MICROWAVE-POWERED AIRSHIP SYSTEM DESIGN **FOR HIGH-ALTITUDE POWER RELAY AND OTHER APPLICATIONS**

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Abstract: The design of a stratospheric airship platform with 1 -MW DC power output from beamed microwave power from the ground is presented. The ground and airborne major subsystems are described. A rough cost estimate is given for an application as a laser power beamer for providing supplemental power to LEO spacecraft photovoltaics. The airship is 1000-ft long and 150-ft in diameter. A limited beamsteering 60-70-m-diameter antenna equipped with magnetrons is proposed for the transmitting antenna on the ground. A 50-kW laser with a 4-cm mirror is aboard the airship. The airstat can also be used for observation and telecommunication applications.

I. INTRODUCTION*

There is renewed interest in Earth atmosphere-based semi-geostationary, high-altitude, platforms [1] or airstats. They can be unmanned helicopters, circling airplanes or aerodynamically-shaped [2] powered airship Applications for commercial cellular and other civil and government telecommunications and observation uses are the main drivers. The platforms range from conventional-powered aircraft (UAV) [3], solar-powered aircraft [4], solar-powered airships [5], to microwave-powered aircraft [6] and airships [7] and hybrid combinations [IS]. Proposed loiter times range from 4 hours to over 6 months, before being relieved by rotating scheduled additional units [9].

This paper presents and examines a concept for a next generation air-stat. It will employ a high-powered, megawatt class stratospheric airship for a beamed power relay to spacecraft for purposes of augmenting their LEO photovoltaic power capability. Given the high-power airstat capability, other applications such as relaying deep space optical communications arc possible.

Currently, the cost of electric energy in orbit (approximately $ 800/kwh [10]) is as much as 10,000 times that of its cost on Earth. The economic incentive is to deliver lower cost electric energy to orbiting space'craft.

A principal commercial appeal of beaming power to space is the burgeoning fleets of 1,110 telecommunication service spacecraft [11]. If properly designed upfront for power throttling or when refurbished, they then benefit from increased power aboard each space'craft. They could potentially service more customers and with higher SNR down links, supporting higher data rates.

For the airship power relay proposed here, microwave power beamed from the Earth to the airship is collected with a rectenna and converted to DC power. The on board DC power not required for station keeping propulsion is available for a payload. The DC power is converted to laser power and beamed to the LEO spacecraft solar panels. A notional concept sketch is shown in Fig. 1.

The paper organization is to first present a background to this system application, its available applicable technology and then system requirements and constraints. Next the proposed ground, stratospheric and space segments will be discussed and a rough cost estimate of a point-design will be given.

II. BACKGROUND

Using high-alitude platforms for observation and communications had its genesis in the first manned balloons for military purposes. Early civilian circling aircraft applications were for public TV broadcasts using modified DC-6s for Midwest Program on Airborne Television Instruction (MPATI) [12]. Bill Brown at Raytheon demonstrated a microwave-powered helicopter maintained aloft for 24 hours in an Air Force-sponsored demonstration in Ott. 1964 [13].

The Canadians demonstrated a microwave-powered rectenna-equipped, free-flying airplane model SHARP in 1987 [14] and the Japanese flew MILAX in 1993 [15]. Prof. Kaya and others demonstrated a microwave-powered airship in Japan in 1995.

A solar-powered aircraft Pathfinder by AeroVironment, achieved an altitude record of over 50,000 ft in an 11-hour flight Sept. 1995. The US Air Force is working on a manned 747 aircraft equipped with a laser for beaming power at missiles during ascent after lift off.

Flight endurance on station is a key commercial system parameter. The longer the flight duration, the greater

