Orbital Power Beaming for Extraterrestrial Exploration

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Collecting solar energy in space for use on Earth has been considered for many years, but has been held back for cost reasons. However, there may be nearer-term uses for this technology in exploring the Moon, Mars, and other bodies in space. By collecting energy in space and beaming to assets on the surface of a planet, the mass needed to be landed on the planet's surface for power generation/collection may be decreased by lowering requirements on collector area, storage batteries, nuclear material, and shielding. Furthermore, waste heat can be dissipated in space. Lunar exploration may benefit through the ability to receive power on a solar array during the two-week-long lunar night. Mars polar exploration may benefit through the ability to receive power during the long Martian winter, when the sun is not visible. The availability of beamed power at laser wavelengths can facilitate base operations as well as propellant production from in situ resources.

I. Introduction

Wireless power transmission (WPT) has the potential to provide power in situations where the user is widely separated from the power source and a line of site exists between the two. The ultimate goal of many WPT studies and experiments is often the transmission of power from orbiting solar power satellites to the terrestrial consumer grid.[1,2,3] Nearer-term applications such as transmission of power to a forward military base,[4] to a remotely-piloted aircraft[5] in the Earth's atmosphere, or to a rover in a shadowed lunar crater[6,14] from an illuminated mountain peak, have also been considered. The emphasis of our current study is the transmission of power from orbiting energy sources to users and equipment on the surfaces of planetary bodies such as the Moon and Mars. Currently, exploratory spacecraft carry their own power supply, whether it is photovoltaic panels or Radioisotope Thermoelectric Generators (RTGs). Future exploration may be enabled by separating the power source from the user. Leaving the power source in orbit can lessen the amount of mass that needs to be transferred to the surface by lowering requirements on solar collector area, storage batteries, nuclear material, and shielding. Furthermore, providing power during long periods of darkness during the lunar night or Mars polar winter can ease thermal stresses on surface vehicles. Leaving the power source in orbit may allow the number of assets on a given planetary surface as well as the mission life of each asset to increase, while providing increased flexibility in mission architecture. The latter can be attained by using the power beaming satellite to transmit power to more than one surface asset. The number of satellites can eventually be increased so that a network-centric power system evolves.

II. Advantages of Beamed Power

As mentioned above, less mass will need to be transferred to the planet surface because the need for fuel (nuclear or chemical) or storage media (e.g., batteries) will be minimized, as will the size and/or number of orbit-to-surface transfer vehicles and the total propellant requirements on such vehicles. Fuel savings can apply both to radioisotope energy sources and propellant brought from Earth saved by powering propellant manufacturing on the surface of a planet.

By transmitting power from orbit to the night side of a planet, greater time-averaged power densities can be achieved, resulting in less collection area on the planetary surface than would be needed for dependence on the sun alone. Such a collector presents a smaller "target" for surface hazards such as dust storms on Mars, as well as easier repair or replacement if damage does occur. A smaller collector area also lessens the challenge of preparing smooth graded surfaces on irregular heavily-cratered bodies. Dual use of surface solar arrays for collecting both solar power and laser beamed power may be possible for single-junction photovoltaic cells. Power beaming to multi-junction cells may be possible by use of multiple beams of different wavelengths. Heat rejection, especially for radioisotope

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systems, is carried out in space; an important consideration because convection is challenging on the surface of bodies such as Mars and non-existent on the Moon and asteroids.

A power source in orbit also provides flexibility in mission architecture by allowing for reuse and/or multitasking of the space-based power system to serve several surface systems. For example, a spacecraft in a near-polar orbit around Mars can serve assets in both the north and south polar regions during their respective sunless winter periods. A spacecraft in a stationary orbit can be repositioned to a different longitude, or its beam redirected as needed.

III. Technological Considerations

The major technological considerations for the overall system design are the nature of the orbital power source and the wavelength of the power beam.

