replace (BLOR) model to a more efficient 21st century build, launch, operate, service and protect (BLOSP) based on a standardization philosophy.
4. Potential economic viability exists in satellite/spacecraft market segments such as: refueling, upgrade, repair, and perhaps relocation and removal. An affordable, robust, reliable, on-orbit infrastructure is required for efficient and ready access to these market segments.
5. Basic technological and scientific knowledge presently exists at a low to medium maturity level throughout North America, Europe and Asia. When needed, this capability can be rapidly transitioned and/or matured toward the level of sophistication envisioned to develop robotic systems for space-based, spacecraft/satellite servicing in the LEO-to-GEO domain, via either ground or space-based operators. International cooperation will be necessary for this to occur cost-effectively
6. U.S./International government investment in a LEO-to-GEO NSSPI can be guided and supported by common, long-range, national and/or international goals and objectives to establish a robust space exploration and development enterprise.
7. U.S./International government leadership is needed to strategically develop and mature high-risk, space robotics technologies in order to bring them into service by the early-to-mid 21st century. This is necessary to reduce the need for and the risk to humans in space.

8.0 Recommendations

As stated in the introduction, the United States will probably continue to lead the world in space throughout the 21st century. With industry and government around the world perched at a crossroads of decision, it appears to be an excellent time for the U.S. Government and industry should initiate a joint, high-level study to thoroughly assess the long-range technological feasibility, and civil-military-commercial viability and utility of a 21st century on-orbit services infrastructure. Assuming that such a study yields favorable prospects, the following eight suggestions are offered with respect to government and industry roles in establishing a potential satellite, space-based servicing infrastructure. The seven recommendations presented below expand on the proposed, high-level programmatic framework plan (introduced earlier in Figure 2) in relation to NASA’s currently projected SLI(OSP/NGLT)/STS/ISS systems design, development, and operations activities:

1. An agreed upon, high-level agenda should be formulated whereby NASA leads the design and development of a LEO-to-GEO NSSPI spacecraft carrier and infrastructure. This could be introduced as a piggybacked, civil-to-commercial transition strategy for the already established, military (fully autonomous robotics) focused, DARPA Orbital Express/ASTRO program. (SCD: 2005)

2. NASA should take the lead to reestablish a formal space telerobotics program and invest in the development of space telerobotics technologies as a required evolutionary step toward fully autonomous robotics. This investment should also support the focused development/application of power, propulsion, and communications and other required technologies for both near- and far-term NSSPI spacecraft carrier systems needs. (SCD: 2005)
3. NASA should lead the assessment of ground facilities and infrastructure that would be required for integration, environmental testing, etc., of potential NSSPI subsystems. The potential for significantly increased regional economic development activity should also be quantified. (SCD: 2005)
4. NASA should lead the establishment of a government/industry collaboration to define high-risk enabling systems/technologies such as space robotics, electronics, power, propulsion, and communications, structures, etc. required for the development of a LEO-to-GEO NSSPI. (SCD: 2007)
5. U.S. industry should be encouraged to initiate a broad review to quantify the potential business, market and economic benefits (both on-ground and in Earth orbit) of establishing a 21st century spacecraft and satellite servicing sector. (SCD: 2009)
6. NASA should lead the establishment of an intergovernmental partnership to assume the risk of constructing the "Spacecraft Carrier," fuel and parts depots, etc., i.e., the core infrastructural subsystems of the LEO-to-GEO NSSPI. (SCD: 2010)
7. U.S. Industry should be encouraged to lead the establishment of an international, strategic alliance to partner with the intergovernmental entity above, coordinate the standardization of satellite subsystems, serviceability requirements, and develop and deploy the SRSPS subsystem of the LEO-to-GEO NSSPI. (SCD: 2011)

9.0 List of Acronyms

ATM	Air Traffic Management
BLOR	Build Launch Operate and Replace
BLOSM	Build Launch Operate Service and Maintain
BLOSP	Build Launch Operate Service and Protect
BMDO	Ballistic Missile Defense Organization
BOL	Beginning of Life
C^3	Command Control and Communications
CNS	Communications Navigation and Surveillance
D2C	Defense to Commercial
DARPA	Defense Advanced Research Projects Agency
DARS	Digital Audio Radio System
DBS	Direct Broadcast System
DERA	Defense Evaluation and Research Agency
DoD	Department of Defense
DHS	Department of Homeland Security
DTH	Direct-to-Home
EISC	European Interparliamentary Space Conference
ELV	Expendable Launch Vehicle
ESA	European Space Agency
EVA	Extravehicular Activity
FSS	Fixed Satellite System

GEO	Geostationary Orbit
GRC	Glenn Research Center
GPS	Global Positioning Satellite
GSI	Ground Support Infrastructure
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ISBC	International Space Business Council
ISS	International Space Station
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MSS	Mobile Satellite System
NASA	National Aeronautics and Space Administration
NCOS	National Commission on Space
NEXT	NASA Exploration Team
NSSPI	National Spacecraft Servicing and Protection Infrastructure
NGLT	Next Generation Launch Technology
OSP	Orbital Space Plane
PRLV	Partially Reusable Launch Vehicle
RASC	Revolutionary Aerospace Systems Concepts
RMS	Remote Manipulator System
ROI	Return on Investment
RONI	Return on National Investment
SAIC	Science Applications International Corporation
SCD	Suggested Completion Date
SEI	Space Exploration Initiative
SIA	Satellite Industry Association
SLI	Space Launch Initiative
SMM	Solar Maximum Mission
SRSPS	Specialized Robotic Servicing and Protection Spacecraft
SSF	Satellite Servicing Facility
STS	Space Transportation System
TBD	To Be Determined
TCS	Transformational Communications System
UK	United Kingdom
UMD	University of Maryland
U.S.	United States

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Appendix A

Examination of Prospects for Satellite Servicing

A Common Government/Industry Strategy for the Development of Space

Presented on August 5, 2002, to the Assistant Associate Administrator, NASA Headquarters, Office of Space Flight, Advanced Systems.

Contents

List of Acronyms

AU:	Astronomical Units
BLOR:	Build, Launch, Operate, Replace
C3:	Command, Control, Communication
DoD:	Department of Defense
DARPA:	Defense Advanced Research Projects Agency
EM:	Electromagnetic
GEO:	Geostationary orbit
ISS:	International Space Station
LEO:	Low Earth Orbit
MEO:	Medium Earth Orbit
NASA:	National Aeronautics and Space Administration
NEXT:	NASA Exploration Team
OSD:	Office of the Secretary of Defense
R&D:	Research and Development
RASC:	Revolutionary Architecture Systems Concepts
REA:	Regional Economic Areas
RF:	Radio Frequency
SIA:	Satellite Industry Association
TDRS:	Tracking and Data Relay Satellite
USAF:	United States Air Force
USG:	United States Government
XSS:	Experimental Small Satellite

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Appendix A

Approach

- Develop open-ended question set.
- Conduct individual, in-person interviews with a representative group of satellite industry experts.
- Characterize, interpret, and summarize responses.
- Formulate satellite servicing infrastructure concept based on results.
- Formulate recommendations.

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Appendix A

Introductory Framework

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Appendix A

Premises

- Satellite industry established by governments during the 1960s.
- Government (NASA-"NEXT/RASC;" OSD/DoD/DARPA -"Orbital Express," etc.) at cross-roads considering 21st century space investments.
- $80 billion satellite industry at cross-roads considering 2000s growth prospects.
  - Viability weakening (unfavorable regulatory and competitive environment - terrestrial fiber, foreign encroachments, etc.)
- A robust, 21st century satellite servicing industry sector is a potential emerging prospect.

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Appendix A

Definition

Satellite Servicing implies the offering of services to satellite owners or operators that involve the direct manipulation of spacecraft hardware or assets on-orbit for the purposes of refueling, upgrade, repair, inspection, relocation, burial, etc.

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Appendix A

Stepping Stones

Report of the NASA Exploration Team
Setting a Course for Space Exploration
in the 21st Century
October 2001

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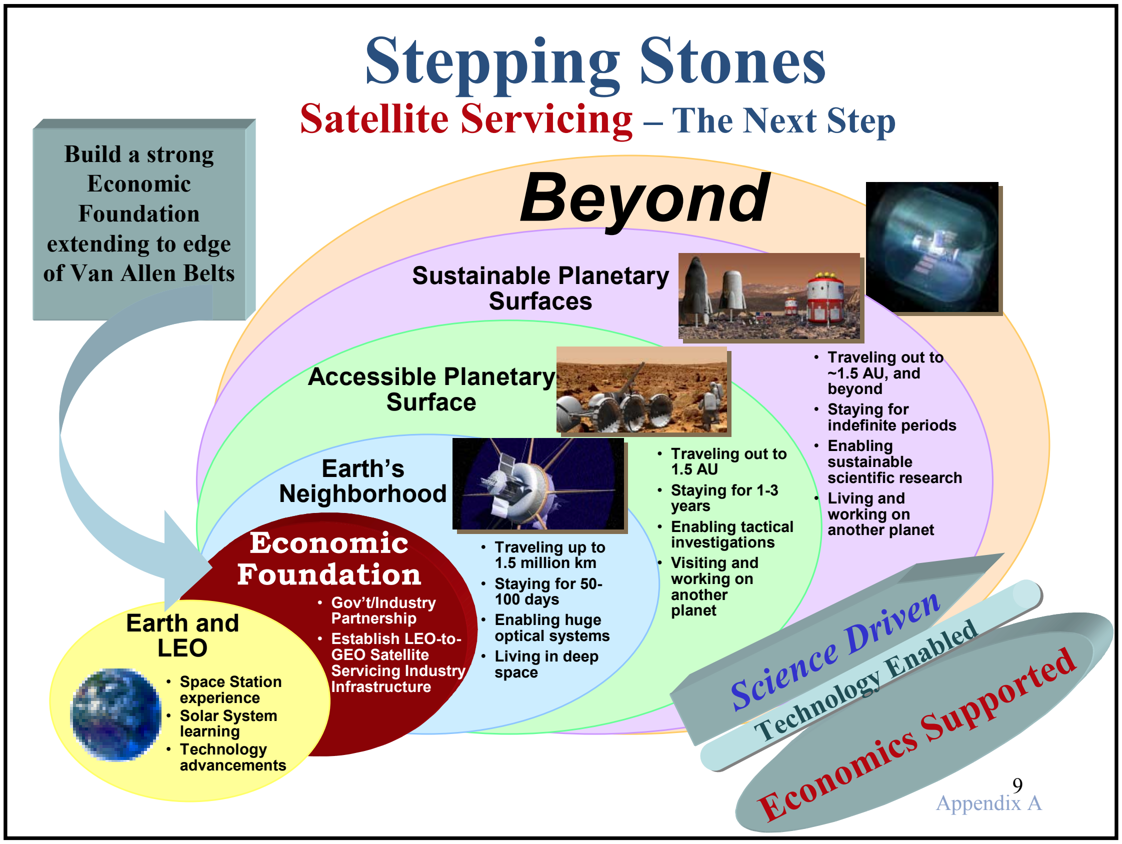

