AN INTEGRATED MISSION PLANNING
APPROACH FOR THE SPACE EXPLORATION
INITIATIVE

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AN INTEGRATED MISSION PLANNING APPROACH FOR THE SPACE EXPLORATION INITIATIVE

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Abstract

A fully integrated energy-based approach to mission planning is needed if the Space Exploration Initiative (SEI) is to succeed. Such an approach would reduce the number of new systems and technologies requiring development. The resultant horizontal commonality of systems and hardware would reduce the direct economic impact of SEI and provide an economic benefit by greatly enhancing our international technical competitiveness through technology spin-offs and through the resulting early return on investment. Integrated planning and close interagency cooperation must occur if the SEI is to achieve its goal of expanding the human presence into the solar system and be an affordable endeavor. An energy-based mission planning approach gives each mission planner the needed power, yet preserves the individuality of mission requirements and objectives while reducing the concessions mission planners must make. This approach may even expand the mission options available and enhance mission activities.

INTRODUCTION

The direction of the American space program, as defined by President Bush, is to expand human presence into the solar system. Landing an American on Mars by the 50th anniversary of the Apollo 11 Lunar landing is the goal. This challenge has produced a level of excitement among young Americans not seen for nearly three decades. The exploration and settlement of the space frontier will occupy the creative thoughts and energies of generations of Americans well into the next century. The return of Americans to the moon and beyond must be viewed as a national effort with strong public support if it is to become a reality. Key to making this an actuality is the mission approach selected. Developing a permanent presence in space requires a continual stepping outward from Earth in a logical progressive manner. If we seriously plan to go and to stay, then not only must we plan what we are to do and how we are to do it, we must address the logistic support infrastructure that will allow us to stay there once we arrive.

A fully integrated approach to mission planning is needed if the Space Exploration Initiative (SEI) is to be successful. Only in this way can a permanent human presence in space be sustained. If SEI is to be affordable and acceptable, careful consideration must be given to such things as "return on investment" and "commercial product potential" of the technologies developed. An integrated power and propulsion infrastructure based on energy would reduce the number of new systems and technologies requiring development. The resultant horizontal commonality of systems and hardware would reduce the direct economic impact of SEI, while an early return on investment through technology spin-offs would be an economic benefit by greatly enhancing our international technical competitiveness. Such an approach will help win congressional support, help to secure financial backing, and ensure that human expansion into the solar system becomes a reality.

ENERGY TRANSMISSION

Space initiatives range from the development and exploitation of near-Earth space to missions to the outermost planets. The National Aeronautics and Space Administration's (NASA) mission to planet Earth will use orbiting satellites to collect data on planetary conditions in support of studies of global climate change.

The Department of Defense (DOD) plans to increase its number of surveillance, navigation, and communications satellites in Earth orbit to support military missions and objectives. The success of all these efforts hinges on a single common need: the availability of power to operate the systems being proposed. Sufficient power must be available when and where it is needed. The power must be compatible with the various space systems being considered for deployment. Even more important, the method of power production and utilization must be acceptable from political, social, and economic perspectives and perceptions. These requirements all can be met by adopting a space power architecture based on energy transmission. The selection of energy transmission, commonly called power beaming, as the future space power approach would be a major step toward ensuring U.S. space program goals are achieved and the United States reestablishes and maintains its position of leadership in space.

ECONOMICS

Power beaming is a cost-effective approach to meeting space power needs. Building on existing technology development, base-load space power needs could be met for about the same cost as solar but with only half the on-orbit mass. Coupling power beaming with state-of-the-art electric propulsion technology, a beam-powered electric orbital transfer vehicle (EOTV) could deliver to geosynchronous Earth orbit (GEO) 80% of the mass initially placed in low Earth orbit (LEO) for about half the cost of a chemical OTV (Coomes, Johnson and Widrig 1990). Chemical upper stages today deliver only 20% to 25% of the initial mass in LEO to GEO.

By separating the power system from the end-use application, a standard power transmission satellite design can be adopted. A standard design would simplify technology development and system requirements. The power satellite design could be optimized for power production and transmission independent of the end-use mission requirements, thus reducing development costs. The more efficient dynamic systems would be more attractive because of their removal from mission platforms. Central-point power generation and distribution would reduce the total number of power systems needed and would greatly reduce or eliminate the need for onboard energy storage. The mass and volume savings on each satellite would allow the user to increase the satellite payload fraction, thus enhancing mission capabilities. This should increase the revenue-earning potential of each user satellite.