The nature of the orbital power source will depend on the planetary body itself. For the Moon, where insolation in orbit is similar to that in Earth orbit, solar collectors may be practical. With no atmosphere to cause drag or attenuate the beam, large collectors on the power beaming spacecraft may be feasible, even at relatively low altitudes. However, the stability of low lunar orbits may be problematic due to lunar mass concentrations. For Mars and destinations beyond, the increased distance from the sun may make orbital solar collectors extremely large. Further challenges to solar collectors may exist in other locations, such as the high radiation environment around the moons of Jupiter. A nuclear power source may therefore be preferable in those situations. However, mass and operations concepts issues will have to be traded. Thin-film solar cells may be extremely lightweight, so solar energy may still be considered, at least for Mars. A nuclear power source may add flexibility in the choice of orbit because it can provide power even when in the planet's shadow. However, it may introduce other challenges, such as the need for a good view factor of space to radiate heat.

Choice of wavelength regime will depend, in part, on beam divergence considerations. Since beam divergence is proportional to wavelength, and because the size of the extraterrestrial facilities under consideration requires lower power levels than are usually considered for commercial use on Earth, the emphasis here will be on laser (visible and near-infrared) wavelengths, rather than microwaves. For the Moon, the choice of optical beam wavelength is flexible. Lasers may be used without concern for weather outages. The specific choice of wavelength will depend on mass and efficiency of available equipment, compatibility with solar cell bandgaps for conversion back into electrical power, and in the case of Mars, ability to penetrate the atmosphere. For rough order-of-magnitude system designs, the choice of wavelength is not crucial, so a representative near-infrared wavelength will be considered as a notional choice for system sizing purposes.

IV. Orbital Considerations

The orbit(s) of choice will vary from one planetary body to another. Factors include planetary mass (which determines orbital period for a given semi-major axis), the oblateness of the planet (which determines perturbations of the orbital plane), and the rotation period of the planet (which is a factor in the feasibility of repeating ground track orbits). Mission planners may also need to consider multiple uses of the spacecraft for communications, observation, and navigation, with the orbit chosen to balance these needs. These needs may not necessarily conflict and will be similar in some ways to planetary observation spacecraft. Such spacecraft must point various subsystems in different directions; i.e., sensors toward the planet's surface, solar arrays toward the sun, and communications antennas toward the Earth.

The principal requirement for a power beaming satellite (or any satellite that must interface with a surface asset) is frequent access (continuous, if possible) to the ground site. Therefore, the most commonly considered orbit for power beaming systems has been stationary orbit; i.e., geostationary orbit for Earth at an altitude of 35,786 km and areostationary orbit for Mars at an altitude of 17,032 km. In the absence of perturbations from the Earth or the sun, the Moon would have a selenostationary orbit at an altitude of 86,715 km. However, the gravitational perturbation from the Earth (and to a lesser extent, the sun) is significant, leading to the existence of the Lagrange libration points,[15] which are relatively stationary with respect to the surface of the Moon. Stationary orbits are effective in maintaining access to surface locations at low and middle latitudes, as shown in Fig. 1. However, they may be very low on the horizon, or even below the horizon, in the polar regions. These regions may be prime candidates for power beaming from orbit due to their scientific interest and their lack of sunlight for long periods of time. The need to find alternate orbits for high latitudes may be even more important for power beaming than for communication and navigation because the relatively low elevation angles usually considered acceptable for these applications may not be acceptable for power beaming.

A. Lunar Orbits

For the Moon, beaming from the Earth-Moon L1 or L2 Lagrange regions[15] may be considered for continuous access. These points are in the direction toward and away from Earth, respectively. Such locations may be feasible for power beaming to the night side of the Moon.

