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A SOLAR ELECTRIC PROPULSION MISSION FOR LUNAR POWER BEAMING

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ABSTRACT

As the NASA Vision for Space Exploration takes shape, one of the key issues that will affect the lunar exploration is the ability to provide electric power to various surface locations. This power should be available through daylight times as well as night times. While nuclear reactors and radioisotope power sources are a choice for continuous power, it is the purpose of this paper to explore the advantages of an electric propulsion spacecraft plus laser power beaming to provide power to any location on the lunar surface. The starting point for the electric propulsion mission is a 500 km altitude. Thrusting only occurs when the satellite is in sunlight. Radiation damage that occurs during transit of the Earth's radiation belts is taken into account. The satellite is placed in a 30,000 by 500 km orbit around the moon where it beams power to locations within 45º north or south of the equator. Laser power beaming only occurs when the satellite views the sun and the surface location is in the dark. Power delivered to the surface over a two year mission is presented along with the results of adding a second satellite. With two satellites, the maximum time when the site won't receive power at night is about three days. This significantly reduces the need for a lunar storage system.

INTRODUCTION

As the NASA Vision for Space Exploration takes shape, one of the key issues that will affect the lunar exploration is the ability to provide electric power to various surface locations. This power should be available through daylight times as well as night times. While nuclear reactors and radioisotope power sources are a choice for continuous power, it is the purpose of this paper to explore the advantages of an electric propulsion spacecraft plus laser power beaming to provide power to any location on the lunar surface.

The major benefit of solar electric propulsion (SEP) is that more payload can be delivered for less cost than by chemical means. In addition, SEP allows orbital adjustment to permit a range of orbital characteristics to fit the application. One disadvantage is that it takes longer to reach the moon, but this is not a limiting factor for this example. Many options exist for orbits around the moon. In this case, we have chosen an equatorial Molniya-type orbit with an apogee of 30,000 km and a perigee of 500 km. In this orbit, the satellite can beam power to locations within 45º north and south of the equator when it is in sunlight and the site is in darkness. A previous study examined laser beaming from the L1 and L2 positions [1]. Our purpose was to examine the benefits of a lower lunar orbit.

For both the laser beaming spacecraft and the lunar surface receiving photovoltaic array, the Stretched Lens Array (SLA) on the SquareRigger platform will be used. This array easily achieves a specific mass of 300 W/kg for sunlight and over 800 W/kg for laser wavelengths in the 800 to 900 nm range. Results presented below include the inclusion of a second satellite as well.

SOLAR ELECTRIC PROPULSION MISSION

One of the key issues to be resolved in a solar electric propulsion mission to the moon is the impact the Van Allen radiation belts will have on the spacecraft solar array. Previous studies [2, 3] for a 600 kW reusable lunar tug gave some insights into the time that might be spent in the radiation environment. That vehicle delivered a 22 MT cargo to the lunar surface, hence was a much larger and slower spacecraft than the one envisioned here.

In that study, the lunar tug made five round trips between earth and the moon over five years. The total 1 MeV equivalent electron fluence accumulated over a 273 day initial outbound trip was calculated to be ~4.7×10^{14} e/cm^2 for 20 mil covers at maximum power.

For this study, a much smaller spacecraft is proposed. This vehicle had a 4343 kg total mass with a capacity for at least 1400 kg of Xenon propellant. The power level was a nominal 100 kW using a Stretched Lens Array on the SquareRigger platform with multi-junction solar cells. The mass of that array is a nominal 300 W/kg with 300 W/m^2 specific area. The conceptual spacecraft used multiple Hall thrusters each able to operate at power levels between 10 and 50 kW. At maximum power, the thrusters will produce a total thrust of ~5 N. The mission begins at an altitude of 500 km with thrusting occurring only during the sunlight period of the orbit. This sized vehicle could easily be sent to orbit by the Zenit 3SL launch vehicle.

