SATELLITE BEAMED POWER FOR LUNAR SURFACE ASSETS.

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Introduction: Solar power satellites have long been promoted for terrestrial use [1], but the advantage over ground-based assets has never been convincingly demonstrated. In contrast to the terrestrial case, however, orbiting infrastructure for space power satellites is less expensive and simpler to emplace than ground facilities for use on other worlds. Moreover, a cost-effective architecture is one that minimizes the surface footprint at the expense of resources in space. The confluence of several factors now make beamed power systems practical for solar system exploration in the near-term. This is particularly true for lunar exploration, where the night is 14 Earth days long and there is both scientific and exploration interest in visiting permanently shadowed regions.

Mission architecture: For the architecture described here, the orbital element collects solar radiation with photovoltaic panels and uses the electrical power to direct a high power laser at a photovoltaic array on the surface. This allows surface instruments to maintain full operation without access to sunlight.

Since the divergence of the power beam is proportional to the wavelength, the need to limit the size of the surface receiver favors optical over microwave transmission. With a coherent optical beam, the angular dispersion can be made equal to or less than the pointing accuracy of the projector, which is typically of order 1 arcsecond. That limitation suggests placing the satellite in a low orbit rather than in a stationary location, transmitting only when the orbiter passes over the ground station. The result is low duty cycle transmission and high duty cycle solar collection, which eliminates the need for an oversized solar collector for the orbiter and makes it possible to deliver significant power to the ground from a modest sized spacecraft with a small aperture (20-50 cm for 1 arcsecond).

To meet the power needs of larger missions (such as crewed surface operations), the best scaling strategy is to position a necklace of solar power satellites in a common orbit, each radiating to the surface in turn. These satellites could also provide near-continuous communications and GPS-like navigational support to a ground station. We also note that the same technology can be applied with little modification to point-to-point power beaming across the lunar surface.

Orbital element: For the orbital element we postulate a self-contained small spacecraft with ~ 6 m^2 of solar arrays in a low lunar orbit, nominally 200 km perilune. The solar panels would charge a battery during most of each orbit, except when in eclipse, and would discharge for ~4 minutes during each pass over the landed station while homing in on a retroreflector mounted on the station. With a 2.2 hr orbital period, this strategy corresponds to a 3.2% duty cycle. An optical system with ~1 arcsecond pointing accuracy could project ~6 kW to the surface with 1 arcsecond dispersion using a 20-50 cm mirror, illuminating a spot on the surface as small as 1 m (though in practice, 2-3 m is more realistic allowing for jitter, aberration, and elongation from an angle up to 45º). On the surface, this flux density is comparable to overhead sunlight.

Laser power of 3-6 kW can be readily achieved today by joining the outputs of multiple fiber lasers via spectral combining [2], a technique capable of producing tens of kW of output. Other components needed for an operable system, including steerable optics compatible with high power loads, are commercially available for space applications. The telescope, pointing and tracking elements, radiator, battery, and solar panels are high TRL commercial components that can be adapted to a free-flyer platform.

Landed element: Assets on the ground need not be different from those used on a typical solar-powered mission, such as the UltraFlex family of deployable solar arrays such used for the Phoenix and InSight missions. Those missions used 2.1 m diameter arrays, but up to 6m implementations have been developed by the manufacturer, Orbital STK (the specific size needed would depend on the dispersion and pointing accuracy of the incident beam). With the orbital element described above, such an array would produce nearly 3 kW-hr for the surface every 24 hrs, comparable to an MMRTG such as on the Curiosity mission at Mars. Moreover, the conversion efficiency of photovoltaics tuned to a specific laser wavelength can significantly surpass that of solar spectrum conversion.

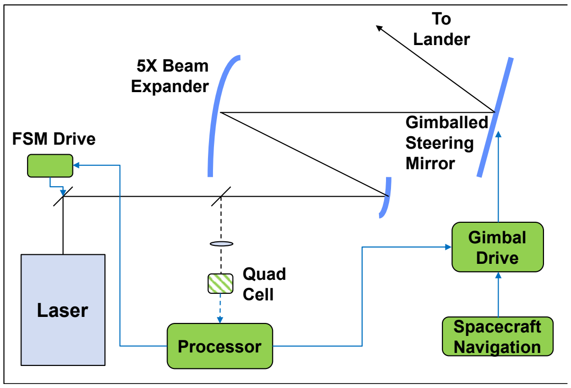

Fig. 1 Notional optical train showing focusing and pointing systems. The dotted line indicates quad cell feedback assuming a beacon or retroreflector on the surface.

Design approach: Notional optics are shown schematically in Fig. 1. An off-axis 5X beam expander provides high efficiency without obscuration while a flat gimballed coarse steering mirror requires minimal moving mass, and hence offers fast response. A fast steering mirror (FSM) for fine pointing is controlled by a PID loop based on detection of a tracking signal from a retroreflector at the center of the photovoltaic receiver. A 5 cm reflector aperture would collect at least 5W from the beam, corresponding to ~12.5 mW within the minimum 20 cm aperture of the orbiter. A quad cell detector would then use this signal to generate a feedback response to the fine steering mirror (FSM). To detect the reflected signal while radiating 3-6 kW to the ground is straightforward if the radiating beam is time gated.

An alternative approach to acquisition and tracking provides the feedback signal digitally from the ground. In this case, the photovoltaic array itself is configured in quadrants, or a set of 4 small photodiodes is overlain on the array to the same effect. The power measured in each of these quadrants is then used to generate a feedback signal, which is radiated digitally to the spacecraft whenever the beam drifts too far from the optimal position (but no faster than a 1 kHz cadence). If the signal is lost entirely, it may be re-acquired by expanding or rastering the beam.

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