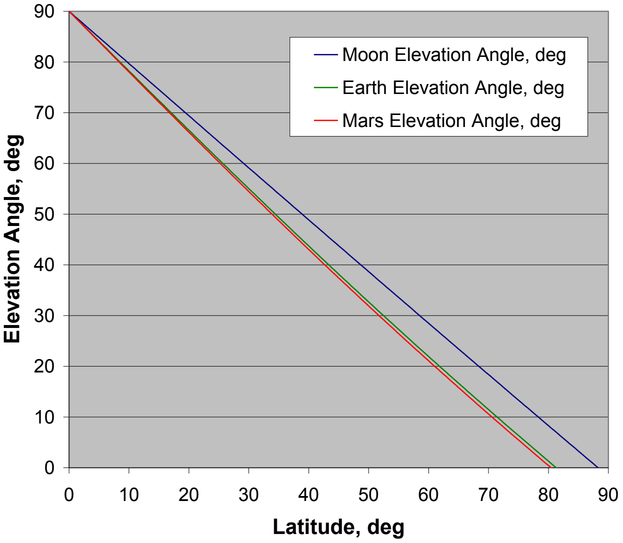

Figure 1. Elevation angles as a function of latitude for stationary orbits, assuming that the satellite is over the same longitude as the ground receiving site. For lunar stationary orbit, the Earth-Moon L1 point was used.

To minimize beam divergence from the Lagrange point distances, and to access higher latitudes, it is tempting to consider lower altitude high inclination orbits such as sun-synchronous orbits. As will be seen (Fig. 4), sun-synchronous orbits for Earth and Mars are near-polar. However, for the Moon, sun-synchronous orbits are not possible for altitudes greater than 204 km and are far off polar below that. Furthermore, very low lunar orbits may be perturbed by lunar mass concentrations and have very brief ground station access times. Thus, higher orbits should be considered. For more rapidly rotating bodies such as the Earth[7] and Mars (see Section IV-B, below), orbits with a daily repeating ground track may be appropriate. This will allow one or perhaps two passes per day, the latter occurring when the satellite accesses the ground site on both the ascending and descending nodes, provided that the orbital plane and true anomaly are chosen appropriately. However, since the repeat time is once per lunar day; i.e., once per month, this gives at most two directly overhead passes per month. However, direct overhead passes are not necessary because very little lunar rotation occurs during a single orbit of a spacecraft in lunar orbit. Thus, a spacecraft can access a ground site for several consecutive orbits. For example, an orbiter in a lunar polar orbit can access a lunar pole and be in sunlight when it does (see Fig. 2). For a lunar equatorial region, the same orbiter can access a ground site for consecutive orbits over a period of just under four Earth days, followed by gaps of just under 10 days (see

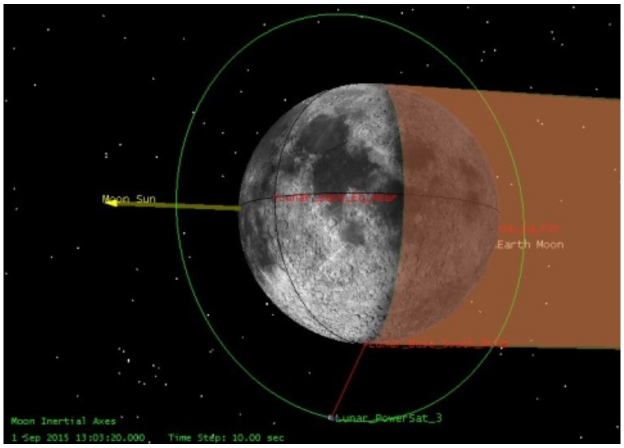

Figure 2. An orbiter in a lunar polar orbit can access the lunar South Pole and be in sunlight when it does. The red shaded area is the Moon's shadow.