Stepping Stones
Satellite Servicing – The Next Step
Build a strong Economic Foundation extending to edge of Van Allen Belts
Beyond
Sustainable Planetary Surfaces
Accessible Planetary Surface
Earth's Neighborhood
Economic Foundation
Earth and LEO
• Space Station experience
• Solar System learning
• Technology advancements
• Gov't/Industry Partnership
• Establish LEO-to-GEO Satellite Servicing Industry Infrastructure
• Traveling up to 1.5 million km
• Staying for 50-100 days
• Enabling huge optical systems
• Living in deep space
• Traveling out to 1.5 AU
• Staying for 1-3 years
• Enabling tactical investigations
• Visiting and working on another planet
• Traveling out to ~1.5 AU, and beyond
• Staying for indefinite periods
• Enabling sustainable scientific research
• Living and working on another planet
Science Driven
Technology Enabled
Economics Supported
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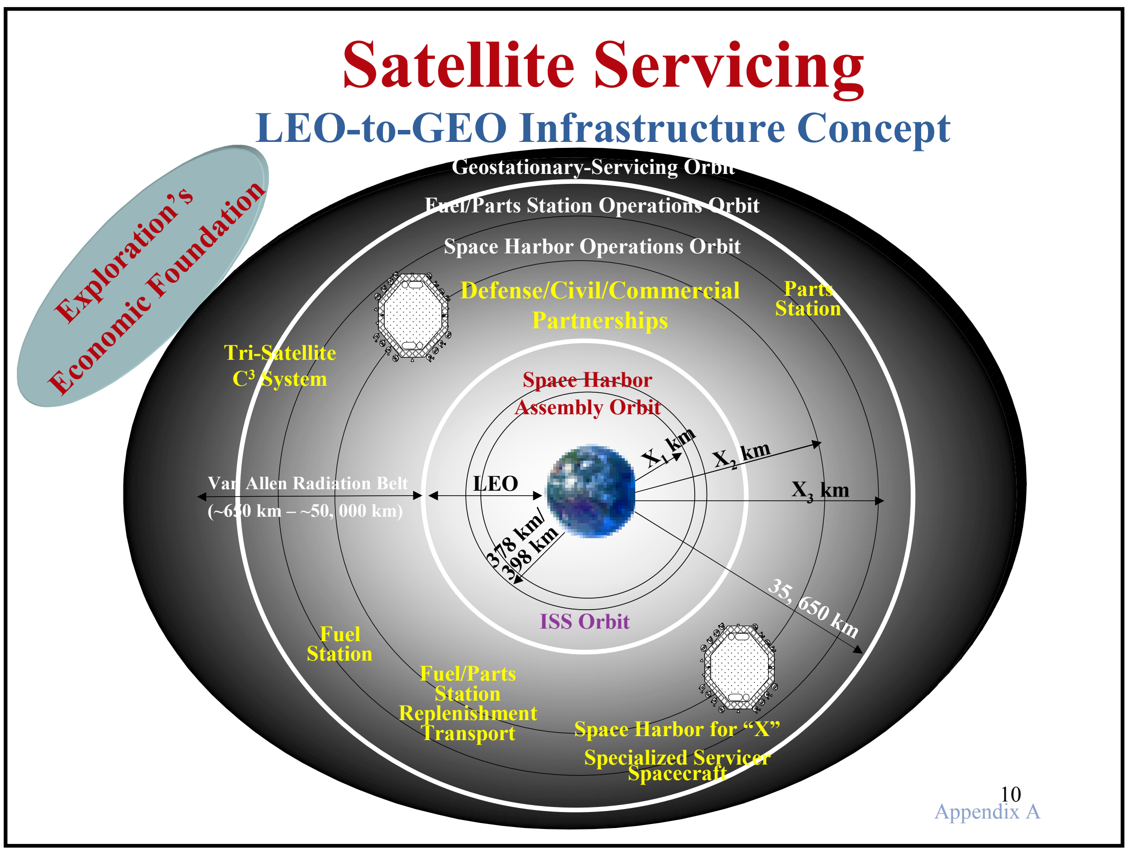
Appendix A



Satellite Servicing
LEO-to-GEO Infrastructure Concept
Exploration's Economic Foundation
Geostationary-Servicing Orbit
Fuel/Parts Station Operations Orbit
Space Harbor Operations Orbit
Defense/Civil/Commercial Partnerships
Parts Station
Tri-Satellite C³ System
Space Harbor Assembly Orbit
X₁ km
X₂ km
X₃ km
Van Allen Radiation Belt (~650 km – ~50, 000 km)
LEO
378 km/ 398 km
ISS Orbit
35, 650 km
Fuel Station
Fuel/Parts Station Replenishment Transport
Space Harbor for "X" Specialized Servicer Spacecraft
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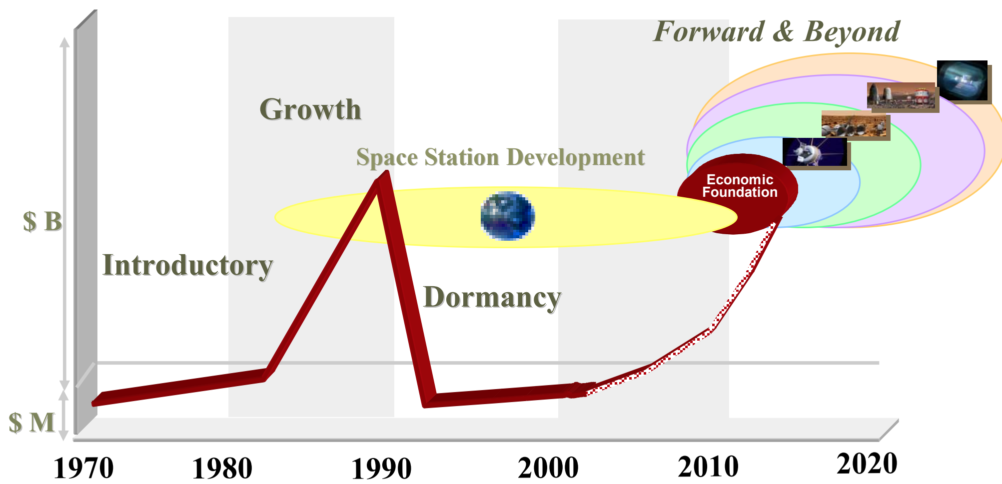
Appendix A

Satellite Servicing

Investment Profile

(Qualitative/Not to Scale)



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Appendix A

Satellite Industry Interviews

conducted between May 4, 2002 and July 6, 2002

Interview Results

(See separate Appendix for detailed responses)

Opinions, Perspectives, and Impressions of a representative group of ten industry, academia, and government experts.

All Interviews were conducted in person at each interviewee's company location.

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Appendix A

Introduction

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Appendix A

Interviewees

1. **Maj James Shoemaker, USAF, Ph.D.,** Program Manager, Orbital Express, DARPA
2. **Dave Akin,** Director, Space Systems Laboratory, University of Maryland
3. **Rud Moe,** Program Manager, Hubble Space Telescope, NASA Goddard
4. **Ben Chang, Ph.D.,** Vice President, Satellite Engineering and Program Development, Intelsat
5. **James Crocker,** Vice President, Space Exploration Systems, Lockheed Martin Corporation
6. **Steven Keppers,** XSS-11 Program Manager, Lockheed Martin Corporation
7. **Bruce McCandless II,** Chief Scientist, Reusable Space Transportation Systems, Lockheed Martin Corporation
8. **Laurence Price,** Director, Crew Return Vehicle, Lockheed Martin Corporation
9. **Peter Hadinger,** Chairman, Satellite Industry Association; Director, Telecommunications Policy, TRW
10. **Richard DalBello,** Executive Director, Satellite Industry Association

Eight interviews conducted: Six individual and two paired

DARPA Interview focus: Orbital Express program overview

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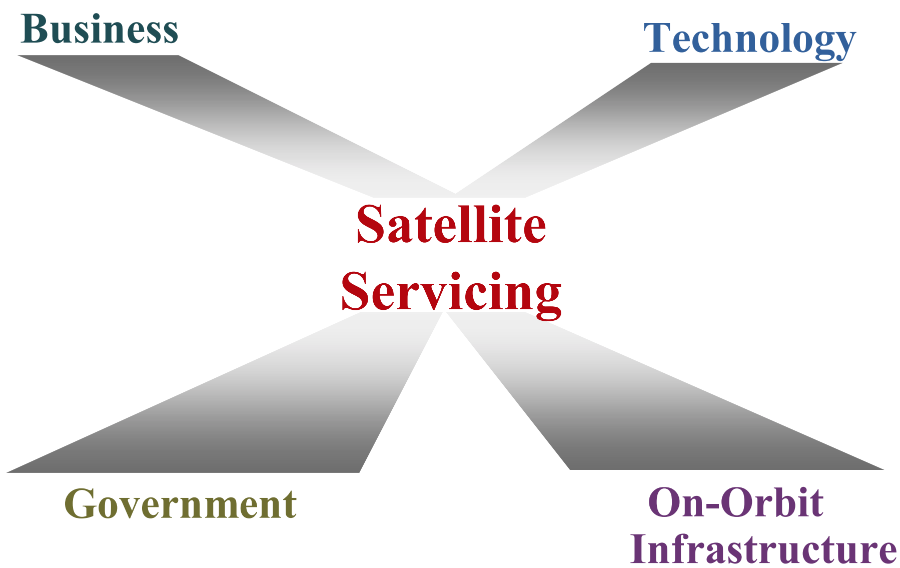
Appendix A

Question Categories

Five-dimensional Assessment



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Question Subcategories

Business	Technology	Government	On-orbit Infrastructure	Satellite Servicing
Economic Viability	Challenges	NASA Roles & Responsibilities	Future Commonality	Business Potential
International Environment	Applications		Roles & Responsibilities	Industry Needs
Challenges			Economic Utility	Satellite Evolution
Vision			Business Potential	Market Sectors
Competitive Needs				Market Segments
Technology Life Cycle				Key Technology
Trends				Location
				Logistics

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Appendix A

Characterization of Responses

Encouraging - with some Concerns

Question Categories	RT: Responses Totals	WT:Weighted Totals	Characterization Ratings (WT/RT)
Business	P's=5 E's=4 C's=8 H's=0 N's=6 23	5x5=25 4x4=16 8x3=24 0x2=0 6x1=6 71	3.1 Concerned
Technology	P's=5 E's=2 C's=2 H's=1 N's=0 10	5x5=25 2x4=8 2x3=6 1x2=2 0x1=0 41	4.1 Encouraging
Government	P's=0 E's=3 C's=2 H's=0 N's=0 5	0x5=0 3x4=12 2x3=6 0x2=0 0x1=0 18	3.6 Concerned & Encouraging
On-orbit Infrastructure	P's=4 E's=6 C's=4 H's=0 N's=0 14	4x5=20 6x4=24 4x3=12 0x2=0 0x1=0 56	4.0 Encouraging
Satellite Servicing	P's=5 E's=33 C's=5 H's=0 N's=0 44	5x5=25 33x4=132 5x3=15 0x2=0 0x1=0 173	3.9 Encouraging
Combined Avg. (E's & C's)	E's=44 C's=8 52	44x4=176 8x3=24 200	3.8 Encouraging

Positive (P) = 5 Encouraging (E) = 4 Concerned (C) = 3 Hesitant (H) = 2 Negative (N) = 1

Business

Questions & Responses

See Appendix B for Detailed, Individual Responses

Business

Economic Viability

Question 1

Does the satellite industry believe that the current "build, launch, operate and replace (BLOR)" business model is satisfactory, sufficient and efficient, and should remain in place for the foreseeable future?

Aggregate Summary of 6 Responses

No confidence in long-term viability of current business model

- **Chronic overcapacity**
- **Launch and insurance costs**
- **Negative investment/market image**
- **Government stagnation**

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Appendix A

Business

International Environment

Question 2

To what extent are other governments providing support to their satellite industry?

Europe Japan Russia China Other (Identify)

Aggregate Summary of 3 Responses

European and Chinese industries gaining significant advantage through government subsidies

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Appendix A

Business

Challenges

Question 3

To what extent do the following factors drive decisions on satellite design & evolution?

- Reducing spacecraft cost
- Extending spacecraft life
- Reducing risk of spacecraft failure
- Improving spacecraft
- Performance/capabilities
- Strategic business plans/motivations
- Responding to competitors actions

Aggregate Summary of 3 Responses

Key Drivers

- Reducing spacecraft cost
- Strategic business plans/motivations

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Appendix A

Business

Challenges

Question 4

Apart from lowering the cost per kilogram to orbit, have satellite owners/operators identified any other major obstacles to growth that are beyond the industry's risk threshold?

Aggregate Summary of 2 Responses

Cost and launcher payload size limitations

- Forces premature application of new technologies
  - Increased risk of satellite failure

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Appendix A

Business

Question 5

Vision

Have satellite owners/operators/manufacturers formulated a collective vision of their industry's future growth prospects?

What is your vision of the commercial satellite industry's future growth prospects, and, do others share it?

Aggregate Summary of 6 Responses

Industry currently has no collective vision

- Unable to discern growth-path
  - Survivalist instinct due to recent and severe, multi billion dollar investment and competitive failures

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Appendix A

Business

Technology Life-cycle

Question 6

At what age does a functioning satellite generally become technologically obsolete and what is the significance of this state from:

A primary owner/operator standpoint?
An aftermarket owner/operator standpoint?
A manufacturer standpoint?