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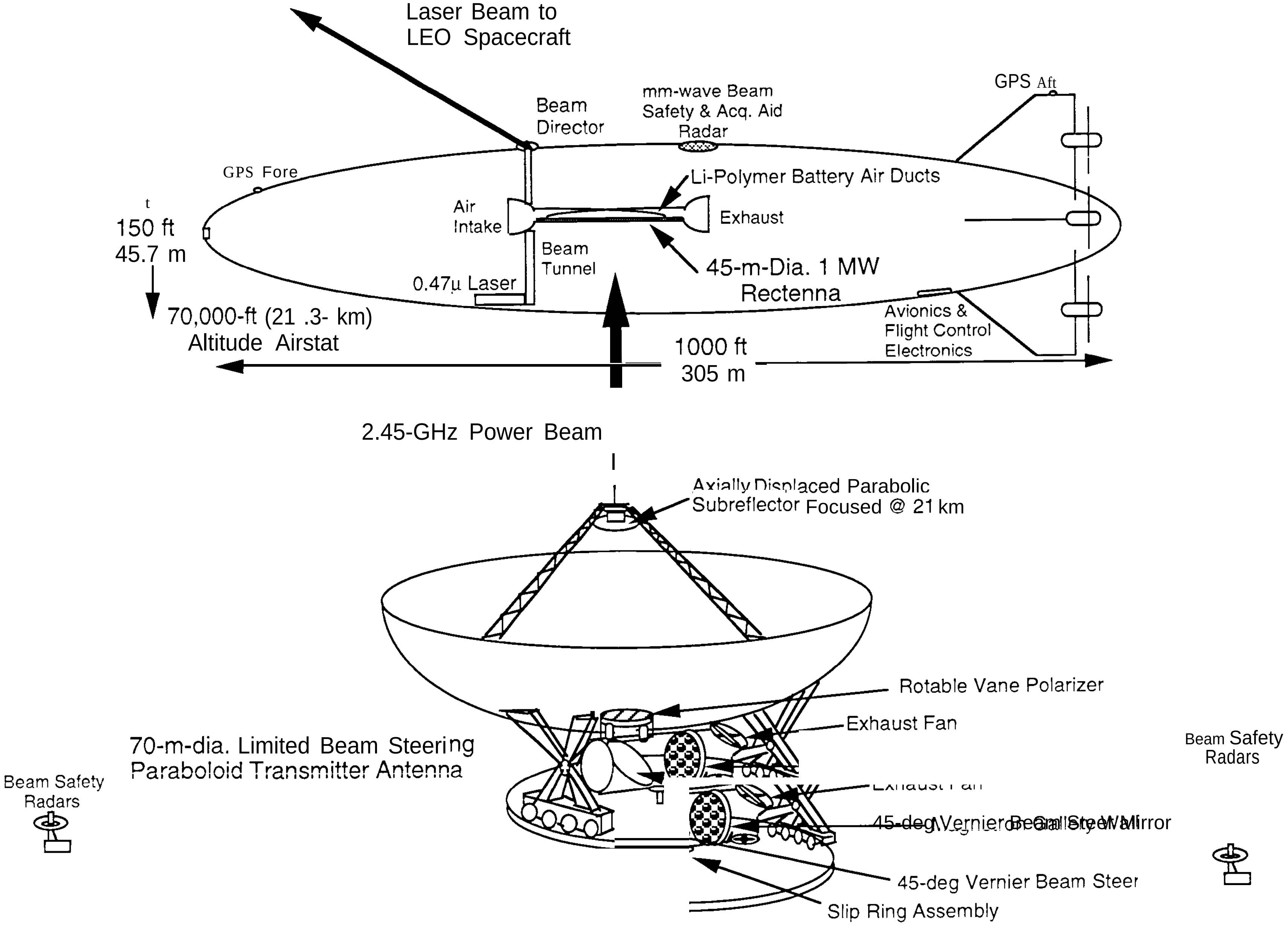

Figure 1. Conceptual Airship LEO Power Relay System

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the system availability because of minimizing the hazard of cross wind takeoff or launches and landings or recoveries, and ascent and descent through the jet stream turbulence.

An early world record of 60h7m was set for airborne endurance in Belgium in 1928 by Louis Croy and Victor Groenen. In 1929 the US Army trimotored airplane the "Question Mark", a Fokker F-7, set a refueled endurance record of 15(th40n)l 5s on Jan 7. Elinor Smith and Bobby Trout set an early world endurance record for women of 42h4m41s in Nov. 29, 1929 [16]. A current world's record for refueled flight is for 553h41m30s (over 23 days) set in Northbrook, IL by John and Kenneth Hunter in 1930 [17],

in the unmanned or UAV category, the Condor airplane stayed aloft for two and a half days in 1989 [18]. Thus, the technology for unmanned high-altitude platforms is proceeding.

Current studies of stratospheric platforms consider payloads of the order of a few thousand pounds and payload powers of 10s of kW. We are interested in the next generation with a power on the order one megawatt. How big will an airship be? What might it cost? What horsepower is required for stationkeeping? What applications may be of interest?