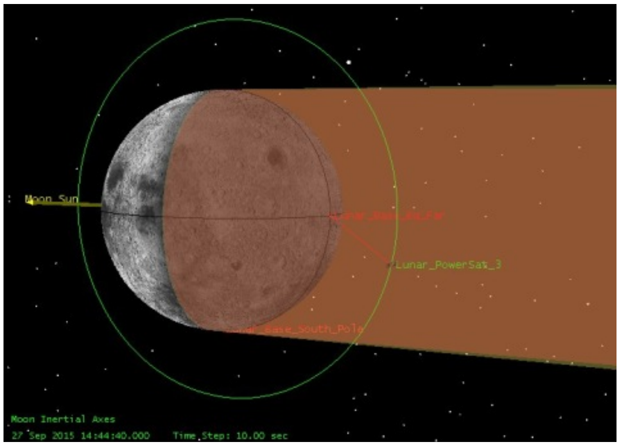

Figure 3. An orbiter in a lunar polar orbit can access a site in the lunar equatorial region for consecutive orbits for just under 4 Earth days, followed by gaps of just under 10 days. The orbiter is in the Moon's shadow during lunar night access.

Fig. 3). The precise altitude of the orbit must be determined through trade studies that balance factors such as access time (leading to higher orbits) and beam divergence (leading to lower orbits). Another important consideration is gravity perturbations. Orbits that are too low may require additional stationkeeping due to lunar mass concentrations. Very high orbits may be subject to perturbations from the Earth and the sun. For orbits of a few thousand km, access times of a few hours are possible.

The location of the ground site can influence the design of the spacecraft. For the polar regions, the orbiter will be in sunlight during ground site access times, so it can be solar powered, with little need for onboard power storage. For equatorial regions, the orbiter will be in shadow during many of the ground site access times, necessitating either onboard storage or a nuclear power source.

B. Mars Orbits

For Mars, power beaming from stationary orbits may be considered.[6] A Mars stationary orbit has an altitude of 17,032 km, just under half that of an Earth geostationary orbit. Therefore, beam divergence will be less than for Earth stationary orbits. Because of Mars' smaller size, the apparent size of Mars as seen from Mars stationary orbit will not differ much from Earth as seen from geostationary orbit. The range of latitudes that are feasible for power beaming will therefore be nearly the same. Ruggedness of terrain may place further limits on where the stationary orbit is visible on Mars' surface.

Low and medium orbits around Mars may also be feasible for power beaming. An example of a "Medium Mars Orbit" or MMO is the orbit of the inner moon Phobos, with an average altitude of 5,982 km. It is nearly equatorial and nearly circular, with an inclination of 1.08 degrees and an eccentricity of just 0.0151. The use of this orbit may be synergistic with Phobos missions and Phobos basing for Mars surface missions. Crewed missions to Phobos have been suggested[8] as a means of initiating human exploration of Mars at lower cost than surface missions. Phobos may provide a platform from which astronauts may teleoperate robots on the surface of Mars with little latency, and eventually use in situ resources. Phobos is not eclipsed by Mars during portions of the Martian year, so during those times, solar power can be collected on the Mars-facing side of Phobos when it is over the night hemisphere of Mars, and power beamed to the night side of Mars. When Phobos is eclipsed by Mars, stored power can be transmitted to Mars, or power can be generated using RTGs. A disadvantage of co-orbiting with Phobos is that if the orbit of the spacecraft is perturbed, it may drift toward Phobos over a period of weeks to months, posing a collision hazard.

A sun-synchronous orbit may be desirable (see Fig. 4), preferably one with a repeating ground track, so that a given asset on the surface of Mars can receive beamed power each day. Depending on its inclination and precise positioning of the line of nodes, a sun-synchronous orbit may allow the satellite to access the night side of the planet while the satellite itself is in sunlight (though this does not matter if the satellite uses RTGs instead of solar power). As is the case for Earth, a Mars sun-synchronous orbit will be nearly polar, so ground sites in arctic regions can benefit from beamed power from orbit during the long Martian winter. Power beaming can be scheduled at the same local time during each sol. This will allow batteries on surface assets to be recharged daily from the same depth of discharge. In addition, energy storage on the spacecraft can be minimized by using a sun-synchronous terminator orbit. Such an orbit may pass over a low latitude location once or twice per sol. For high latitudes, more than two accesses per sol may be possible. A selection of possible Mars orbits is shown in Table 1.