Aggregate Summary of 4 Responses

Owner: 7 to 12 years
Manufacturer: 3 to 5 years
Potentially viable aftermarket

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Appendix A

Technology

Questions & Responses

See Appendix B for Detailed, Individual Responses

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Appendix A

Technology

Competitive Needs

Question 7

Name five specific spacecraft/satellite technology advancements, which if brought into service within the next 10 to 15 years, would provide a significant competitive advantage for the U.S. satellite industry?

Aggregate Summary of 3 Responses

- **Higher power (Nuclear, Adv. Solar Cells & Batteries)**
- **Higher bandwidth (Laser/Optical)**
- **Lower launch cost**
- **Lower operational cost**
- **Improved lifetime (Electronics, E-Propulsion)**

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Appendix A

Technology

Trends

Question 8

Is satellite manufacturing (for GEOsats in particular) moving towards standardization? If not what is preventing the industry from moving in that direction?

Aggregate Summary of 4 Responses

- **Early-stage standardization at component level**
- **Customization of certain electronics and payload components resist trend**
- **Acceleration depends on new business paradigm**

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Appendix A

Technology

Challenges

Question 9

Have satellite owners/operators/manufacturers identified any other major technological obstacles to growth that are beyond the industry's risk threshold?

Aggregate Summary of 2 Responses

- **Risky, capital-intensive image of launch**
- **Need for higher levels of autonomy**
  - **Reduction of operating cost without compromising safety**

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Appendix A

Technology

Application

Question 10

How effectively do the needs or performance requirements of satellite owners/operators drive the evolution of satellites?

(Do they just restrict their systems to current technology?)

Aggregate Summary of 2 Responses

Owners/operators risk averse

- Adopt new technologies if
  - Technological risk minimized
  - Performance benefits clear

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Appendix A

Government

Questions & Responses

See Appendix B for Detailed, Individual Responses

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Appendix A

Government

Question 11

NASA Roles & Responsibilities

What could NASA be doing to help the satellite industry achieve greater levels of market/economic performance in the future?

Aggregate Summary of 5 Responses

Invest in high risk, high payoff systems and technologies

- Establish laser/optical communications program
- Eliminate categorization of spectrum bands
- Initiate development of TDRS replacement
- Develop infrastructure with commercial potential
- Develop one reliable launcher for the future
  - while supporting current Atlas/Delta launch systems
- Serve as military-DARPA/commercial transition agent
- Address cost drivers for human systems

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Appendix A

On-orbit Infrastructure

Questions & Responses

See Appendix B for Detailed, Individual Responses

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Appendix A

On-orbit Infrastructure

Future Commonality

Question 12

Considering the potential benefits of satellite servicing, the satellite industry's growth needs, and NASA's long-range exploration goals, what might be the common infrastructure needs between these two entities over the next 15 years?

Aggregate Summary of 3 Responses

- **A civil-commercial servicing infrastructure**
  - **piggy-backed on Military-DARPA investment**
- **A market for rendezvous and docking technology**
  - **through establishment of standards**

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Appendix A

On-orbit Infrastructure

Future Commonality

Question 13

Given NASA's desire to build a stepping-stone to Lunar/Martian settlement within the next 30 to 50 years, and given the satellite industry's future market/growth interests, what do you think may be the common infrastructure needs over the next 15 years?

Aggregate Summary of 2 Responses

An integrated civil, commercial, military, space-based relay infrastructure, in addition to transportation and servicing

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Appendix A

On-orbit Infrastructure

Question 14

Roles & Responsibilities

What should the roles and responsibilities of each of the following entities be in the establishment of a potential, future, on-orbit, commercial satellite servicing infrastructure?

NASA
The U.S. Satellite Industry
Other U.S. Government Agencies
Other Countries or Regional Economic Blocks

Aggregate Summary of 6 Responses

- **NASA:** takes lead, provides on-orbit infrastructure and risk capital/support R&D
- **Industry:** invest in standardization, develop servicer market, pay marginal cost to transport parts, pay usage fees
- **Other U.S.G. Agencies:** participate as partners
- **Other Countries/REAs:** seek roles in new industry sector development

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Appendix A

On-orbit Infrastructure

Question 15

Economic Utility

Looking out around the year 2015, would the establishment of an on-orbit, commercial satellite servicing infrastructure be of potential high utility to satellite owners or operators?

Aggregate Summary of 3 Responses

Yes: once technological and business risks have been minimized

- Government established infrastructure
  - Robots: Human Supervision
  - Humans: Special Services

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Appendix A

Satellite Servicing

Questions & Responses

See Appendix B for Detailed, Individual Responses

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Appendix A

Satellite Servicing

Business Potential

Question 16

At approximately what fraction of total asset value might satellite servicing be cost attractive to satellite owners or operators?

Aggregate Summary of 6 Responses

Between 25% and 60% of total asset value, which includes launch cost

- **Fraction tends to the high end of range depending on proximity to BOL and particular servicing objective**

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Appendix A

Satellite Servicing

Business Potential

Question 17

What approximate increased premium might satellite owners/operators pay satellite manufacturers for a "serviceable" satellite if this option were available in the future?

Aggregate Summary of 4 Responses

None: not unless insurers or government provided serious incentives in terms of insurance or tax breaks.

- A partnership between a leading manufacturer and an insurer in this vein might attract industry followers.

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Appendix A

Satellite Servicing

Industry needs

Question 18

Is robotic or human satellite servicing a capability that the satellite operators and manufacturers would like to see developed and economically maximized?

Aggregate Summary of 5 Responses

Yes: concerns about additional weight impact, payload accessibility/standardization, economic case, and developmental cost

- Industry would resist change
- Government must trigger market, pay developmental or non-recurring cost
- Insurers should provide reduced rates incentives
- Servicing most desirable near BOL
- Lowest cost for same reliability

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Appendix A

Satellite Servicing

Satellite Evolution

Question 19

How might satellites change to exploit or take advantage of on-orbit servicing, if the price were right?

Aggregate Summary of 3 Responses

- Components/Interfaces Standardized
- Component accessibility increased
  - Heavy bolting reduced
- Fuel access ports incorporated
- Docking and rendezvous aids incorporated

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Appendix A

Satellite Servicing

Market Sectors

Question 20

If satellite servicing became a reality around 2015, where would the market be?

- GEO only
- GEO and MEO only
- GEO, MEO and LEO

Aggregate Summary of 5 Responses

GEO, MEO and LEO
- GEO Market: Life extension awaiting replacement
- LEO Market: disposal of Russian nuclear satellites
- Competition: Replacement
  - Replacement becomes less economical as scale and/or capitalization increases

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Appendix A

Satellite Servicing

Market Segments

Question 21

If robotic satellite servicing were made to exist between 2010 and 2015, which of the following on-orbit, commercial satellite servicing capabilities might be of the most interest economically to the satellite owners or operators?

Inspection	Upgrade	Maintenance	Other
Refuel	Reboost	Replacement	
Repair	Retrieve	Rehabilitation	

Aggregate Summary of 6 Responses

Top four: Refuel, Upgrade, Repair, Inspection.

- **Added: Relocation (GEO), Removal (GEO)**
  - **Critical Technologies:** dexterous repair and rendezvous and grapple

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Appendix A

Satellite Servicing

Key Technology

Question 22

What would be the best means by which to most effectively (cost and performance-wise) accomplish on-orbit satellite servicing?

Robots (Fully autonomous)
Tele-robots (Semi-autonomous – i.e., ISS astronaut/ground controlled robots)
Astronauts
Other

Aggregate Summary of 6 Responses

Tele-robotics (Consensus)

- **Scenario Options:** ground-based operator, ground-based line-of-sight operator, space-based operator
  - **Human function:** operate/supervise, intervene if robot cannot perform task

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Appendix A

Satellite Servicing

Location

Question 23

Where should satellite servicing be performed for maximum efficiency?

- At their orbital stations
- Away from their orbital stations

Aggregate Summary of 5 Responses

Orbital station (Consensus)

- Line-of-sight control to minimize GEO-to tele-operator time-delay
- Should not interfere (EM/RF) with nearby satellites
- Transporting elsewhere, especially LEO, too energy intensive

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Appendix A

Satellite Servicing

Logistics

Question 24

If satellite servicing became a reality, where would you expect satellite supplies (fuel, replacement parts, etc.) to be stored?

- On-orbit
- On the ground (i.e., launched on demand)

Aggregate Summary of 4 Responses

- **On-orbit:** Fuel, other commodity replacement parts
  - Under-utilized launchers could be used for low-cost, depot resupply missions
- **Ground:** Special order parts

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Appendix A

Summary of Findings

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Appendix A

Summary of Findings

Business

1. **Economic Viability:**
   - **No confidence in long-term viability of current business model.**
2. **International Environment:**
   - **European and Chinese industries gaining significant advantage through government subsidies.**
3. **Challenges:**
   - **Reducing spacecraft cost; Strategic business plans/motivations; Cost and launcher payload size limitations.**
4. **Vision:**
   - **Industry has no collective vision - unable to discern growth-path.**

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Appendix A

Summary of Findings

Technology

1. Competitive Needs:
   - Higher Power (Nuclear, Advanced Solar cells & Batteries), Higher Bandwidth (Laser/Optical Communications),
   - Lower launch cost,
   - Lower operational cost,
   - Improved lifetime (Electronics, E-Propulsion)
2. Trends:
   - Standardization.
3. Challenges:
   - Risky, capital-intensive image of launch; Need higher levels of autonomy.
4. Application:
   - Owners/Operators risk averse.

Summary of Findings

Government

1. NASA Roles & Responsibilities:
   - Invest in high risk, high payoff systems and technologies.

Summary of Findings

On-orbit Infrastructure

1. **Future Commonality:**
   - **Military-civil-commercial servicing infrastructure.**
   - **Integrated civil, commercial, military, space-based relay infrastructure.**
   - **Transportation infrastructure.**
2. **Roles & Responsibilities:**
   - **NASA takes lead - invests in high risk infrastructure.**
   - **Industry invest in standardization; pays marginal costs and usage fees.**

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Appendix A

Summary of Findings

Satellite Servicing

1. **Business Potential:**
   - **Cost attractive at 25% to 60% of total asset value.**
     - **High-end BOL bias**
2. **Satellite Evolution:**
   - **Components/Interfaces Standardization**
   - **Component accessibility**
   - **Fuel Access Ports**
   - **Docking and Rendezvous aids**
3. **Market Sectors:**
   - **GEO, MEO and LEO**

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Appendix A

Summary of Findings

Satellite Servicing (Continued)

5. Market Segments:
   - Refuel, Upgrade, Repair, Inspection
     - Added: Relocation (GEO), Removal (GEO)
6. Key Technology:
   - Tele-robotics.
7. Location:
   - Orbital station.
8. Logistics:
   - On-orbit storage of fuel and other commodity replacement parts
   - Ground storage of special order parts.

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Appendix A

Appendix B

Detailed Supplement to Appendix A

Examination of Prospects for Satellite Servicing

A Common Government/Industry Strategy for the Development of Space

Interview Data & Results

Opinions, perspectives, and impressions gathered via in-person interviews with ten, senior industry, government, and academia experts.

Interviews conducted between May 4, 2002 and July 6, 2002

Presented on August 5, 2002 to the Assistant Associate Administrator, NASA Headquarters, Office of Space Flight, Advanced Systems.