For this case, the total mission time to the moon was about 89 days beginning at 28º inclination using the same methodology used in the tug study [2]. The total time was divided into 1000 km segments and SPENVIS (the free web site hosted by the European Space Agency) was used to determine the total equivalent radiation dose for power. This total radiation dose was found to be ~1.5×10^{14}e/cm^2 for triple junction cells with 20 mil equivalent cover glasses and 28 mils back shielding. Because detailed design of the spacecraft was beyond the scope of this paper, these two doses represent the range of estimates of damage to the solar array. Fig. 1 shows the loss of power for the tug and this spacecraft as a function of cell cover glass thickness.

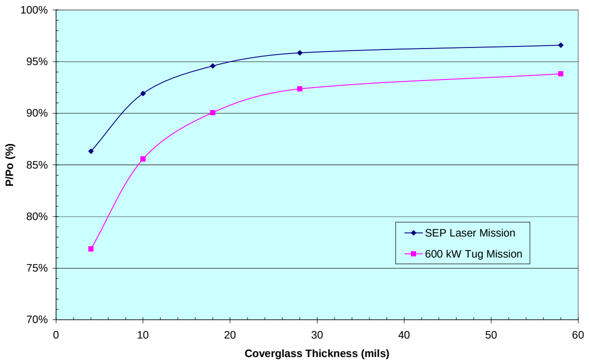

Fig. 1: Preliminary radiation damage assessment

It is immediately apparent that a nominal cover glass thickness of 18 mils (with 2 mils additional shielding from the stretched lens) will be sufficient to limit the loss of power to a level to a maximum of 10% for the tug case and 5% for our case. For the purpose of this study, we will assume the conservative value for solar array damage of 10%. This paper will now focus on the results of laser power beaming to the lunar surface.

LUNAR ORBIT RESULTS

A wide range of potential orbital parameters exists for an equatorial satellite that can view locations between 45º north and south. We did an initial survey using Satellite Tool Kit®

v.7.1 encompassing circular and elliptical equatorial orbits with apogees as high as 55,000 km. Based on examination of these orbits, we selected an orbit of 500 km perigee and 30,000 km apogee as being the best match of long coverage time over a two year period and a somewhat short time with no coverage whatsoever. The orbital condition required that we would beam when the site was in shadow and the satellite was in sunlight. Of course, beaming when the site and the satellite were illuminated is possible.

We arbitrarily chose a start time of July 1, 2008 and continued the mission through June 30, 2010. Fig. 2 shows the hours without coverage for sites at ±45º from the equator. There was little difference between the two sites, so the rest of the paper will use a site at 45º north for the analysis. Of course, sites at lower latitudes will receive more coverage, but the details won't be presented here.

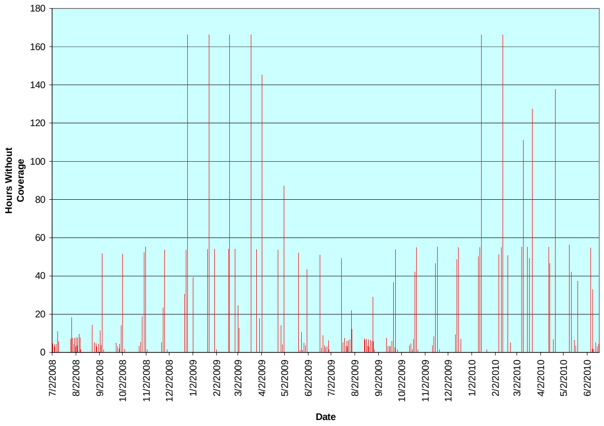

Fig. 2: Time when satellite does not view sites

Simple inspection of this chart shows the maximum duration with no coverage by this one satellite for these sites to be 164 hours or nearly 7 days. This would require a massive storage system, assuming the night-time power requirement is the same as in day-time. Over the two year period, there were only ten times when the dark time exceeded 84 hours.

In order to reduce the dark period length, a second satellite was added. However, one of the critical issues is the angular relationship between the first satellite and the second one. Accordingly, a plot was made of access time of the second satellite to the 45º north site as shown in Fig. 3. This figure shows that the total access time ranges from 3500 hours to about 3870 hours at a 55º offset between the two. Configuration of the satellites is shown in Fig. 4.