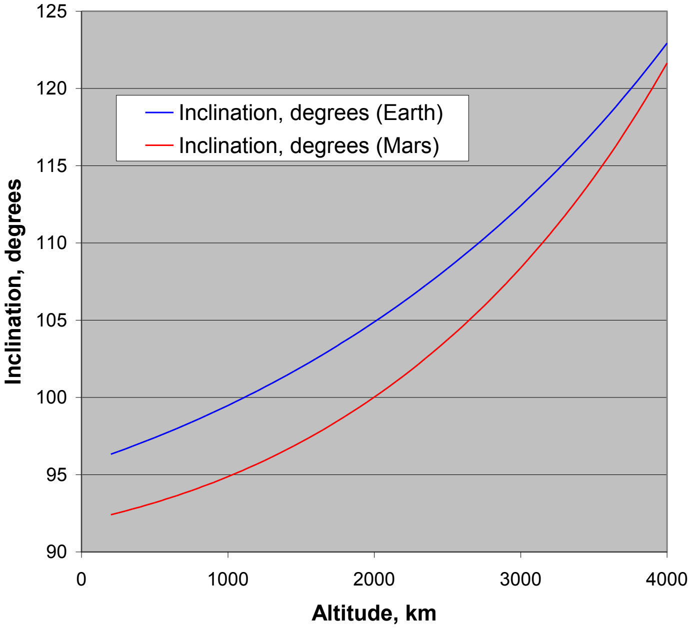

Figure 4. Like Earth, sun-synchronous orbits are possible in low Mars orbits for near-polar inclinations. Such orbits may facilitate power beaming at the same local time each diurnal cycle.

Table 1. Possible Mars orbits. Sun-synchronous terminator repeating ground track orbits making 5 to 12 orbits/sol will always be in sunlight.

Average Altitude, km	Inclina-tion, deg	Eccen-tricity	Orbital Period, hours	No. Orbits/ Mars Day	Description
124	92.24	0	1.76	14	Lowest circular sun-synch repeating ground track
302	92.66	0	1.90	13	Circular sun-synch repeating ground track
505	93.21	0	2.05	12	Circular sun-synch repeating ground track
1,716	98.28	0	3.08	8	Circular sun-synch repeating ground track
2,192	101.34	0	3.52	7	Circular sun-synch repeating ground track
2,797	106.37	0	4.11	6	Circular sun-synch repeating ground track
3,597	115.55	0	4.93	5	Circular sun-synch repeating ground track
4,719	136.55	0	6.16	4	Circular sun-synch repeating ground track
5,982	1.08	0.0151	7.66	3.22	Phobos's orbit
6,434	Any	0	8.22	3	Repeating ground track
17,032	0.00	0	24.62	1	Mars stationary orbit
23,459	1.79	0.0005	37.11	0.664	Deimos's orbit

C. Orbits Around Other Bodies

The lessons learned from power beaming to the Moon and Mars may be extensible to other planetary bodies and moons. The precise power beaming architecture will have to be tailored to the environment and orbital mechanics particular to each body. Among the issues that will need to be worked out are the existence and stability of stationary and Lagrange point orbits around the moons of the gas giants. Orbits in which the Earth is in view most of the time are desirable for communications access. Access to the sun is not important for its own sake because solar power is not practical in the outer solar system. Since the angular separation between the Earth and the sun is relatively small (as seen from the outer solar system), a sun-synchronous orbit would likely keep the Earth in view. However, establishing sun-synchronous orbits for the moons of the outer planets is probably not necessary because of the long orbital period of these planets. Orbits around these moons that have a reasonably small nodal regression rate may remain in an approximately fixed orientation with respect to inertial space for months or even years.