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List of Acronyms

ACTS:	Advanced Communications Technology Satellite
AFRL:	Air Force Research Laboratory
AU:	Astronomical Units
BLOR:	Build, Launch, Operate, Replace
C3:	Command, Control, and Communication
DoD:	Department of Defense
DARPA:	Defense Advanced Research Projects Agency
ELV:	Expendable Launch Vehicle
EM:	Electromagnetic
EOL:	End of Life
FCC:	Federal Communications Commission
FTS:	Flight Tele-robotics Servicer
GaAs:	Gallium Arsenide
GEO:	Geostationary orbit
GRC:	Glenn Research Center
GSFC:	Goddard Space Flight Center
IRR:	Internal Rate of Return
ISS:	International Space Station
ITU:	International Telecommunications Union
JIT:	Just In Time
LEO:	Low Earth Orbit
L:	Libration
MEO:	Medium Earth Orbit
MSS:	Mobile Satellite Service
NASA:	National Aeronautics and Space Administration
NEXT:	NASA Exploration Team
NORAD:	North American Aerospace Defense Command
OSD:	Office of the Secretary of Defense
R&D:	Research and Development
RASC:	Revolutionary Architecture Systems Concepts
REA:	Regional Economic Areas
RF:	Radio Frequency
SEI:	Space Exploration Initiative
SIA:	Satellite Industry Association
SLI:	Space Launch Initiative
SSL:	Space Systems Laboratory
TDRS:	Tracking and Data Relay Satellite
TWT:	Traveling Wave Tube
USAF:	United States Air Force
UMD:	University of Maryland
USG:	United States Government
XSS:	Experimental Small Satellite

List of Interviewees[1,2,3,4]

1. **Maj James Shoemaker, USAF, Ph.D.,** Program Manager, Orbital Express, DARPA
2. **Dave Akin,** Director, Space Systems Laboratory, University of Maryland
3. **Rud Moe,** Program Manager, Hubble Space Telescope, NASA Goddard
4. **Ben Chang, Ph.D.,** Vice President, Satellite Engineering and Program Development, Intelsat
5. **James Crocker,** Vice President, Space Exploration Systems, Lockheed Martin Corporation
6. **Steven Keppers,** XSS-11 Program Manager, Lockheed Martin Corporation
7. **Bruce McCandless II,** Chief Scientist, Reusable Space Transportation Systems, Lockheed Martin Corporation
8. **Laurence Price,** Director, Crew Return Vehicle, Lockheed Martin Corporation
9. **Peter Hadinger,** Chairman, Satellite Industry Association; Director, Telecommunications Policy, TRW
10. **Richard DalBello,** Executive Director, Satellite Industry Association

[1] Eight interviews conducted: Six individual and two paired (shaded boxes: 7 and 8, 9 and 10).
[2] All interviews were conducted in person at each interviewee's company location.
[3] For data aggregation purposes, the order of names listed below has been scrambled and does not correspond with the order of responses given to each question throughout this data and results document.
[4] DARPA interview focus: Orbital Express program overview.

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Question 1: Business: Economic Viability	Does the satellite industry believe that the current "build, launch, operate and replace (BLOR)" business model is satisfactory, sufficient and efficient, and should remain in place for the foreseeable future?
Responses of 6 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: [This] model works fine. As a commercial operator, we see whether it is cost-effective or not. We have to bear insurance [costs]. Industry must pay insurance. Industry is still trying faster, better, cheaper. The problem's with reliability.	♦ **Concerned** – **Insurance costs concerns** – **Satellite reliability concerns**
Interviewee Q: [The nation's] launch infrastructure is not healthy today. Cost of launch is a major driving force. If launch were one-tenth the cost, there would be interest to justify trial markets. You can't put a $1 million bird on an $80 million ride. With respect to BLOR, satellite lives are so long. A satellite that gets on orbit and stays for 5 years has paid for itself. Any more [time] makes it a "cash cow."	♦ **Concerned** – **Launch costs concerns** – **Satellite market stunted** – **Satellites' attractive ROI potential overcomes current negatives**
Interviewee R: I can't answer with any definitive knowledge. I assume that they will answer yes, not having been in the industry, not having had the experience.	**(Passed)**
Interviewee S: I think that they think the current model is a high overcapacity. It has to be restructured to work away cost. A lot of people will go out of business [otherwise]. Investments were made in a "bubble" economy. The first in never gets the advantage. The driving conviction was: if you build it they would come, or if you build it, people would find new markets. This was the fuel that generated huge investments. Capital is now moving to areas where there is a product – away from the hype. Our company made huge investments in MSS in the infrastructure to launch. However, cell phones got there [to market] first. Fiber, cell phones, etc., all put this part of the satellite industry on rocky ground. There is a military market for satellites. High bandwidth does not address what the [military's] "warfighter" needs. The military was going to rely on the commercial satellites. They need high bandwidth, point-to-point access, anywhere on the globe from day to day.	♦ **Concerned** – **Industry over-capacity** – **Bleak investment outlook** – **Commercial market errors** – **Military market potential**

Responses to Question 1 continue on next page.

Question 1: Business: Economic Viability	Does the satellite industry believe that the current "build, launch, operate and replace (BLOR)" business model is satisfactory, sufficient and efficient, and should remain in place for the foreseeable future?

Responses of 6 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee T: Probably. I don't think so. There seems to be a lack of conviction about what it is that we want to – DoD and NASA. I think there is inefficient use of resources. I don't know what to attribute that to. NASA has gone through with the ISS, DoD, with the Cold War over, has a new Terrorist force, Dessert Storm. The emphasis has become fast response focused. There is a lot we need to make up our minds [about]. Launching is still a very expensive proposition. It's expensive, no matter how you launch. I don't see any major changes in that. I think that there are many things going on to impact that. It seems that the current concept [BLOR] is what we will see for a while. I'm not optimistic about the order of magnitude reduction in cost to $1000/lb access to space. I think we need to have these goals. If we get halfway there that's great. SLI is behind the right things for manned systems, safety, etc.	♦ **Negative** – **Government indecisiveness** – **New, military organizing principles raise concerns** – **Launch technology goals concerns** – **Safety emphasis acceptable**
Interviewee U: The satellite life is growing. That's saving money. The user doesn't want to pay before the satellite is on-orbit (for IRR considerations). The launch vehicle is 5% of the cost of the system. We [the U.S.] moved all payloads to shuttle back in the 1980s. When shuttle exploded, we moved back to ELVs. In the early 1990s we [our company] made a $100 million investment in Athena. Commercial satellites are [an] impressive business case – [but there is] not enough market to support that. Commercial launch vehicles are not in equilibrium – [the] commercial satellite user is beyond market. NASA needs to figure out how big a vehicle they want to fly. They have been keeping the Delta healthy.	♦ **Concerned** – **Commercial market uncertain** – **Government action suggested** – **Competitive concerns** – **Fairness concerns**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: No confidence in long-term viability of current business model: Chronic over-capacity; Launch and insurance costs; Negative investment/market image; Government stagnation.

Question 2: Business: International Environment	To what extent are other governments providing support to their satellite industry (score 1 to 5, 1-not at all, 5-a great deal)? a. Europe b. Japan c. Russia d. China e. Other (Identify)
Responses of 3 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee S: The Europeans (rating=5) are heavily subsidizing there satellite industry. They are followed by the Chinese (rating=4). I suspect that although there is no visibility into their system to confirm this. The Japanese (rating=3) are less inclined as it would appear. We just sold them launchers. The Russians have no money to support their industry.	♦ **Concerned** – **European practices worrisome** – **Comparable U.S. Government action desired**
Interviewee T: Both European and Chinese (rating=5) governments appear to heavily support or subsidize their respective satellite industries. Russia (rating=4) is also a practicioner, and Japan (rating=3) to a lesser degree. With respect to Europe, we have there participation in many jobs, e.g., ISS, however, when we try to market products to them, e.g., commercial satellite imaging, [it has been difficult].	♦ **Concerned** – **European and Chinese practices worrisome** – **Comparable U.S. Government action desired**
Interviewee U: The Russians and Chinese (rating=5). The Europeans (rating=4). Perception means a lot. U.S. industry has the perception that Europe subsidizes (e.g., SPOT Image). Way back when, all [U.S.] satellite companies built airlines. Now it's only two: Boeing and Airbus. Japan (rating=3). In the "Other" category, India (rating=5) will probably lean toward commercial.	♦ **Concerned** – **Russian and Chinese practices noted** – **Comparable U.S. Government action desired**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: European and Chinese industries gaining significant advantage through government subsidies.

Question 3:
Business: Challenges

To what extent do the following factors drive decisions on satellite design and evolution (Score 1 to 5, 1-not important at all, 5- extremely important)?

a. Reducing spacecraft cost
b. Extending spacecraft life
c. Reducing risk of spacecraft failure
d. Improving spacecraft performance/capabilities
e. Strategic business plans/motivations
f. Responding to competitors actions

Responses of 3 Industry/Government/Academia Executives & Program Managers	Response Characterization, Interpretation & Summary
Interviewee S: Reducing spacecraft cost and strategic business plans/motivations (both ratings=5). Extending spacecraft life, reducing risk of spacecraft failure, improving spacecraft performance/capabilities, and responding to competitors actions (all three are rating =4). Strategic business plans/motivations is the most important. Extending spacecraft life is a cost issue and trade study (cost vs. value equation, etc.). Reducing risk of spacecraft failure is related to reducing spacecraft cost and extending spacecraft life.	♦ **Encouraging** – **Reducing spacecraft cost** – **Strategic business plans/motivations**
Interviewee T: Reducing spacecraft cost, improving spacecraft performance/capabilities, and Strategic business plans/motivations (all three are rating=5). Reducing risk of spacecraft failure (rating=4). Extending spacecraft life (rating=3). Responding to competitors' actions (rating=2). Reducing spacecraft cost is paramount. Improving spacecraft performance/capabilities is almost a given. Strategic business plans/motivations are important to commercial and government interests. Companies are in business to make money. Reducing risk of spacecraft failure is high on the list. We're pretty conservative. There is good aversion to risk in DoD and NASA since most systems are "one shot." From the commercial standpoint also, if you launch a "rock," that's bad news. In responding to competitors' actions, I think there is the commercial focus on time to market. DoD and NASA remain strong influences driving competition. For example, if a contract competition is lost, it is very rare that any company would continue the development of a competing system outside of a contract.	♦ **Encouraging** – **Reducing spacecraft cost** – **Improving spacecraft performance/capabilities** – **Strategic business plans/motivations**

Responses to Question 3 continue on next page.

Question 3: To what extent do the following factors drive decisions on satellite design & evolution (Score 1 to 5, 1-not important at all, 5- extremely important)?

Business: Challenges

a. Reducing spacecraft cost
b. Extending spacecraft life
c. Reducing risk of spacecraft failure
d. Improving spacecraft performance/capabilities
e. Strategic business plans/motivations
f. Responding to competitors actions

Responses of 3 Industry/Government/Academia Executives & Program Managers (cont.)	Response Characterization, Interpretation & Summary
Interviewee U: Reducing spacecraft cost and strategic business plans/motivations (rating=5) – you have to be able to predict when your satellite will fail in order to know when to order a new one. Responding to competitors actions (rating=4). Reducing risk of spacecraft failure (rating=2) – because commercial industry is insured and they don't build one-of-a-kind systems, paying for an estimated 2% reliability is not [attractive]. Basically, if it doesn't affect the business case, it's not important. Extending spacecraft life is related to cost. Improving spacecraft performance/capabilities (rating=5 if it fits the business case; rating=0 if it doesn't).	♦ **Encouraging** – **Reducing spacecraft cost** – **Strategic business plans/motivations**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Key Drivers: Reducing spacecraft cost: Strategic business plans/motivations.

Question 4: Business: Challenges	Apart from lowering the cost per kilogram to orbit, have satellite owners/operators identified any other major obstacles to growth that are beyond the industry's risk threshold?
Responses of 2 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: Cost itself [constitutes an obstacle]. Availability of launch vehicles that could launch bigger satellites [is also an obstacle]. Operators are forced to use new technology because launch vehicles can't launch bigger satellites. New technology puts a risk to operator.	♦ **Concerned** – **Cost** – **Launchers limit satellite growth** – **Forced to increase satellite capability with risky technology**
Interviewee R: There are specific tasks [technologies] that could be used to increase capabilities or extend life: transportation, power processors, TWTs, power supply, station keeping propellant, electric propulsion for station keeping. Arguably, Boeing has adapted new technologies like new solar concentrators. They have experienced short-comings in the power conditioning systems. In an environment where you can't service, you have to be risk averse.	♦ **Encouraging** – **Technology can increase capabilities** – **If you can't service, you can't take risks**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Cost and launcher payload size limitations: Forces premature application of new technologies; Increased risk of satellite failure.