For the same power output, a laser energy receiver would be much smaller than a solar photovoltaic (PV) energy collector, thus reducing satellite drag. Decreased drag on the spacecraft would extend the useful life of onboard consumables needed for stationkeeping and attitude control, thereby extending the revenue-producing lifetime of a satellite. By trading drag reduction for increased power, highly fuel-efficient electric thrusters could be used for stationkeeping and/or attitude control, increasing a satellite's revenue-producing lifetime even further.

The commonality of power systems technology developed for power beaming would support military, commercial, and civilian space activities including advanced NASA missions to the Lunar and Mars surface. The long-life continuous nuclear power sources developed for beam-power satellites would also support nuclear electric propulsion for Lunar and Mars cargo transport spacecraft and OTVs. As the manned development of space progresses and a Lunar base is established, refurbishment and upgrading of beam-power satellites could become a Lunar-based endeavor, providing increased economic incentive for Lunar development.

Adopting power beaming does involve some economic uncertainties that must be addressed. As with any centralized system, the initial capital investment will be higher than that for smaller distributed systems. To keep power-user costs down, this higher initial capital cost must be spread over a longer operating time, thus increasing the need for long-life reliable systems. To ensure continuous power availability even in the event of a power satellite failure, the beam-power distribution grid must include excess generating capacity. Onboard limited backup and/or keep-alive power capabilities will be required to accommodate temporary power transmission loss.

Each beam-power satellite represents a significant portion of the power grid assets, and each unit is a high-value asset. This increases the economic consequences of a system failure or loss at launch or transfer from LEO to high Earth orbit, even though significantly fewer launches are required. Operation from high orbit implies additional expense for transportation to get the beam-power satellite on station. Because each power satellite is a high-value asset, periodic maintenance and/or repair may be used to extend beam-power satellite lifetime. This could imply additional transportation costs or higher repair and maintenance costs because the beam-power satellite is in high Earth orbit. These costs depend directly on the final operating scenario selected and must be factored into any deployment and operating analysis or evaluation that is performed.

Power beaming is a different method of providing power in space. As such, it will require a change by mission planners in their approach to meeting space power needs. The economic impact of transition from the one-on-one, onboard power approach to a central-point generation and distribution power approach could range from a minimum level (involving only change in configuration of existing solar power systems from rectangular to circular geometries) to a maximum level (requiring totally new receiver systems). A more complete understanding of the commonality between solar and laser-beam receiver technologies is necessary before transition impacts can properly be assessed.

MISSION APPLICATIONS.

Energy transmission can support a broad range of mission applications, because it is an integrated power approach that makes no distinction regarding the end use of the power delivered. Energy transmission provides two major mission benefits: increased power availability and easy transportability. Increased power availability alleviates the latent demand for power that exists with mission planning but is never directly faced. Power beaming is a space power utility approach separating production from use. It allows each mission planner the same access to power, yet preserves the individuality of mission requirements and objectives. Mission planning, an exercise in compromise, constantly trades off mission goals and objectives that can be achieved with a given payload against the amount of onboard power that can be packed into the finite satellite volume available. Power beaming provides more power with less volume of the satellite used and is a highly transportable and versatile method for supplying power as man expands his influence out into the solar system.

NASA's Office of Exploration has been examining the viability of putting a permanently manned base on the moon and on Mars. These bases will have a variety of power requirements for the base and for surface activities away from the base, such as mining or exploration. Power for transport vehicles or rovers will be needed to support these remote activities. The logistic support for these bases will require the use of electric propulsion on space transports for resupply of materials and equipment. A megawatt-class electric cargo transport with a long-life nuclear electric power source has new importance and greater value when coupled with an easily transported energy transmission system (Coomes and Dagle 1992).

Near-Earth Mission Applications.

Near-Earth mission applications include a mix of both military and civilian systems. Earth-orbiting satellites considered here include satellite operations from LEO to GEO and from equatorial to polar orbits. Low Earth orbiting satellites include remote sensing, intelligence gathering, and research satellites, while those in geosynchronous orbit consist primarily of communications satellites (Maral and Bousquet 1986), and in between are navigation satellites. All of these satellites typically use solar panels and lightweight batteries to provide the required power. Communications satellites constitute a major portion of the commercial satellites in Earth orbit while military satellites comprise the majority overall. In the near term, communications satellite operators are not likely to embrace power-beaming technology. However, the increased demand for power of direct broadcast and the anticipated market this would have may entice these users into adopting power beaming for future satellites.