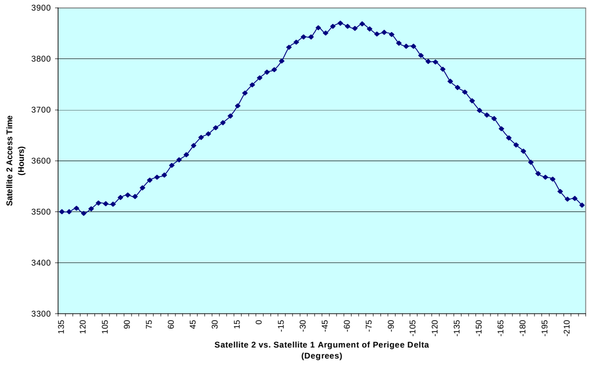

Fig. 3: Satellite 2 access times with satellite 1 fixed

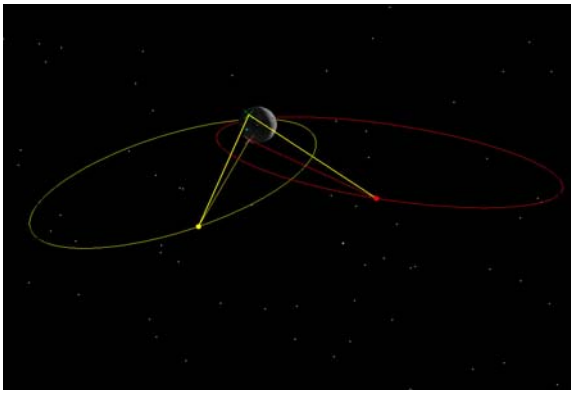

Fig. 4: Visual depiction of the two satellites

With this completed, the time when no satellite is able to cover the lunar sites at 45º north or south has dropped dramatically to a maximum of 84 hours (3.5 days) as shown in Fig. 5. Furthermore, there are only eight of these periods over the two-year span. In addition, in many cases the duration drops to 54 hours (2.25 days). Both these options

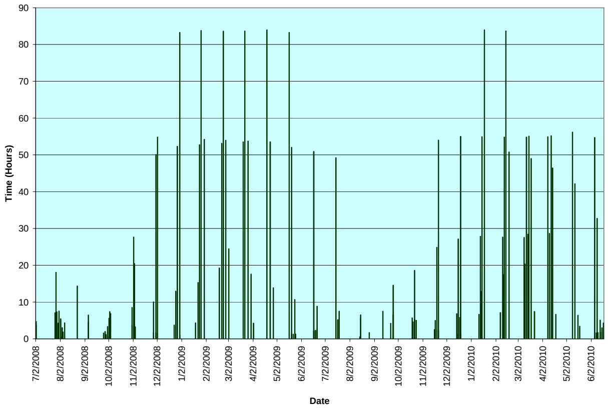

Fig. 5: Time spans when neither satellite views site

represent significant mass savings for a lunar site. It should be remembered that sites closer to the equator will have shorter “dark” times.

A plot of both the two satellite access times as well as the maximum length of any single dark time for elliptical, equatorial orbits with apogees up to 55,000 km showed that the 30,000 km apogee condition is appropriate for this mission to generally achieve the best of both options. The dark times have been substantially reduced – to generally less than three days.

In addition, there are many times when both satellites view the site over the same time period. This suggests the option of having increased power at these times for increasing the activities at the site. However that would require use of planar arrays on the surface. Although it isn’t certain what activities would be conducted at night, it would seem reasonable that propellant production from the regolith could easily take advantage of this “bonus” in power. Fig. 6 shows a period where there is a major coverage of the site by both satellites. The exact amount of power delivered will depend on the orbital conditions of each satellite as well as the base location. This chart also shows that there are some very short periods of darkness as shown above in Fig. 5.