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Question 5: Business: Vision	Have satellite owners/operators/manufacturers formulated a collective vision of their industry's future growth prospects?
Responses of 6 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: No vision. It's the market and some prediction that's driving the industry. They are just looking for the opportunities. At satellite 2001/2, no one is talking about 10 years away.	♦ **Negative** – **No vision driving industry** – **No one looking out 10 years**
Interviewee Q: No. If the satellite industry were still in existence in 10 years it would be good. The question is, how robust will it be in 10 years. The competition between [terrestrial] fiber and satellites will always remain.	♦ **Negative** – **Possible industry extinction in 10 years** – **Fiber competition perpetuating**
Interviewee R: I don't think so. I don't think they are looking at anything but selling the next satellite. Back in the 1970s, people talked about setting up "satellite farms." Iridium failed because of an old approach. There is utility in building power, utilities and payload elements, and make it maintainable.	♦ **Negative** – **Industry too near-term focused** – **LEO investment failed due to old approach**

Responses to Question 5 continue on next page.

Question 5 (rephrased): Business: Vision	What is your vision of the commercial satellite industry's future growth prospects, and, do others share it?
Responses of 6 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee S: I think that my view and that of the industry is consistent in that we're going to see flat growth for the foreseeable future. The reasons are two-fold: [Firstly], the limiting consideration for space is bandwidth. I don't think anybody saw the fiber explosion [coming]. So for the foreseeable future (5-10 years), it's extremely difficult to see what sorts of opportunities will emerge that could compete with fiber for bandwidth. {Secondly], the fact of the matter is that you can get long-distance telephone for 34 ¢/minute. The fiber advantage is also that you do not have the "long delay." Unfortunately for satellites, the fiber guys got there first (with respect to financing, etc.)	♦ **Negative** – **Flat growth outlook** – **Fiber explosion unforeseen** – **Difficult to see survival path** – **Fiber absorbed the financing**
Interviewee T: It seems like it's separated, but probably tied to the whole "dot.com" boom and bust. I think that there are some efforts that have been tried where there was no market – e.g., Iridium, Teledesic, etc.). There were some successful systems up there from a Defense, U.S. government standpoint. We are very reliant on these systems. Government generates that because we have adversaries. This appears stable. I think so [it is shared by others]. Your comment about LMC leaving global communications is an opinion about how we [at LMCO] see things today. It seems that the market has flattened out.	♦ **Negative** – **Commercial market didn't exist** – **Government systems successful** – **Commercial market flat**
Interviewee U: The outlook is good, but [the market] probably won't be growing as fast. Direct broadcast TV satellites have a lot of capacity. "Joe Sixpack" wants to go into Wal-mart, buy a television [with a built-in satellite receiver], plug it in and get satellite TV. In order to do that, you need more powerful satellites. The Internet is another underbooked area. There will always be a need for a space-based capability – an opportunity for a better solution to certain requirements. For example, sending large airlines to small cities has proved expensive and uneconomical. The same is perhaps true for fiber. This is why satellites will continue to have a role (in the rural market, schools, Indian reservations, etc.).	♦ **Positive** – **Outlook good, market growth slow** – **Need for space-based solution will always exist** – **Fiber will reach its limits**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Industry currently has no collective vision: Unable to discern growth-path; Survivalist instinct due to recent and severe, multi-billion dollar investment and competitive failures.

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Question 6:

Business:
Technology Life-cycle

At what age does a functioning satellite generally become technologically obsolete and what is the significance of this state from:

a. A primary owner/operator standpoint?

b. An aftermarket owner/operator standpoint?

c. A manufacturer standpoint?

Responses of 4 Industry/Government/Academia Executives & Program Managers	Response Characterization, Interpretation & Summary
Interviewee R: Obsolescence for the primary owner occurs around 10 to 12 years. From an aftermarket owner standpoint, you probably aren't concerned about obsolescence. You are probably more concerned about how long it will last. From a manufacturer's standpoint it would be about 5 years before significantly increased transponder capabilities are achieved (and put on the market).	♦ **Positive** – **12-year primary life** – **New model in 5 years** – **Aftermarket concept acceptable**
Interviewee S: Five to ten years is the typical on-orbit lifetime.	♦ **Positive** – **10-year primary life**
Interviewee T: From a primary owner standpoint obsolescence occurs around 10 years. From an aftermarket owner standpoint it is roughly 5 years beyond sale – this may be approaching EOL. From a manufacturer standpoint it's about 5 years.	♦ **Positive** – **12-year primary life** – **New model in 5 years** – **Aftermarket concept acceptable**
Interviewee U: Primary owner obsolescence occurs around 7 years, or the 7 to 10 year point, if there is a resale market. From a manufacturer standpoint it takes about 3 years to come up with a new model.	♦ **Positive** – **10-year primary life** – **New model in 5 years** a. **Aftermarket concept acceptEncouraging**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Owner- 7 to 12 years; Manufacturer- 3 to 5 years; Potentially viable aftermarket.

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Question 7: Technology: Competitive Needs	Name five specific spacecraft/satellite technology advancements, which if brought into service within the next 10 to 15 years, would provide a significant competitive advantage for the U.S. satellite industry?
Responses of 3 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee S: ♦ Higher power ♦ Higher bandwidth ♦ Lower launch cost ♦ Lower operational cost ♦ Improved lifetime	♦ **Positive**
Interviewee T: ♦ Laser communications (optical). Anything that improves bandwidth. ♦ Single stage to orbit – launch side. This will certainly cut down on launch cost and help reduce time to market. ♦ Electronic wiring. Battery technology keeps improving. I'm not sure about nuclear. Electronics keeps shrinking. ♦ Silicon is almost gone. We are now up to triple junction GaAS. ♦ Communications between assets in space and to the ground are important.	♦ **Positive**
Interviewee U: ♦ Electric Propulsion – significant advantage in fuel, lower mass, therefore more mass for transponders. ♦ Single event upsets ♦ Nuclear [power] at GEO	♦ **Positive**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Higher power (Nuclear, Adv. Solar Cells & Batteries); Higher bandwidth (Laser/Optical); Lower launch cost; Lower operational cost; Improved lifetime (Electronics, E-Propulsion).

B14

Question 8: Technology: Trends

Is satellite manufacturing (for GEOsats in particular) moving towards standardization? If not what is preventing the industry from moving in that direction?

Responses of 4 Industry/Government/Academia Executives & Program Managers	Response Characterization, Interpretation & Summary
Interviewee R: I suspect it is moving toward standardization. You see Boeing moving to standard buses because it is cost-effective. Certainly you [can] have a buyer specifying. Electronics for launch vehicles is always custom. I think you are seeing steps to more economies of scale, but I think there is a large part of the market (a long history) that you optimize the design to meet the specific case. Every satellite [today] is custom built. This tends to keep the cost high.	♦ **Positive** – **Better economies of scale** – **Standard buses cost-effective** – **Customization keeps costs high** – **Electronics always custom**
Interviewee S: It is. We're in negotiations with Loral. It's moving towards more common systems. We currently have the same vendors for star trackers, etc. However, further consolidation is inevitable (globally) because of the overcapacity.	♦ **Positive** – **Moving to common systems** – **Vendor consolidation afoot** – **Consolidation inevitable**
Interviewee T: I think there is an attempt at certain component levels – electronics, battery, etc. Once you get beyond that it's all custom. Seems like it's more appropriate to do a fast design/development than to reuse or standardize.	♦ **Concerned** – **Component level activity** – **Fast custom design more appropriate**
Interviewee U: Perhaps, in terms of JIT, modularity, etc. However, there are business case barriers. There isn't a [high enough] rate to justify with a business model.	♦ **Hesitant** – **Business case barriers** – **Insufficient rate to justify**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: Early-stage standardization at component level; Customization of certain electronics and payload components resist trend; Acceleration depends on new business paradigm.

Question 9: Technology: Challenges	Have satellite owners/operators/manufacturers identified any other major technological obstacles to growth that are beyond the industry's risk threshold?
Responses of 2 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee S: We didn't have a problem with capital when we thought there was a business. We only have a problem now. Here I'd say "launch" again. Building and launching is risky. This is where most of the insurance cost lies. Building launchers is very capital intensive.	♦ **Hesitant** – **Problems attracting capital** – **Launching has riskier image**
Interviewee T: A lot of systems had to stretch the risk threshold. I guess higher levels of autonomy. We're used to having a lot of human intervention to operate systems. Lots of people in rooms – that costs money. But we've learned that that's safe. Trusting your system to do more by itself is a leap. However, considering orbital express, etc., there is a definite push in that direction (DARPA, AFRL, SLI)	♦ **Encouraging** – **People cost money, increase safety** – **Autonomous systems are on the rise**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: Risky, capital-intensive image of launch; Need for higher levels of autonomy - Reduction of operating cost without compromising safety.

B16

Question 10: Technology: Application	How effectively do the needs or performance requirements of satellite owners/operators drive the evolution of satellites? (do they just restrict their systems to current technology?)
Responses of 2 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee Q: It's all about cost. If a compelling case can be made, then investment is generally made by manufacturers - e.g., the first Ka-band satellite launch is 2004. It's also about risk. When satellite operators thought they would get more from tripple junction Gallium Arsenide (GaAs) solar array cells they went for it. The business case was made. They have gotten burnt with the application of several new technologies (antenna unfurling, reaction wheels, etc.)	♦ **Encouraging** – **Investments generally made by manufacturers** – **Strong business case needed** – **New technologies applied cautiously**
Interviewee R: I'm not an expert, but, the community tends to be highly risk averse. All they are looking for is evolutionary improvements on prior systems.	♦ **Concerned** – **Industry highly risk averse**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Owners/operators risk averse; Adopt new technologies if - technological risk minimized, performance benefits clear.

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Question 11: Government: NASA Roles & Responsibilities	What could NASA be doing to help the satellite industry achieve greater levels of market/economic performance in the future?
Responses of 5 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee Q: NASA should address the launch capacity issue. In addition, the agency should establish a viable lasercom/optical communications program, given that the gain difference between radio and optics is about four orders of magnitude. (First use will probably be military.) The agency also needs to do something to replace TDRS. NASA doesn't have a space-based tracking system. The TDRS system is a waypoint in orbit to relay signals from deep space to Earth. TDRS will expire in 10 years; What will replace it? In the area of spectrum, there are bands that are restricted. Most of the categorizations are unnecessary. NASA builds its satellites for a different band than commercial; commercial equipment is built for commercial bands. [this should be changed].	♦ **Encouraging** – **Establish lasercom/optical communications program** – **Consider TDRS replacement** – **Help eliminate unnecessary categorization of spectrum bands**
Interviewee R: To a certain extent, some of NASA should do things that are high risk, high pay-off, when no one can make a business case. NASA should invest in (or lead the way in) a servicing capability. NASA is not good at developing infrastructure that is generally applicable to commercial investment. NASA is good at developing generic capabilities (e.g., low cost access to space). NASA is good at developing and putting [such capabilities] into the public domain.	♦ **Encouraging** – **Focus on high risk and high payoff investments where no business case exists** – **Develop infrastructure with commercial potential**

Responses to Question 11 continue on next page.

Question 11: Government: NASA Roles & Responsibilities	What could NASA be doing to help the U.S. satellite industry grow and achieve greater levels of market/economic performance in the future?
Responses of 5 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee S: Launch vehicles are critical. That is a substantial portion of the cost. The whole industry is based fundamentally on an ability to get assets into space. The rocket "Atlas," "Delta," etc., were military assets that were converted to commercial use by NASA. That's the road. When NASA went off with the Shuttle they broke that – i.e., the [linkage] between military, commercial and civil. We need to have a very reliable low cost national launcher. We can't support a multitude of small launchers. We need the Atlas and Delta subsidized more heavily than they currently are.	♦ **Concerned** – **Serve as commercial transition agent for common military systems** – **Increase Atlas /Delta subsidy** – **Develop one reliable launcher**
Interviewee T: [Help is] currently [needed] in the launch area. Manned systems are especially hard to work with as they drive costs. We have a lengthy process to work through Safety Review Boards to make sure that we don't harm the safety of the astronauts. That requires a lot of analysis.	♦ **Concerned** – **Address cost drivers related human systems**
Interviewee U: Provide stability by reducing ups and downs. NASA developed Ka-band technology with ACTS. NASA should invest in high risk/return technologies (similar to a Hughes or former Bell Labs model).	♦ **Encouraging** – **Stabilize investment cycle** – **Invest in high risk technologies**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: Invest in high risk, high payoff systems and technologies: Establish laser/optical communications program; Eliminate categorization of spectrum bands; Initiate development of TDRS replacement; Develop infrastructure with commercial potential; Develop one reliable launcher for the future - while supporting current Atlas/Delta launch systems; Serve as military-DARPA/commercial transition agent; Address cost drivers for human systems.