III. SYSTEM DESIGN CONSIDERATIONS

A principal problem of wireless power transmission (WPT) to LEO spacecraft from Earth-based or even high-altitude platforms is that the curvature of the Earth gets in the way of the beams. The ultimate system would require multiple sites over the surface of the Earth in order to provide continuous power. The contact times from a point on the Earth to any given spacecraft vary from seconds to minutes, given that the platform site and the spacecraft orbits are compatible. The repeat times also vary. However, we consider only a supplemental-beamed power system for starters. What can be done with only one site, particularly providing power during eclipse periods?

High altitudes are desired for the platform in order to serve large coverage areas both on the ground and in space,. The range of coverage on the ground and maximum contact time on orbit provided by a high-altitude airstat are proportional to the square root of the altitude. At high altitude an airship must be able to combat the winds aloft to remain near geostationary. For practical purposes there is only a fairly well-defined altitude region where this may be economically possible. This is because the thrust power required for maintaining headway in winds varies as the cube of the wind velocity.

Currently, our detailed knowledge of the high-altitude winds aloft is limited. Winds are generally highest in winter in the northern hemisphere. However, the NOAA Climatic Center used over 20 years of twice daily rawinsonde soundings to gather statistics for a NASA study [19].

The wind velocity as a function of altitude goes through a pronounced maximum at the jet-stream altitudes around 35,000 ft, which is to be avoided. Large engines and high power would be required there. However, there is also a pronounced minimum wind speed around 70,000-ft altitude. This is the desired altitude area to stationkeep the platform. In higher winds, the airship, if blown off station, will have to seek refuge drifting and awaiting lower winds to use on board power storage to return to the power beam (meaning that the system availability will be even less when that occurs). A strategy of advancing upstream as far as possible before the forecasted peak wind onset may aid in staying near the power beam.

Wave'length Considerations

The power-beaming wavelengths are a key system parameter. A small footprint on the power-receiving host is desired in order to be minimum invasive. Hence, the large areas associated with long microwave wavelength rectennas are undesirable.

Maximum usage of existing in-space equipment should be a system goal. Having to space qualify new equipment is costly, thus, the beam should approach sunlight wavelengths if possible. That is, a laser beam illuminating the LEO spacecraft solar cells is desirable, and in particular during the transit through the Earth's shadow. Furthermore, operating a high-density laser power beam above the Earth's atmosphere at a wavelength that is strongly absorbed in the troposphere will promote beam safety by allaying fears of zapping persons on Earth.

Nevertheless, the power beam must not be greatly dimmed or doused by Earth-associated propagation impairments such as clouds and rain. The impact of this requirement is such that approximately 10-cm-long wavelength microwave radiation is desired for the WPT beam's transit through the lower atmosphere.

This microwave solution is in conflict with the ultimate laser WPT delivery to the LEO spacecraft. Thus the intermediate power converting relay platform is proposed to change wavelengths,

IV. SYSTEM REQUIREMENTS AND CONSTRAINTS

In order to provide a driving focus for the system, it is desirable to have over one Megawatt of DC power available aboard the airship, which has a payload capability of 5,000 lbs (23 ret).

A constraint is that prover for station keeping is primary. Payload and battery charging are secondary. The propulsion requirements thus factor into the system availability. We will require that the airship shall at least be capable of station keeping in the 95 percentile winter winds of 94 knots or 156 ft/sec given in Ref. 19.

The microwave beam will track the airship within its applicable beam steering range of +/- 30 deg. Limited beam following by the vehicle will be possible. The microwave power beam will focus on the center of the rectenna and track its polarization orientation within 10 deg. Power beam safety subsystems will be required to protect errant airmen and unregistered spacecraft.

Access to an actively-maintained LEO spacecraft orbital elements data base is required for locating customers, but also for avoiding overspray of beams to non-customers.

V. THE GROUND SEGMENT DESIGN

Redundant (two), limited-steering, variable-focus, beam-waveguide cassegrain antennas, each equipped with a gallery of phase injection-lockd magnetrons are proposed for the microwave power transmitting antennas of the system ground segment as shown in Fig. 1. Two entirely separate antennas are proposed at each ground site in order to have redundancy for system availability and to permit downtime for off-line maintenance.

The ground segment also includes a beam safety subsystem, an operations control and monitoring facility, a hangar for storage and maintenance of spare airships in support of several power beaming sites, the billing data collection and spacecraft acquisition data interfacing equipment.