For larger systems, power system area and mass become significant factors. The most notable large space system currently planned is the Space Station Freedom. Providing the power the station will require is a

major issue at present. The initial station design was to have an average power of 75 kWe for housekeeping, attached payload requirements, and module payloads. The power was to be provided by eight large PV arrays covering a total of over 2200 m². Current station designs are now calling for 37.5 kWe, but this will still require over 1100 m² of solar panel area. With power beaming, a 7.5-m diameter laser energy receiver (45 m²) could provide the station with 130 kWe. With three beam-power satellites orbiting at 20,000 km, the space station could be provided continuous power and the onboard batteries could be reserved for emergency power only. By pointing the laser energy receiver at the sun, 5 to 10 kWe of additional emergency power would be available. One approach for Space Station Freedom includes meeting growth power requirements with solar dynamic systems. These units would have solar collectors 50 ft in diameter and produce 25 kWe of power each. The use of solar collectors would be amenable to power beaming, as the collectors could also be used as laser energy collectors with little (4% or less) loss in efficiency--and this could be compensated for by increasing the laser intensity.

The Industrial Space Facility (ISF) is a commercial venture of Space Industries, Inc., to provide an Earth-orbital facility from which to conduct research and manufacturing operations. The ISF would use solar arrays to provide up to 10.8 kWe to its customers and require a panel area of approximately 250 m². With power beaming and 45 m² of receiver area, this system could also be provided with upwards of 130 kWe. With the ISF 120 out of phase with the station, it too could be provided continuous power from the same three beam-power satellites.

GEO and polar platforms, now being studied as part of the Space Station Program by the General Electric Company, would support such missions as Earth biological and geological observations, oceanographic and ice activity studies, Earth atmospheric monitoring and research, solar observations, and plasma physics measurements. By reducing the power feed to the station and the ISF to 90 kWe, these platforms could be supplied as multiple users of the same three beam-power satellites with 20 to 40 kWe.

The single most viable application is a beam-powered EOTV operating between LEO and GEO would justify the development and deployment of a beam-powered system. A fully operational EOTV (Dagle 1991) would use the same three beam-power satellites to ensure that continuous power for the EOTV. With this system, Dagle showed that a 6000 kg payload could be delivered to GEO in 100 days for an initial mass of 7221 kg delivered to LEO. A comparable chemical propulsion system using advanced engine technology would require a gross weight of over 22,500 kg to deploy the same payload. Although the trip time for the chemical system is only hours, the beam-powered OTV cost per kilogram is only one-half that of the chemical system. In addition, the lower thrust of electric propulsion would allow the satellite to be transported fully deployed. In this way, satellites could be operationally checked out in LEO and repaired or returned to Earth if necessary, saving millions of dollars worth of hardware.

Lunar Mission Applications.

The technology base developed to support near-Earth energy transmission would eliminate the need to land large power sources on the Lunar surface. Lunar surface power could be available almost immediately upon arrival if electric propulsion is used for the Lunar cargo transport craft. Consider the scenario where energy transmission has been implemented in support of near-Earth operations and mankind is ready to expand outward by establishing a manned Lunar base. By then the first generation power transmission satellites in Earth orbit should be reaching the end of their operational life. Systematically, each old power satellite is being replaced with a second-generation power satellites with upwards of 10-MWe capability. The power and propulsion technologies needed to establish and provide logistics support for a permanently manned Lunar base have been developed and operationally tested in support of near-Earth energy transmission. The cargo transport vehicle, needed to initially deliver the materials and equipment from Earth orbit to Lunar orbit and later to provide continued logistical support to the manned base, would be a straight-forward engineering effort based on the beam-powered EOTV and power satellite technologies. By adding an energy transmitter to the cargo manifest, a Lunar beam-power transmission system would readily be available. The Lunar transporter would deliver its cargo to the proper Lunar parking orbit and then move out and take up position

at the L1 libration point 35,000 miles above the Lunar surface. From here, depending on the design of the power transmission system, a 10-MW nuclear electric power system could provide upwards of 5-MW of electrical power for use on the Lunar surface, greatly enhancing current planned activities and enabling new mission options not previously considered possible because of power limitations.

Mars Mission Applications.