Question 12 On-orbit Infrastructure: Future Commonality	Considering the potential benefits of satellite servicing, the satellite industry's growth needs, and NASA's long-range exploration goals, what might be the common infrastructure needs between these two entities over the next 15 years?
Responses of 3 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee S: Considering that the military is going to do satellite servicing, what could NASA do to "piggy-back" to make satellite servicing commercially viable. XSS-U rendezvous and docking with other satellites – that's the capability you need to service. We're leveraging this for NASA's Mars sample return and rendezvous mission.	♦ Positive – **Piggy-back on military satellite servicing investments to make commercially viable** – **Broaden market for rendezvous and docking technology**
Interviewee T: Certainly, you've got to get some standards. From an infrastructure standpoint, you've got to begin with servicing in mind, and get it designed into the missions – Launch capability, robotics, infrastructure to keep spare parts or upgraded components that meet the interface requirements.	♦ **Encouraging** – **Establish standards** – **Build future infrastructure with servicing in mind**
Interviewee U: Somehow you've got to develop the case. There are two issues: (1) repairing on-orbit at BOL, and (2) repairing on-orbit at EOL. For early failures, you'd definitely want to go up there. This is where the value of the satellite is much larger than [cost] of servicing. NASA should also consider building a road to mega-satellites. This would avoid the multitude of satellites at any [shareable] location in GEO. Multiple clients could plug in their respective capability/service.	♦ **Encouraging** – **Develop the case for BOL/EOL servicing** – **Develop "sharable" mega-satellites for use at GEO**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: A civil-commercial servicing infrastructure - piggy-backed on Military-DARPA investment; A market for rendezvous and docking technology through establishment of standards.

B20

Question 13: On-orbit Infrastructure: Future Commonality	Given NASA's desire to build a stepping-stone to Lunar/Martian settlement within the next 30 to 50 years, and given the satellite industry's future market/growth interests, what do you think may be the common infrastructure needs over the next 15 years?
Responses of 2 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee Q: What will we do to follow TDRS. There will have to be an infrastructure to support space missions. Having a space-based relay infrastructure whether Defense, NASA, or Commercial [in origin], will be invaluable.	♦ **Positive** – **Establishment of a space-based relay infrastructure will be invaluable**
Interviewee R: I support this in areas of transportation, operations, servicing, etc. however, there is really a basic incompatibility between a long-range vision of 20-30 years and a mind-set that focuses on the next quarter.	♦ **Concerned** – **Transportation and servicing** – **Concerned about long-range vs. short-range incompatibility**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: An integrated civil, commercial, military, space-based relay infrastructure, in addition to transportation and servicing.

B21

Question 14:
On-orbit Infrastructure: Roles & Responsibilities

What should the roles and responsibilities of each of the following entities be in the establishment of a potential, future, on-orbit, [commercial] satellite servicing infrastructure?

a. NASA
b. The U.S. Satellite Industry
c. Other U.S. Government Agencies
d. Other Countries or Regional Economic Blocks

Responses of 6 Industry/Government/Academia Executives & Program Managers	Response Characterization, Interpretation & Summary
Interviewee P: Private industry does not have the resources (manpower or dollars) to do this sort of thing. NASA should therefore take the lead. NASA can probably work with ESA or NASDA like the Space Station model. Industry executives are looking at the next quarter. Government will have to invest by itself initially until industry sees a need or market.	♦ Concerned – Industry lacks resources – NASA should take lead – Explore international arrangements – Government invests initially until market is visible
Interviewee R: NASA's role should be to support research and advance technologies. It should also conduct flight experiments because no one else will do that. The U.S. satellite industry should seriously incorporate servicing so that it eventually provides a market for a commercial servicer. With respect to other government agencies, I'm not too big on DoD. Anything that could service satellites can service DoD satellites. It's also critical that the State Department get out of the way of [i.e., removes any unnecessary] ITAR/export controls. If the U.S. does not establish commercial servicing someone else will do it.	♦ Encouraging – NASA supports R&D – Industry adopts servicing and develops servicer market – Regulatory agencies should step back – Another country will take the commercial servicing market if we don't

Responses to Question 14 continue on next page.

Question 14: On-orbit Infrastructure: Roles & Responsibility	What should the roles and responsibilities of each of the following entities be in the establishment of a potential, future, on-orbit, [commercial] satellite servicing infrastructure? a. NASA? b. The U.S. Satellite Industry? c. Other U.S. Government Entities? d. Other Countries or Regional Economic Blocks?
Responses of 6 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee S: (a) NASA could provide a storage depot for components. Needed parts use transportation to the depot on a marginal cost basis (i.e., vehicles going anyway would have extra items added [to their manifests- at no fractional cost by weight. NASA would provide an OTV to get to destination – autonomous transfer vehicles. The interfaces could be designed by working with industry. (b) The satellite industry could pay the marginal costs. If customers wanted to buy capability, they would buy a satellite that was serviceable (but at a high cost). (c) Other government agencies could participate with NASA to fund some of the infrastructure. For example DARPA/Orbital Express, and AFRL/XSS. Someone could fund the OTV. NASA could buy a second XSS and help get rid of the recurring cost. Instead of partnering, we could create a market and buy [or retrofit] a second XSS [that is already designed for a similar purpose]. (d) To service fringe satellites we would have to change the full cost. Somehow, we would have to give the U.S. an advantage. If we opened it up to everyone, what would produce an advantage for the U.S. We would have the problem of attracting Europe. They are already having trouble supporting Ariane – i.e., too few launches. They wouldn't want to do anything to extend the life of satellites. Japan might. Our whole launch industry is in a very precarious position. Europe is subsidizing Ariane. It must be addressed together, i.e., satellites and launch vehicles. The key problem is that if you had the ability to service satellites, there would be a competitor to new satellites. All you would do is drive the cost down. Everybody is loosing money. In the short-run, nobody will support it, because of overcapacity in satellites and launch vehicles.	♦ **Concerned** – **NASA could provide storage depot for components** – **Industry pays marginal cost to transport of parts** – **Establish joint governmental venture to fund infrastructure** – **Europe would probably view servicing as a threat to Ariane** – **Japan might be interested** – **Servicing will be a competitor with new satellites** – **Nobody will support servicing in the short-run**

Responses to Question 14 continue on next page.

Question 14: On-orbit Infrastructure: Roles & Responsibilities	What should the roles and responsibilities of each of the following entities be in the establishment of a potential, future, on-orbit, [commercial] satellite servicing infrastructure? e. NASA? f. The U.S. Satellite Industry? g. Other U.S. Government Entities? h. Other Countries or Regional Economic Blocks?
Responses of 6 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee T: I'm afraid if you left the commercial people to do it, it won't get done; it hasn't happened yet. If someone thought they could turn a buck, then probably. There tends to be interest from DoD. They tend to play close to the vest though. NASA, from a commercial standpoint, is the logical choice, however the ISS experience does not bode well.	♦ **Encouraging** – **Won't happen if left to commercial industry** – **DoD has a closed interest** – **NASA is the best champion** – **ISS experience raises skepticism**
Interviewee U: I don't think that aerospace contractors are going to put up any money to get this thing going. NASA is going to have to get the ball going. You can rely on the manufacturers to invest in satellite standardization. You can get DoD involved since they would want to have some say in who gets close to their satellites. You probably want foreign participation since you'd want to service their satellites. In addition, there have been (and will probably continue to be) a lot of U.S. satellites exported, so you'd like to be able to service them.	♦ **Encouraging** – **Too risky for industry to initiate investment** – **NASA must get ball rolling** – **Industry will invest in satellite standardization** – **Foreign participation desirable for strategic business objectives**
Interviewee V: NASA should provide a great deal of the risk capital for infrastructure development. The U.S. satellite industry should provide expertise for a fee, to provide technologies and pay usage fees. NASA already has satellite servicing capitalization. Other U.S. government entities should buy-in as partners. The military may however do its structure from the ground up.	♦ **Encouraging** – **NASA provides risk capital** – **Capitalize on existing capabilities** – **Industry provides paid expertise and pays usage fees** – **Other agencies participate as partners**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: NASA - takes lead, provides on-orbit infrastructure and risk capital/support R&D; Industry - invest in standardization, develop servicer market, pay marginal cost to transport parts, pay usage fees; Other U.S.G. Agencies - participate as partners; Other Countries/REAs - seek roles in new industry sector development.

B24

Question 15: On-orbit Infrastructure: Economic Utility	Looking out around the year 2015, would the establishment of an on-orbit, [commercial] satellite servicing infrastructure be of potential high utility to satellite owners or operators?
Responses of 3 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: Yes. Even today we wish we had some capability there already.	♦ **Positive** – **Wish it existed today**
Interviewee R: I certainly think so. I don't think they would, this is because (as we discussed earlier) of their risk averseness. Satellite servicing is a big headache [such] that they would prefer to leave things the same.	♦ **Concerned** – **Personal viewpoint supportive** – **Industry's risk averseness of concern; may prefer status quo**
Interviewee U: In the future we will put people further out (L1, planetary, etc.). At that point the roll of the humans will be to supervise robots. Humans can be used for things other than the purpose for which they were intended.	♦ **Positive** – **Humans and robots will perform servicing in space** – **Humans will supervise robots** – **Humans will perform unanticipated tasks**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Yes - once technological and business risks have been minimized. Government established infrastructure - robots under human supervision; humans provide special services.

B25

Question 16: Satellite Servicing: Business Potential	At approximately what fraction of total asset value might satellite servicing be cost attractive to the satellite owners or operators?
Responses of 6 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: There are three main things a satellite operator might consider: Schedule: How soon can the repair equipment be there. How soon can some replacement satellite be built and sent there. Cost: If it costs more [to do servicing] than launching a new satellite, then it's probably not a good idea. Additionally, if cost exceeds the expected revenue stream after repair, then there is no benefit. Condition: How long a life or what is the condition of the existing satellite. If it's old and run down, why fix it? If the mission can be shared then cost will come down. If they were designed for servicing, cost will also come down.	♦ **Encouraging** – **Servicing must be much faster than replacing** – **Servicing must be cheaper than replacing** – **Servicing may be maximally beneficial near BOL** – **Shared servicing missions reduce costs** – **Designing for servicing for reduces costs**
Interviewee R: The reliability of servicing efficiency accompanying servicing of a functioning spacecraft affects the cost. Satellite servicing might be attractive at around one quarter to one third the total asset value. This would be enough to make it reasonable, but low enough to make it a significant benefit over replacement.	♦ **Encouraging** – **25 to 35%** – **Reliability of servicing affects the cost**
Interviewee S: It's a time value thing. There are two considerations here. Firstly, if you had a satellite and it is launched to orbit, and it failed at BOL, then servicing might pay about 50 to 60% to fix it. This would probably not be reasonable in 5 years, at about 50 to 75% of the remaining economic life. The other thing is that the cost of satellites is coming down. So at any time, depending on how much useful life, one would have to look at the current cost of replacement. This would determine [whether to pay for servicing or not.]	♦ **Encouraging** – **50 to 60% for BOL repair** – **Unreasonable to repair after 5 year old since 50 to 75% of economic life remains** – **Cost of new satellites falling; replacement increasingly competitive**

Responses to Question 16 continue on next page.