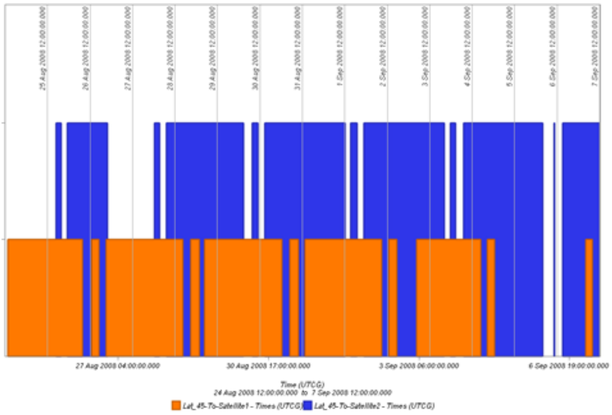

Fig. 6: Two satellite overlapping coverage

LASER BEAMING RESULTS

Laser beaming from the satellite in this elliptical orbit yields a complex beam pattern and intensity. For the 45º north site, the solar arrays will be tilted at the latitude. The satellite will rise over the horizon and move about 180º in azimuth. At the same time it will increase in elevation to 45º as shown in Fig. 7. This chart provides the combined beam incidence angles for this site. Because the moon is only slightly tilted on its axis, these angles will remain essentially constant. It is assumed that the surface array would track the source in one axis as it moves in azimuth. This will fulfill the need to have a ±2º angle of incidence on the lens in azimuth. With proper design of the array, no north-south adjustment will be necessary.

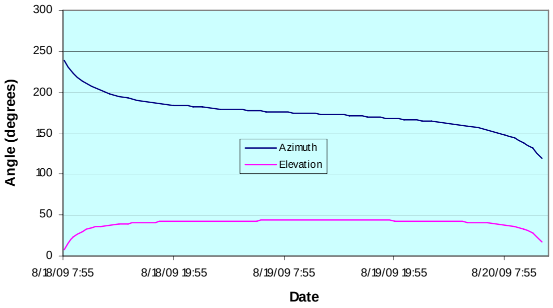

Fig. 7: Laser beam incidence angles

As the satellite rises over the horizon, it will be at a low, ~500 km altitude. The laser beam will be very intense and the coverage area will be small. As it moves toward its apogee of 30,000 km, the beam intensity will drop and the beam area will expand. Fig. 8 shows the variation of laser beam intensity in terms of equivalent AM0 sunlight from a 4 m^2 transmitter aperture. This chart is for a three day period in the month of August, 2009. In this calculation, we assume a laser power level of 40 kW, and a wavelength of 850 nm, which is ideal for GaAs cells. It is important to note that the intensity of the laser beam is approximately 0.2 equivalent suns over most of its traverse and peaks at only 2 “suns”. A

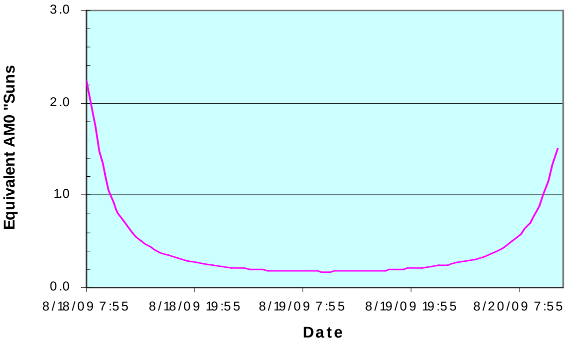

Fig. 8: Equivalent solar intensity of laser beam

second beam with a planar array could increase power to the site without causing array temperatures to rise too high.

As the satellite moves toward its apogee, the diameter of the laser beam will increase. If we assume a 60 kW surface Stretched Lens Array that uses GaAs cells, we can compute the maximum diameter of the laser beam relative to that area as shown in Fig. 9. Thus in this case also, the 30,000 km apogee does not cause the laser beam to exceed the area of the nominal 60 kW solar array.