The development of a manned Mars base would be a natural progression and extrapolation of the power infrastructure developed for the Lunar base. The power infrastructure established on Mars would be a seasoned technology, having been fully tested during Lunar development. Energy transmission systems can be transported to Mars and implemented directly, again eliminating the need to land large power sources on the Mars surface and making surface power available almost immediately upon arrival.

A logical approach to the development of a manned Mars outpost is the proposed split Mars mission scenario. An unmanned nuclear electric cargo vehicle would be sent to Mars, carrying all the supplies and equipment needed by the manned mission that would follow later, using a chemical propulsion system. The use of a nuclear electric-propelled cargo vehicle offers several unique mission options not possible with a chemically-powered cargo vehicle (Coomes et al. 1988). Because the cargo vehicle would be sent in advance, it could carry the fuel needed for the manned return flight. This option is also possible with a chemically-powered vehicle but requires tradeoffs of other mission objectives to accommodate the added mass. The mass savings of electric propulsion would reduce the impact of this option on the overall mission. With the cargo vehicle already in orbit around Mars, a backup return vehicle is available for the crew, should the primary manned space craft become disabled. By proper modular design and common interfacing of systems of the cargo vehicle and the manned Mars spacecraft, the crew could reconfigure the two spacecraft and use the propulsion system of the cargo vehicle to propel them home. Taking advantage of the fuel savings offered by electric propulsion and with no need for the life support, habitat, or additional shielding systems a manned spacecraft would require, a cargo transport vehicle could carry enough supplies in a single flight to support several manned flights to Mars. By configuring the spacecraft to take advantage of aerobraking at Mars, even more propellant could be saved and additional supplies could be carried. If the nuclear electric power system is designed for long-life operation and includes a beam-power transmission system, electric power can be supplied from space to support a broader range of activities on the Mars surface. Placing the power and propulsion unit in geosynchronous Mars orbit (GMO) above the selected landing site, 20% to 60% of the onboard electric power capacity would be available at the Mars surface to support mission activities, both manned and unmanned. Automated systems deployed from the cargo vehicle or left operating when the crew returns to Earth could convert raw materials on the Mars surface into usable form, available to the manned flights that follow.

Upon arrival at Mars, the transport vehicle would deliver its cargo to the desired parking orbit and move outward, taking a position in GMO above the desired landing site. From there it would beam power to the Mars surface. Initially, this electric power would be used to operate fully automated systems released earlier and, having landed on the Mars surface, would prepare the landing site for the Mars crew arriving later. This same system would later provide the surface power needed to support crew activities after their arrival. With megawatt levels of electric power available on the Mars surface, mission activities could be expanded. The power-beaming option can provide the energy needed to support a manned Mars base that would allow a Mars colony to develop and grow.

CONCLUSIONS

Central-point space power generation and distribution by energy beams--power beaming--is technically feasible and should be included in the U.S. space power program as an option that warrants serious consideration as our future baseline approach to meeting this nation's space power requirements. Power beaming is a true integrated approach to providing power in space. It can provide significant benefit to this nation's overall space efforts and offers an opportunity to greatly enhance U.S. space leadership. Power

beaming is a viable concept that allows power to be generated at one location and transmitted to a remote user at another location by energy beams. Power beaming can provide power users with up to 10 times more power than a solar PV system for the same collector area or, conversely, power beaming could provide the user with the same power as a solar PV system with only 10% of the collector area. A beam-powered electric OTV would reduce the cost of satellite transfer from LEO to GEO to half that for a chemical-based OTV and would increase the payload capability delivered to GEO for existing launch systems lift capability to LEO. A space power architecture based on power beaming would support both military and civilian space operations and would be mission-enhancing, if not enabling, for manned activities planned for beyond-Earth orbit. Power beaming would increase the acceptability and use of nuclear power in space by mission planners and satellite designers because it isolates the end-use satellite from the nuclear power source while providing significantly more power than a solar source. The SP-100 Program can serve as the baseline power system technology for the first-generation beam-power satellites. SP-100 technology-based beam-power satellites of 500- to 1000-kWe output could be developed and deployed in the 2000 to 2010 time frame. Second-generation beam-power satellites could use multimegawatt power system technology. These would be phased in as replacements for first-generation systems, with beam-power satellite output capability reaching levels of 10 MWe to 20 MWe by 2030. Compared with solar PV with energy storage or onboard nuclear reactors, power beaming results in the lowest total power system mass placed in orbit.

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