The transmitting antennas, proposed to operate at 2,45 GHz, are on the order of 50-70-m diameter and have steering limited to +/- 30 deg from zenith. This limited range of tipping will reduce the subreflector support mass and the antenna height above the ground and thus hold down the steel cost. An articulated tiltable and axially-displaced parabolic subreflector will permit limited vernier beam steering and zoom beam focusing.

The use of cooker tube magnetons will also reduce costs and phase injection locking with filament power removed after starting will improve the spectral purity of the transmitted signals. The highly efficient magnetrons (order of 75%) permit air cooling of the transmitters.

The beam-waveguide antenna feed will allow use of rotary venetian blind polarizers to control the orientation of the linearly-polarized radiated power beam. This permits the airship rectenna to be linearly polarized for mass reduction and ease of DC power collection.

A phased array of slotted waveguide panels fed by phase injection-locked magnetrons was also considered, but the limited beam steering range of +/- 4-8 deg. [20] was considered too restrictive, although only a single transmitting array per site would be required as compared to two dishes per site.

Beam Power Safety

The ground segment will be home to the microwave and laser power beam safety subsystem. The ground and airborne transmitters must be interlocked through here. Although the ground transmitter can be located in a controlled airspace, the safety subsystem must react to unexpected airborne intrusions such as a flight emergency. Therefore, active monitoring of potential intrusions with radars will be required. Both low-altitude slow craft, as well as high-altitude fast jets must be detected. If a passenger aircraft will enter the beam, the beam must be turned off. In addition to the radar, the FAA air traffic central data could be monitored for possible intrusions. Site-based search radars interlocked with the beam serve as FAA data backup and provide detection for unscheduled hang gliders and others.

The average RF field intensity in the aperture of a 70-m-diameter transmitting antenna radiating 3.13 MW will be 81.3 mW/cm2. Along the power beam the power density will be the greatest at an altitude of approximately 8 km (26,240 ft.) with a magnitude of approximately 500 mW/cm2. This is due to aperture phase focusing effects along the center line of the beam. Airborne biota such as geese with a radar cross-section of 1/2 ft2 (0.0465 m2) are not expected to be harmed as their transit through the beam at about 20 mph (8.9 m/s) will only last about 8 sec. During that time interval they will intercept only about 300 joules (Watt-see) (71 cal) which would raise the temperature of a 5 lb bird (2,268 grams) by only about 0.03 degC, assuming 100% water. The continuous airflow of flight should quickly dissapate even that small temperature rise compared to their muscle-induced internal power dissipation.

Assuming a drag coefficient of 0.05 and 4-ft2 "wing" area at 2,000-ft altitude requires about 7.6 W of flight power to be continuously expended,

The laser beam will be designed to attenuate rapidly in the lower atmosphere and its on-off state will be tied into the space track data base on vehicles in orbit. The beam will additionally be surrounded with a rarfar of its own for backup nearby intrusion detection.

Alarmed warning fences will surround the microwave antennas and high-voltage equipment at the site. Doors and hatches in the magnetron gallery, BWG and antenna surface will be interlocked with the microwave transmitter.

VI. THE AIRBORNE SEGMENT

The airborne segment, as shown in Fig. 1, may consist of an unmanned, remote-controlled, helium-inflated, pressurized, multiple ballonet airship. The airship will be equipped with a rectenna for collecting and converting RF power to DC, electric energy storage, electric motors driving reduction gearboxes equipped with propellers for station keeping propulsion and carrying a payload of a high-power laser subsystem for beaming laser power to LEO spacecraft.

The airship may be launched in a reefed configuration with the tail propulsion assembly first. This has not yet been decided. A more detailed study and operations sequencing is needed to select the safest, most reliable course.

The airship size is estimated to be approximately 150-ft diameter by 1000-ft long. This will yield a volume of slightly over 14 million cuft. With 3% ullage and for 94% gas purity, the resulting lift of Grade A Helium at 70,000-ft altitude [21] is slightly under 50,000 lb. The design payload will be 10% of the gross buoyancy at 5,000 lb.

A rather heavy 4.5 oz/yd2 hull envelope fabric of 46,030 yd2 is assumed, massing 14,500 lb. with the inclusion of an additional 12% for seams, etc. The fins, patches, liners, valves, and control surfaces take 23% of the lift at 11,200 lb. The net buoyancy is 23,040 lb, for a fraction of displacement of 0.4.58. The 5,000 lb. payload plus avionics, fans and wiring totals 6,750 lb.