V. System Mass Considerations

The utility of orbit to surface power beaming will depend, in part, on mass considerations. Mass of a power beaming system, and the opportunities it presents, must be traded against alternatives. For areas where sunlight is not available, RTGs may be traded against storage of beamed power. The "… highest specific power nuclear power source ever flown by the U.S."[9] is the Galileo General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG), having a power level of 300 We, a mass of about 55.9 kg, and therefore a specific power of 5.37 We/kg. This would seem to be far lower than that for solar arrays, though the low time-average insolation on the surface of Mars, combined with the mass of storage batteries, could make a Mars surface-based solar power system quite heavy. The capacity of batteries is expressed in terms of specific energy, not specific power, but this can be converted to power by considering the amount of time that the battery must store the energy for. Storage batteries can be recharged by a solar array receiving either sunlight or beamed power. The interval from the start of one recharge cycle to the start of the next is one sol and/or the time it takes for the planet to rotate once with respect to a power beaming satellite's orbital plane. However, the use of multiple satellites or multiple passes per sol for a single satellite can decrease this interval. State-of-the-art for batteries for space applications is about 100 to 200 W-hr/kg including parasitic mass (wiring, connectors, structure, etc.),[10] so a figure of 150 W-hr/kg should suffice for an estimate. If the battery must store enough energy to supply a specified number of watts of power over the duration of one sol, then, for Mars, this is equivalent to a system having a specific power similar to that of the GPHS-RTG. Thus, the utility of an orbital power beaming system will depend on the feasibility of decreasing energy storage requirements on the surface through use of ambient sunlight, more frequent power beaming, or eliminating storage entirely, for regions where a satellite in stationary orbit can be accessed.

An example of a power system for Mars can be shown by considering a modest-size surface base. Ramohalli, et al.,[11] estimate that such a base may use in the tens of kilowatts. We will take, as an example, a base using 36 kW average power. The precise number is somewhat arbitrary; this is the same as our previous assessment[7] of (peak) power beaming to military Special Operations Forces units on Earth, and is an approximate thousand-fold scale-up of the Mars Exploration Rovers. The latter produced 900 W-hr/sol during their prime missions,[12] which is equivalent to 36.5 watts time-average power. For a base using 36 kW average power, a system of GPHS-RTGs would mass 6,700 kg, while a system of batteries to store beamed energy for a full day would mass 5,900 kg. Scaling solar intensity in near-Earth space to that in near-Mars space gives a solar array specific power[13] of 28.4 W/kg in near-Mars space. Accounting for the diurnal cycle, seasons, latitude, atmospheric attenuation, and storage loss effectively brings this down to about a tenth of this level, so that the solar array mass required for a 36-kW Mars base would be about 12,000 kg. If state-of-the art solar arrays are used, and the possible increase in efficiency of the cells in the low-temperature environment of Mars is accounted for, the solar array mass will likely be less. In practice, a combination of solar arrays and batteries would likely not need the full mass of batteries for an entire day's storage because direct solar energy can be used during the day. This may not be practical during the winter at high latitudes, but power beaming from orbit can be of use in that case. In any case, the greater the use of beamed power from orbit, the lower the mass of the power system that must be deployed on the surface. Part of this is due to the lower mass of the solar arrays, because the beam intensity can be brighter than sunlight at a particular planet and a monochromatic laser beam can be converted more efficiently than full-spectrum sunlight. The required mass of storage batteries decreases because power need not be stored for as long a period, and high-power operations can be performed while the power beaming satellite is in view, bypassing the batteries during that time.

VI. Conclusions

Initial analysis of beaming power to assets on the surface of a planet shows that there may be a potential savings in mass that needs to be launched from Earth due to a reduction of the required mass on the surface of the planet. Continued trade studies are needed to compare surface and space-based solar and nuclear systems, as well as the mass of on-orbit and surface-based energy storage that may be required in each case. Concepts of operation and orbital analysis should continue in parallel with this as this can affect spacecraft design and energy storage requirements. In the long-term, beamed power can benefit advanced space exploration missions by the added degrees of freedom attained by spatially separating the energy sources from the energy users. This may ultimately pave the way toward economically competitive commercial space-based solar power for Earth.