Question 16: Satellite Servicing: Business Potential	At approximately what fraction of total asset value might satellite servicing be cost attractive to the satellite owners or operators?
Responses of 6 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee T: Here again, you certainly need to consider launch cost in total asset value. In some cases this would come close to the satellite value. In some cases you could go up to 100%. For example, you have no asset that is lead and you need to get product back. Looking at a servicing mission that could take 3 months, or a replacement that could take 3 years, you might want to take the servicing. In general, I'd say 50%. It's complemented by insurance.	♦ **Encouraging** – **50%** – **Total asset value includes launch cost** – **Servicing wins if it takes 3 months compared to 3 years to build/launch replacement**
Interviewee U: The "total asset" should include launch. If you can persuade the insurer to offer a lower premium for a satellite that is serviceable, then [this prospect might become very attractive.] If the cost of insurance now runs about 20% of the satellite cost, then owners/operators can then invest in a lot of standardization for the 1% or 2% savings in insurance costs [that might come from a serviceable satellite premium reduction.]	♦ **Encouraging** – **Total asset includes launch** – **Lower insurance premiums for serviceability could spur market forward** – **Strong incentives to invest premium savings in standardization**
Interviewee V: If the cost of servicing exceeds the residual cost of the satellite, then servicing is pointless. For large capitalization, as mentioned in a previous question, we replace components (e.g. Hubble). For larger, not small replaceable assets, satellite [servicing may be appropriate]. Another spin on this is if the servicer can reach more than one satellite, the servicer would be less expensive than all of them. There are two planes in space where you have access to many satellites, GEO and the Libration points.	♦ **Encouraging** – **Servicing cost cannot exceed a satellite's residual cost** – **Servicing is most cost-effective at GEO and Libration points**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Between 25% and 60% of total asset value, which includes launch cost - fraction tends to the high end of range depending on proximity to BOL and particular servicing objective.

Question 17: Satellite Servicing: Business Potential	What approximate increased premium might satellite owners/operators pay satellite manufacturers for a “serviceable” satellite if this option were available in the future?
Responses of 4 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee R: An operator will not pay for serviceability (i.e., one that is fixed if it failed) if they can buy one that will work. Servicing would have to be paid back by insurance. A buyer will not be willing to pay a premium unless there is insurance. There needs to be some financial benefit, that is, tax breaks or insurance breaks.	♦ **Concerned** – **Operators will not pay to fix if without insurance backing** – **Tax or insurance incentives are needed to help introduce servicing**
Interviewee T: Economics would say that if you were going to double the life you’d double the cost, or double the cost and double the life.	♦ **Concerned**
Interviewee U: They’re probably not interested in paying any more. If you could get one manufacturer and one insurer (as discussed earlier) to do it, then others might follow. [In other words] you must have a partnership between a manufacturer and an insurer. This would allow owners/operators/manufacturers to invest in serviceability, sell product/services in the marketplace, and recoup gain a return on investment.	♦ **Encouraging** – **Industry not interested in paying more** – **Strategy: Get an insurance and a manufacturer market leader to set the example**
Interviewee V: If commercial teams want to build giant communications farms for sports television, for example, why would NASA need it? On the other hand, if it’s about space internet from Mars, then NASA would be interested. Commercial and military satellites are basically “down-lookers,” whereas, NASA satellites are basically “up-lookers.” If it’s in the public interest, then NASA might invest first.	♦ **Encouraging** – **Commercial and Government objectives must be harmonized** – **Up-looker and down-looker satellite may have different needs**

Alignment of Responses	☒ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: None - not unless insurers or government provided serious incentives in terms of insurance or tax breaks. A partnership between a leading manufacturer and an insurer in this vein might attract industry followers.

Question 18: Satellite Servicing: Industry Needs	Is robotic or human satellite servicing a capability that the satellite operators and manufacturers would like to see developed and economically maximized?
Responses of 5 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee Q: We're not against it, but right now it's not of value. The immediate focus should be on improving the [efficiency and effectiveness] of the three key satellite performance areas: i.e., transportation/launch, etc., payload, and bus.	♦ **Encouraging** – **May be valuable in the future** – **At present, we need to improve satellite launch, payload and bus performance parameters**
Interviewee R: Maybe, but mostly no. I suspect that if you were a satellite provider you would make satellite servicing expand your capability, enabling you to recover [costs]. But satellite servicing puts a stress in your organization. It adds weight to your system. A manufacturer or owner would like servicing to be an option early (i.e., near BOL), but if you are a manufacturer, you don't want servicing near EOL because it cuts into your business. Basically, insurers and manufacturers would like to keep the status quo, operators pay, one way or the other. Unlike autos, the definition of good service is to make a satellite that works right out of the box and is highly reliable (TRW priced itself out of the market using this approach). One of the biggest costs is the cost of insurance. One of the ways to drive satellite servicing is for insurers [to say] we'll cut your price if you are serviceable. Most economic analyses looking back to SEI assume the existence of the FTS. One of the orbital parameters is the mass difference between servicer and spacecraft. There is not and will never be an economic case for servicing. There will be not economic case unless you can advance technology and the government steps in and pays for non-recurring costs. Government will probably have to assume the role of "anchor tenant," like it did to support establishment of the "Airmail" system.	♦ **Concerned** – **Servicing adds weight** – **Servicing would stress present industry organizations** – **Insurers/manufacturers would like to preserve status quo** – **Servicing is only desirable at or near BOL** – **There will never be an economic case for satellite servicing** – **Government must pay the development or non-recurring costs** – **Government must also be the market trigger, like earlier examples**

Responses to Question 18 continue on next page.

Question 18: Satellite Servicing: Industry Needs	Is robotic or human satellite servicing a capability that the satellite operators and manufacturers would like to see developed and economically maximized?

Responses of 5 Industry/Government/Academia Executives & Program Managers (cont.)	Response Characterization, Interpretation & Summary
Interviewee S: Absolutely, if we didn't have to pay for it. You'd probably have to design satellites for servicing. Somebody may buy the cheaper satellites if the servicing were available. The customer wants the lowest cost for the same reliability. The insurance industry has a different view. If they were willing to lower their rates, if servicing were available, they may be willing to pay for it if needed.	♦ **Encouraging** – **Industry can't afford it** – **Satellites must be designed for servicing** – **Customers want lowest cost for same reliability** – **Insurers must lower rates for serviceability option**
Interviewee T: I don't know. I'm not a big fan of it. Part of it goes back to the earlier questions on standardization and obsolescence. When I think of what I would want to fix when I service it, most of the time my payload is what I want to fix. It may be that it's more cost-effective to launch a next-generation payload. In general payloads don't lend themselves to standardization – they're generally unique. Could you get them? Maybe, but [you] have to start early. You'd probably get a lot of "push-back" [resistance].	♦ **Negative** – **Payloads offer highest repair value, but are difficult to access** – **Next generation payload may be more cost-effective** – **Payloads are generally unique and not easily amenable to standardization** – **Industry would resist change in this area**
Interviewee U: Satellite manufacturers aren't interested because they don't want to adapt or increase the weight [of their systems]. On the other hand, with over 300 satellites in GEO, it seems that we should have it. In addition, as we consider putting big telescope systems at the Earth-Moon or Earth-Sun Libration points, we will need it. Hubble is a good example. In fact, pick a Hubble servicing mission, and use a dexterous robot with EVA astronauts as back-up. This would start the capability going.	♦ **Encouraging** – **Manufacturers don't want to increase system weights** – **A servicing capability makes sense given all the assets in GEO and potentially at Libration points** – **A tele-robotic demonstration mission should be conducted**

Alignment of Responses	☐ Complementary ■ Varied ☐ Opposite

Aggregate Summary of Responses: Yes - concerns about additional weight impact, payload accessibility/standardization, economic case, and developmental cost: Industry would resist change; Government must trigger market, pay developmental or non-recurring cost; Insurers should provide reduced rates incentives; Servicing most desirable near BOL; Lowest cost for same reliability.

B30

Question 19: Satellite Servicing: Satellite Evolution	How might satellites change to exploit or take advantage of on-orbit servicing, if the price were right?
Responses of 3 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee S: They would need to change their design to make components more accessible. That would increase the price. I do not think that they would use the fact that you had servicing, [and concluded] that they would be less expensive, [albeit] with less reliable parts. You're going to have to sell it or something else. I just don't see how. Building serviceable satellites pushes you the wrong way on the economy of scale. There is enough capacity right now to support 10 times the present number of satellite launches. Overall, it [serviceability] would extend life, but increase cost. The economies of scale would be perennial operations – amortized over the system's life.	♦ Concerned – **Components must be made more accessible** – **In the short-term, extended life, reduced scale economies, increased cost** – **Launch overcapacity creates disincentive**
Interviewee T: Certainly, you would start at the early design stage. You would design in fuel access ports, docking and rendezvous aids, etc. Most things we have now are bolted on to maintain integrity throughout the lifetime. These are tough interfaces. You'd have to look at alternate ways of working that would ease replacement, and that won't impose costs on the system. This is different from the way we do it today. Today most satellites are not designed to facilitate servicing. It gets worse as you get close to payloads. For example, if you design satellites for pictures, there are tight interfaces for attitude control, guidance, navigation, etc. The paradox is that payloads are the high value. Payloads are what you would most want to access, but they are difficult to access.	♦ Encouraging – **Early design of fuel access ports, docking and rendezvous aids** – **Heavy bolting reduced to ease replacement** – **Payloads are desirable but difficult servicing targets**
Interviewee U: You would try to develop standardized interfaces, fasteners, connectors, etc., so you could transfer xenon and hydrazine, etc.	♦ Encouraging – **Development of standard parts**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Components/Interfaces Standardized; Component accessibility increased - heavy bolting reduced; Fuel access ports incorporated; Docking and rendezvous aids incorporated.

B31

Question 20: Satellite Servicing: Market Sectors	If satellite servicing became a reality around 2015, where would the market be? (Explain) a. GEO only b. GEO and MEO only c. GEO, MEO and LEO
Responses of 5 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: GEO only. Not much experience with MEO and LEO. A lot of commercial satellite companies, if their satellite is still working would be interested in extending the life a couple years. This would allow for delays in new satellite manufacture. In other words, you may want to extend the life to match with when the new satellite is delivered. Satellites should be designed for refueling. Also, premature failure after launch (at BOL) should be correctable, if possible.	♦ **Encouraging** – **GEO only** – **Owners may wish to extend life until replacement is delivered** – **Satellites should be designed for refueling** – **BOL failures should be correctable**
Interviewee R: GEO, MEO and LEO. I don't think the underlying physics behind a LEO constellation is bad. Iridium, Globalstar [and others], made mistakes. In addition, there is an incentive to build larger satellites if the launch vehicle exists. The first satellite servicing needed is to capture and dispose of Russian nuclear satellites. They are expected to begin de-orbiting in 10 years. The market penetration model for LEO is unstable. If you make it you drive a large percentage of market quantity. If you don't make it you drive to a zero percent quantity. Commercial satellites will continue to grow and produce greater economies of scale. However, there are a fixed number of GEO slots.	♦ **Encouraging** – **GEO, MEO and LEO** – **Larger satellites will be built if larger launchers exist** – **LEO market for disposal of old Russian nuclear satellites** – **LEO market penetration model unstable** – **Commercial satellites will continue growth and achieve greater scale economies**
Interviewee S: GEO, MEO and LEO. Each is just as likely.	♦ **Encouraging** – **GEO, MEO and LEO, equally**

Responses to Question 20 continue on next page.

Question 20: Satellite Servicing: Market Sectors	If satellite servicing became a reality around 2015, where would the market be? (Explain) d. GEO only e. GEO and MEO only f. GEO, MEO and LEO
Responses of 5 Industry/Government/Academia Executives & Program Managers (cont.)	**Response Characterization, Interpretation & Summary**
Interviewee T: GEO, MEO and LEO. I don't think it depends on where it is. LEO guys need refueling. It is stressful on your bottom-line because you are recycling. I think there is a need. Iridium designed replacement into their system. That's okay, but for high value assets like Hubble, etc., that's not appropriate.	♦ **Encouraging** – **GEO, MEO and LEO** – **LEO guys need refueling too** – **At one extreme, replacement may work for Iridium-types but not for Hubble type systems**
Interviewee V: If capitalization is high, then servicing is attractive. The competition for satellite servicing is replacement cost or throwaways. For GEO, Orbital Express infrastructure is now "pre-designed." For GEO and MEO only, there are launch propulsion and precession problems.	♦ **Encouraging** – **High capitalization attracts servicing** – **Competition is replacement** – **Precession problems** – **Orbital Express pre-designed**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: GEO, MEO and LEO: GEO Market - life extension awaiting replacement; LEO Market - disposal of Russian nuclear satellites; Competition: Replacement - replacement becomes less economical as scale and/or capitalization increases.