For a design maximum airspeed of 94.7-kts (160-fps, 48.78-m/s), an assumed drag coefficient of 0.035, and a propeller efficiency of 86%, the shaft horsepower required to station keep is 1,240 hp or 925 kW electric. At an average wind speed of 52-fps, the horsepower is only 42.5 hp, 31.7 kW. The propulsion subsystem weighs 2,480 lb. assuming a specific mass of 0.5 hp/lb. for motors, gearboxes, converters, controllers, oil coolers, props and prop pitch assemblies.

An energy storage system consisting of Lithium Polymer batteries is assumed, with a specific energy density of 100 Whr/kg. Thirty minutes of peak power capability weighs 10,195 lb. (good for 14.1 hr. at average wind speeds). The polymer does dual duty by serving as the air ducts for rowing intake-cooling and heated-exhaust air around the rectennas. The rectenna is assumed 45-m diameter with a specific mass of 0.7 kg/m2 for a total weight of 2,455 lb.

In the event of an unrecoverable flight control system failure or a catastrophic ripping of the platform envelope the hard parts of the platform such as the laser payload, servo actuators, propulsion electric motors, avionics, etc. will be equipped with ballistic recovery systems (BRS) that will separate from the airship, deploy steerable parachutes equipped with battery-powered line pullers and GPS way point navigation to return to a preplanned recovery site. A 10% additional mass is added for this safety equipment. It totals 1,168 lb.

Megawatt Rectenna Cooling and Breakdown Margins

Cooling of the rectenna is important, blowers are required in a no-wind case. The rectenna is planned to be fixed in the hull of the airship approximately amidships. This position will interfere with a normal ballonet operation and thus the airship may be segmented with multiple ballonets to aid in managing the 17:1 expansion ratio of the helium and the center of buoyancy displacements. Getting fresh ıg air into the rectenna, distributing it, and collecting and removing the heated waste air will require clever pneumatic engineering for light weight. Whether the exhausting waste heat can contribute to thrust is yet to be determined.

The rectenna subarrays will be designed to yield 2700 VDC nominal output. This "high voltage" must use insulated conductors in order to limit corona loss in the thin air. Lower voltage would require too much copper mass. The circular outline rectenna will be electrically isolated into four DC quadrants so that monopulse-like beam position data can be obtained for fine beam steering commands of the ground antennas [21],

RF power breakdown in 70,000-ft altitude air of pressure 33.66 torr due to the field intensity of 1,057 W /m2 near the rectenna center is not calculated to be a problem. Even under full reflected power conditions where the peak flux density quadrupples. The theoretical breakdown power density is 2,728 W/cm2 (Note change of units). The breakdown margin is about 38 dB. Similarly, the close spaced electrodes in the rectenna's circuitry, even at 1 mm, will have an 18-dB margin against breakdown assuming 6W power levels (About 200 elements/m2) in a 50-ohm impedance circuit.

Payload

The recycling laser aboard the airship will be located near the keel due to its mass, but the beam must be projected across the zenith. Thus a system of beam-waveguide mirrors will be used to deliver the laser beam power to the beam director optics located ate>ɪ the airship hull. The final mirrors in the chain will apply beam steering corrections to counteract the airship motions and jitter relative to the spacecraft position. They will be driven in a closed-ltx)p contro system based on optical scatter feedback from the target and customer telemetry.

VII. I'fit{ SPACEBORNE SEGMENT

Due to the Earth's rotation and the LEO orbit geometry, any given compatible orbit spacecraft will only be seen approximately twice per day from a single power relay transmitting location. However, by design, the orbits of the fleet of telecommunication spacecraft have at least one spacecraft always in view of any customer site. Thus on average there should always be some spacecraft in view from a single location for power relay activity.

From the 21 .3-km altitude airstat the maximum usable range to a 700 -km orbit spacecraft, before the beam dips into the lower atmosphere, is about 3000 km with a beam contact time 6 about 13 minutes for an overhead pass. For a 1,390-km orbit maximum range is about 4,400 km and max contact time is 20 min. (For the space station at 460-km altitude, max range is 2,460 km and max contact time is 10.5 min.).

In the, initial development and deployment of the, ground-based power transmitters and airships, there will be inevitable gaps in power beam coverage and the spacecraft will have, to have energy storage to work through the non-contact times.