References

[1] Glaser, Peter E., "Power from the sun: Its future," *Science***,** Vol. 162, Number 3856, pp. 857-861, 22 November 1968. URL: http://www.sciencemag.org/cgi/reprint/162/3856/857.pdf.

[2] National Aeronautics and Space Administration, *The Final Proceedings of the Solar Power Satellite Program Review*, Conf-800491, July 1980. URL: http://www.nss.org/settlement/ssp/library/1981DOESPS-FinalProceedingsOfTheSolarPowerSatelliteProgramReview.pdf.

[3] The Boeing Company, *Space Solar Power End-to-End Architecture Study: Final Report*, NASA Marshall Space Flight Center contract number NAS8-98244, 15 January 1999.

[4] *Space Based Solar Power as an Opportunity for Strategic Security*, Phase 0 Architecture Feasibility Study, Report to the Director, National Security Space Office, 10 October 2007. URL: http://www.nss.org/settlement/ssp/library/final-sbsp-interim-assessment-release-01.pdf.

[5] Schlesak, Joseph J.; Alden, Adrian; and Ohno, Tom, "A Microwave Powered High Altitude Platform," 1988 IEEE MTT-S Digest, pages 283-286.

[6] Henley, Mark; Potter, Seth; Howell, Joseph; and Mankins, John, "Wireless Power Transmission Options for Space Solar Power," 53rd International Astronautical Congress, 10-19 Oct. 2002, Houston, TX, United States, IAC-02-R.4.08. URL: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020091865_2002153398.pdf.

[7] Potter, Seth, and Davis, Dean, "Orbital Reflectors for Space Solar Power Demonstration and Use in the Near Term," AIAA Space 2009 Conference and Exhibition, Paper No. AIAA-2009-6675, Pasadena, CA, 14-17 September 2009.

[8] Lee, Pascal, et al., "Mars Indirect: Phobos as a Critical Step in Human Mars Exploration," URL: http://www.marsinstitute.info/rd/docs/plee/Lee%20et%20al%20Mars%20Indirect%20(2005).pdf.

[9] Bennett, Gary L., "Space Nuclear Power: Opening the Final Frontier," 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), 26-29 June 2006, San Diego, CA. URL: http://www.fas.org/nuke/space/bennett0706.pdf.

[10] Pearson, Chris; Bennetti, Andrea; and Spurrett, Rob; "Advances In Battery Technology Relevant For Planetary Probes," URL: http://ippw.jpl.nasa.gov/20070607_doc/7_11PEAR.pdf.

[11] Ramohalli, Kumar; Lawton, Emil; and Ash, Robert; "Recent Concepts in Missions to Mars: Extraterrestrial Processes," J. Propulsion, Vol. 5, No. 2, pp. 181-187, March-April 1989.

[12] "Power Innovations for the Mars Exploration Rover Mission: Evolving the flat, square solar panel from the Sojourner rover on the 1996 Mars Pathfinder mission into more powerful solar 'wings,'" URL: http://marsrovers.jpl.nasa.gov/technology/bb_power.html.

[13] Landis, Geoffrey A., and Appelbaum, Joseph, "Photovoltaic Power Options for Mars," Space Power, Volume 10, Number 2, pp. 225-237, 1991.

[14] Henley, M.W., Fikes, J.C., Howell, J., and Mankins, J.C., "Space Solar Power Technology Demonstration for Lunar Polar Applications: Laser-Photovoltaic Wireless Power Transmission," 53rd International Astronautical Congress, 10-19 Oct. 2002, Houston, TX, United States, IAC-02-R.4.04. URL: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020091885_2002153397.pdf.

[15] Nave, R., "Lagrange Points of the Earth-Moon System," http://hyperphysics.phy-astr.gsu.edu/Hbase/Mechanics/lagpt.html.