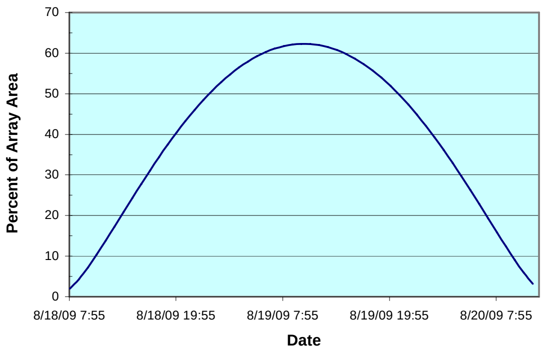

Fig. 9: Percent of 60 kW GaAs solar array area

Finally, what is the amount of laser power that could be delivered to the site at 45º north from a single satellite over this time period? As noted before, the power output of the nominal 100 kW BOL satellite solar array will be determined by the transit time to this orbit around the moon, the radiation damage suffered while traversing the Van Allen belts around the Earth, the efficiency of generating the laser beam, and the thermal conditions of the satellite in orbit. An estimate of the amount of laser power that this initial 100 kW satellite could provide will include a worst-case 10% loss in power traversing the Van Allen belts, the laser beam production efficiency of 50% and mirror losses of 12% for a resulting beam power of 40 kW. This assumes that the array is operating at a normal deep space temperature.

In addition, the characteristics of the Stretched Lens Array on the lunar surface will be important. Because the power will be beamed to the surface at night, the solar array will be cold initially. As the laser beam intensity reaches a maximum level of 0.2 equivalent suns, the array temperature will rise to no more than 28ºC depending on surface features, tilt angle and other considerations. We are assuming a 45% conversion efficiency of the laser beam [4] as determined by tests on GaAs solar cells at various temperatures. This is believed to be a conservative value.

Given these assumptions, Fig. 10 shows the power that could be delivered to the lunar site for a 50% conversion efficiency of satellite power to laser beam. In this case, 18kW could be supplied to this surface site. Beaming from a second satellite as shown before will further increase this power level as noted above. Thus, one satellite can supply 30% of the daytime power at night.

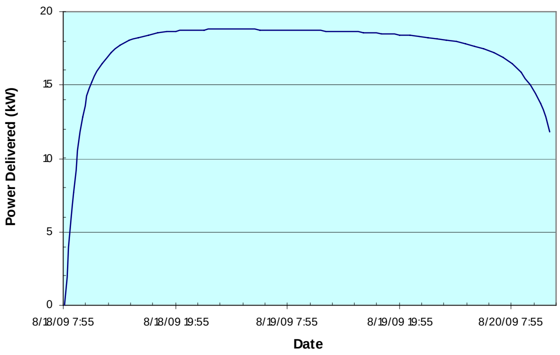

Fig. 10: Laser power delivered to a 45º North site

SUMMARY AND CONCLUSIONS

This preliminary study of an estimated 4343 kg mass solar electric propulsion vehicle going to the moon and beaming laser power to bases at 45º N or S has shown that two satellites in lunar equatorial orbit can provide substantial power to these bases. Over a two year period, there were only eight times when the lack of view time of the 45ºN location reached 84 hours. Over the rest of the two year mission, the times when the satellites did not view the sites dropped to less than 54 hours. Thus the need for energy storage on the lunar surface drops dramatically with this approach.

The surface array was assumed to be made of GaAs cells in a Stretched Lens Array with a surface power in the day time of 60 kW. The power delivered by one satellite was 18 kW and there are many times when both satellites are in view of the site. This offers the opportunity of further increasing the power to the site; however the surface array would have to be a non-concentrating array. With this planar array, the power delivered to the surface could then double to 36 kW.

Depending on the need and location of the surface sites, these elliptical orbits can also cover the back side of the moon and help provide communications to those locations.

The radiation loss in traversing the Van Allen radiation belts will certainly be less than the 10% conservative value used here. In addition, advances in the efficiency of diode lasers in this wavelength range are expected to make this option increasingly attractive for providing power to the lunar surface.

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