The customer spacecraft must be cooperative in that their photovoltaic arrays must be oriented toward the laser power beam for the duration of contact in order to most efficiently transfer energy. Otherwise, the efficiency will vary as the cosine of the angle of incidence.

The air-ship payload laser beam director is designed to produce an approximately 10-m-diameter spot at about 4,000 km range. Assuming an operating wavelength of about 0.47-microns and for 1.33 times diffraction limited optics, the required mirror diameter is 0.4-111, less than 16 inches. The half power beamwidth is 2.5 micro radians, requiring about 250 nano radian pointing accuracy, which is well within state-of-the-art levels. The jitter of the airship platform is not expected to be a problem.

The power in the beam is planned to be 50 kW from a 5% efficient laser. The average power density at the spacecraft at 4,000-km range would be about 640 W/m2, less intense than sunlight at 1,353 W/m2, but yielding similar performance due to less waste heat dissipation in the photovoltaics.

In an attempt to put the system economics in perspective an admittedly optimistic scenario of customer service will be outlined. Reality will be less due to retargeting time, and the resulting availability and overlaps of actual orbit geometries. Nevertheless, assuming an average 6-minute laser prover beaming to a spacecraft with 10% collection-conversion efficiency, then 0.5 kWh of energy is transferred. At $500 per delivered kWh that is $250 per shot. At 100%, duty factor' of 10 shots per hour for 24 hours per day, 365.25 days per year for 10 years, the cumulative billable revenue would be $219 M.

VII. ESTIMATED SYSTEM COST

A spreadsheet was used to calculate the minimum total cost of an airborne power relay system for a range of modeled antenna costs. Also, the diameter of the ground transmitting antenna and the power output of the transmitter can be varied while maintaining the RF power flux density approximate'ly the same at the airship rectenna. The cost minimums are fairly shallow and are near the diameters of 60-70 m with transmitter provers of 3-4 MW RF out.

The slow-tracking, single-frequency antenna cost was modeled as the product of a constant, that ranges in value from $150-$375, times the diameter in mete'rs raised to the 2.5 power. The transmitter cost included 5,217-6667 each 600 W 75% efficient magnetrons at $250/kW, supplied DC power from 95% efficient AC-DC voltage, conversion equipment at $150/kW from 10 year grid power at $0.05?kWh.

The airships were costed at $15M each with a 10% addition for insurance. The 150-ft diameter 83% average efficiency rectenna was estimated at $1,000/m2. The laser payload was estimated at $2 M. Safety radars, a hangar and control room, operations and maintenanace, natural gas-fired turbine backup power contributed further along with the antenna, transmitter, and airship and payload redundancy to a total estimated system capital cost and 10 years of operations of around $100 M ('97). The uncertainty in this estimate is probably in the range of +50% -10%.

IX. CONCLUSIONS AND RECOMMENDATIONS

Airborne near-stationary platforms may in the future provide power beaming relay functions in addition to telecommunications and observation. A microwave-powered system with a 5,000 lb payload and 1 MW DC power output can be supported in 95% winds at 70,000-ft altitude by an airship with approximate dimensions of 150-ft diameter by 1000-ft long. The airstat system has an estimated capital cost of approximately $80 M. Operating costs for 10 years adds about $20 M more. An optimistic laser power beaming enterprise delivering LEO energy at $500/kWh could yield about $200 M revenue in 10 years. Other simultaneous uses for the platform could add to the revenue stream.

To combat the airship drag in peak winds of 94.7 kts requires propulsion power of 925 kW, most of the rectenna output power. Thus energy storage must be used for payload power during that time period. Better high-altitude extreme wind statistical data is needed for better design margins, particularly event duration data. More detailed study is needed on the launch, ascent, stationkeeping and operations scenario for the airship segment of the system. Particularly the transit through the jet stream. A driving requirement for future airstats will be power on board.

Telecommunications applications are time, weather alerts, and beeper or alarm services, broadcast, relay and multipoint communications. In the broadcast category are AM, FM, TV. In the relay category are point-to-point and point-to-multipoint services. These uses can be optically linked to international communications satellites and deep space probes for enhanced networking.

Near-continuous regional Earth sensing will be enabled by the geostationary platforms such as soil moisture monitoring, crop condition, vehicular traffic on the ground or vessels at sea and craft in the air, environmental monitoring both remotely and in situ, local weather, stream flow and floods, ice, migration patterns, land use, aerial photographs for mapping, surveillance, detection and tracking.

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