Question 21: Satellite Servicing: Market Segments	If robotic satellite servicing were made to exist between 2010 and 2015, which of the following on-orbit, commercial satellite servicing capabilities might be of the most interest (economically) to the satellite owners or operators? Rank/Explain) a. Inspection b. Refuel c. Repair d. Upgrade e. Reboost f. Retrieve g. Other, Please specify/explain
Responses of 6 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: Refuel, Repair, Inspection, and Upgrade, in that order. Retrieval is probably of interest to manufacturers. Owner/operator will treat as space debris. If there is a law to redeem space debris then owner/operator will need retrieval.	♦ **Encouraging** – **Top four: Refuel, Repair, Inspection, and Upgrade**
Interviewee R: [I would put] "dexterous" repair first. This is a most required capability. There is almost no place where a simple repair (plug in and out) would suffice. Next, rendezvous and grapple, for example, to move a spacecraft to a different orbit. If an evolutionary approach, then rendezvous/grapple would be a good first start. If technology were frozen today, there would be a one-to-one weight comparison (~2000 lbs). In 10 years, dexterous servicing technology would be in the 300 lb range.	♦ **Encouraging** – **Dexterous repair, Rendezvous and grapple,** – **Today, a dexterous servicer would weigh about 2000 lbs; In 10 years around 300 lbs**
Interviewee V: Refuel is the top choice, but in this case, the critical question becomes: Did the technology change along the life of refuel? If no, then refuel/upgrade would be the preferred approach.	♦ **Encouraging** – **Refuel, Upgrade**

Responses to Question 21 continue on next page.

Question 21 (rephrased): If satellite servicing were made to exist between 2010 and 2015, which of the following on-orbit, commercial satellite servicing capabilities might be of the most interest (economically) to the satellite owners or operators? (Score 1 to 5, 1-least, 5-most)/Explain)

Satellite Servicing:
Market Segments

e. Inspection
f. Refuel
g. Repair
h. Upgrade
i. Retrieve

f. Maintenance
g. Replacement
h. Rehabilitation
i. Other, Please specify/explain

Responses of 6 Industry/Government/Academia Executives & Program Managers	Response Characterization, Interpretation & Summary
Interviewee S: Repair, Upgrade and Maintenance are the top choices (rating=4). Refuel is next (rating=3), Inspection and Rehabilitation followed (rating=2), and Replacement (rating=1). Retrieval is not a servicing need.	♦ **Encouraging** – **Top four: Upgrade, Maintenance, Refuel, Inspection** – **Retrieval is not needed**
Interviewee T: Repair and Upgrade are the top choices (rating=5). Maintenance/Replacement/Rehabilitation are next (rating=4). Refuel and retrieve are next (rating=3). Inspection (rating=2). In the “Other” category, one can consider “Reboost” if the ELV failed. Another is “Relocation” (rating=5), either due to launch failure or to market requirements (this may fall into “Refueling” category).	♦ **Encouraging** – **Top four: Repair, Upgrade, Maintenance, Replacement** – **Relocation is a potentially viable segment**
Interviewee U: Refuel (if you could do it) and repair (if cost-effective – i.e., versus replace, etc.) are the top choices (rating=5. Upgrade (rating=3), Inspection (rating=2), and Retrieve (rating=1). GEO is a tough place from which to retrieve. You would probably use “burial instead. Burial (or an “undertaker” service) could add a year of lifetime to a satellite by having the satellite remain on station until complete EOL. Considering Maintenance, [this begs] the question: Can you build a better gyro, for example, if it didn’t have to last 15 years? In this case, “better” equals “cost less.”	♦ **Encouraging** – **Top four: Refuel, Repair, Upgrade, Inspection** – **Undertaker or burial servicing; could add a year to EOL** – **Maintenance could reduce system cost**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Top four: Refuel, Upgrade, Repair, Inspection. Additionally: Relocation (GEO), Burial (GEO). Critical Technologies - dexterous repair and rendezvous and grapple.

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Question 22: Satellite Servicing: Key Technology	What would be the best means by which to most effectively (cost and performance-wise) accomplish on-orbit satellite servicing? a. Robots (Fully autonomous) b. Tele-robots (Semi-autonomous – i.e., ISS astronaut/ground controlled robots) c. Astronauts d. Other

Responses of 6 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: To be cost effective, it will be [tele] robots, operated from a [spacecraft] vehicle or on the ground.	♦ **Encouraging** – **Tele-robotics with operator on the ground**
Interviewee R: The choice “tele-robot” and “semi-autonomous” is somewhat simplistic. A more complete description would be a “mixture” of humans and tele-robots.	♦ **Encouraging** – **Tele-robotics with human support on-orbit**
Interviewee S: Tele-robotics is the best means. However, some things can’t be done that way. Some things have to be done by astronauts. You would need to have some tug in orbit to facilitate this. Shuttle launch is inadequate.	♦ **Encouraging** – **Tele-robotics with human back-up on-orbit**
Interviewee T: There are probably pieces of servicing that lend themselves to all of those. As far as my crystal ball, man is probably the best tool we have to do complex servicing. If you designed the system to be serviced fast, robotics is the best system, but that would take a lot of infrastructure.	♦ **Encouraging** – **Tele-robotics with complex servicing performed by humans**
Interviewee U: Tele-robotics is the way to go, with an operator on the ground in mobile/portable ground operations stations transportable to any line-of-sight location around the globe, perhaps working in sets of two teams if it’s a tedious operation.	♦ **Encouraging** – **Tele-robotics with mobile, line-of-sight operator on the ground**
Interviewee V: If it’s in LEO and is highly capitalized and built for serviceability, astronauts or maybe robots will service it. If it’s in GEO and highly capitalized, you would need a tele-robot. If the satellite goes out to distant planets in the solar system, it probably would have built-in serviceability, i.e., it can reconfigure itself, software-wise. In other respects, the human roll will be supervisory, with creative intervention if a robot encounters a problem.	♦ **Encouraging** – **High value LEO assets use humans or robots** – **High value GEO assets use tele-robots** – **Humans supervise robots** – **Humans intervene if robot cannot perform task**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Tele-robotics (Consensus): Scenario Options - ground-based operator, ground-based line-of-sight operator, space-based operator; Human function - operate/supervise, intervene if robot cannot perform task.

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Question 23: Satellite Servicing: Location	Where should satellite servicing be performed for maximum efficiency? (Explain) a. At their orbital stations b. Away from their orbital stations
Responses of 5 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee P: [They should be serviced] at their orbital stations. Commercial satellites have little ability to do large orbit transfers. Stanford University is developing a "survey" satellite. This will be useful because many times we want to see the plane where the thruster fires, antenna deformation from design, and solar array deformation related to design parameters. Also, you may want to look into space debris – a "defensive" service. We pay $0.25 million/year to the Aerospace Corporation to see if there is any debris that may collide with our satellites. Aerospace Corporation takes NORAD data and compares with satellite network, etc. NASA should help improve the accuracy of this database	♦ **Positive** – **Service at orbital stations** – **Inspection capability important** – **Space debris defense needs to be improved**
Interviewee S: [They should be serviced] at their orbital stations. I think if you try to bring a satellite down [it could be problematic]. It depends on the infrastructure you have to put them back out there. If you had a tele-robotic system, then it would be better to service them out there. If you brought them back to LEO, it would take a lot of energy to return them to GEO.	♦ **Encouraging** – **Service at orbital stations** – **Tele-robotic is enabling technology** – **Bringing to LEO is too energy intensive**
Interviewee T: [Servicing should be performed] at the satellite's orbital station. Seems like in terms of at least moving mass around in orbit, the mission vehicle is probably larger.	♦ **Encouraging** – **Service at orbital stations**
Interviewee U: [Servicing should be performed] at their orbital stations. There is enough separation to do this. There should be no interference (FCC/ITU) problems. Line-of-sight communications should be used for smallest time delay.	♦ **Positive** – **Service at orbital stations** – **Shouldn't cause interference** – **Line-of-sight control is best**
Interviewee V: [It] depends on what the customer's objectives are for being there. Basically, you'd want to do it at the customer's [orbital] site.	♦ **Encouraging** – **Depends on customer preference**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: Orbital station (Consensus): Line-of-sight control to minimize GEO-to tele-operator time-delay; Should not interfere (EM/RF) with nearby satellites; Transporting elsewhere, especially LEO, too energy intensive.

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Question 24: Satellite Servicing: Logistics	If satellite servicing became a reality, where would you expect satellite supplies (fuel, replacement parts, etc.) to be stored? (Explain) a. on-orbit b. on the ground (i.e., launched on demand)
Responses of 4 Industry/Government/Academia Executives & Program Managers	**Response Characterization, Interpretation & Summary**
Interviewee R: Fuel you store on-orbit. A very small number of standard parts may also be stored on-orbit. Everything else would probably be launched on demand. Even if you had a servicer on-orbit, you still need a launch-on-demand to launch when needed to provide specific parts needed for the servicing mission.	♦ **Positive** – **Store fuel and standard parts on-orbit** – **Everything else, launch on demand**
Interviewee S: I'd store them on-orbit. There is a threat to launch vehicles. I'd use under-utilized launchers to get them to orbit. In fact, if you don't do that there is no advantage to doing satellite servicing. (That's the way you got a flowering of the airlines, through the government's use of commercial airlines for U.S. mail transport.) When you replace a cryogen, you replace 4% of the satellite. It better only cost 4% to get them there. In another way, If something costs more than 20 to 25% of the cost to fix it, you'd fix it only if it were new (i.e., considering the developmental marginal cost). Satellites are getting so cheap, like a commodity. A bus generally costs around $20 million.	♦ **Concerned** – **Store them on orbit, there is no advantage if you don't** – **Use under-utilized launchers to place on-orbit** – **Cryogen/fuel replacement cost should be in proportion** – **Repair at 20/25% cost if new** – **Satellites costs falling, becoming a commodity**
Interviewee T: Probably a mix of both. Some things might lend themselves to on-orbit [storage] like fuel, and standardized components.	♦ **Positive** – **A mix of both** – **Fuel and standardized components on-orbit**
Interviewee U: "Commodities" should be stored on-orbit. "Special order parts," launched on demand. Basically, you would have a combination of both launch-on-demand and on-orbit storage. A servicer might carry along a few of its basic components, spare fuel, etc., if you break it down into commodities and special order parts.	♦ **Positive** – **Basically both are required** – **Store commodities on-orbit** – **Special order parts, launch on demand** – **Servicer can carry a few basic components**

Alignment of Responses	■ Complementary ☐ Varied ☐ Opposite

Aggregate Summary of Responses: On-orbit: Fuel, other commodity replacement parts - under-utilized launchers could be used for low-cost, depot re-supply missions. Ground: Special order parts.

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

The modern world is extremely dependent on thin strings of several hundred civil, military, and commercial spacecraft/satellites currently stationed in space. They provide a steady stream of commerce, defense, and knowledge data. This dependency will in all likelihood increase significantly during this century. A major disruption of any kind in these essential systems and networks could be socially, economically, and politically catastrophic, on a global scale. The development of a space-based, robotic services economy could be useful in mitigating this growing risk, from an efficiency and security standpoint. This paper attempts to suggest what makes sense to invest in next for the logical, economic development of Earth orbit—i.e., after ISS completion. It expands on the results of an advanced market research and analysis study that sampled the opinions of several satellite industry executives and presents these results within a broad policy context. The concept of a “spacecraft carrier” that serves as the nucleus of a national, space-based or on-orbit, robotic services infrastructure is introduced as the next logical step for United States leadership in space. This is viewed as a reasonable and appropriate follow-on to the development of ELVs and satellites in the 1950s and 1960s, the Space Shuttle/RLV in the 1970s and 1980s, and the International Space Station (ISS) in the 1980s, 1990s and 2000s. Large-scale experience in LEO-to-GEO spacecraft/satellite servicing and protection by robotic means is assumed to be an indispensable prerequisite or “stepping-stone” toward the development and preservation of the large scientific exploration facilities that are envisioned by NASA for operation beyond GEO. A balanced, return on national investment (RONI) strategy for space, focused on the provision of enhanced national/homeland security for increased protection, national economic/industrial expansion for increased revenue, and national scientific exploration for increased knowledge is recommended as the next strong, irrepressible goal toward realizing and achieving the official NASA vision and mission.

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