Application of Lighter-Than-Air Platforms for Power Beaming, Generation and Communications

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***Abstract*—Retail power beaming using millimeter waves offers a rapid way to bring electric power to areas such as rural India where the terrestrial wired grid lags the demand for communications, connectivity and other services. Synergy between infrastructure development for communications and for power allows local, regional and global power exchange. This helps to bring renewable power generation devices of all scales into a seamless grid including space-based, stratospheric, low-altitude, and surface infrastructure. This paper presents a conceptual study of how lighter-than-air platforms (LTA) including uninhabited, remoted controlled or autonomous aerostats and airships, may be used for the above purpose. The paper highlights the synergistic application of LTA systems to the delivery of power, generation of a small amount of power, and provision of low-cost communications systems in remote areas. Significant experience has already been accumulated in using LTA systems in India for various purposes. Wind patterns drive the optimum altitude for a self-propelled LTA above 21,000 m, suitable for large stratospheric platforms. Altitudes above 4000 m would enable a tethered LTA to convey millimeter wave power through a waveguide integrated into the tether, tunneling through the high-loss regions of the atmosphere. The millimeter wave power beaming application requires demonstration of the projected antenna mass and other parameters. Tethered aerostats, autonomous powered airships and very high altitude platforms all offer excellent opportunities. Initial sizing explorations show feasible solution spaces.**

***Index Terms*—aerostat, airship, LTA, stratospheric platform, optimization, millimeter wave;antenna;retail power beaming; waveguide**

I. Background and Introduction

Lighter-than-Air (LTA) systems use buoyancy of a gas of low molecular weight than air to come to equilibrium at a selected altitude. Hence they are able to operate even in the absence of relative motion between the platform and ambient air. Though LTA systems suffer from operational limitations, they have some unique capabilities, which can make them a platform of choice for certain applications.

The most commonly known LTA platforms are hot-air or gas-filled balloons. Lacking effective means of steering, they are of limited use. Aerostats and airships are more capable LTA platforms. Aerostats are aerodynamically shaped tethered balloons mounted with fins for stability. Airships are untethered. Onboard propulsion and control systems enable them to handle changes in ambient wind much better, and hence they can relocate and fly around.

Both Aerostats and airships can act as high-altitude platforms for several scientific and commercial applications. They find worldwide use for long endurance aerial observation, imaging and communications, and as aerial advertisement signs. They have excellent green credentials, since their fuel consumption and power requirements are a small fraction of that of any other aerial vehicle for these applications.

A. Summary of Applications

Aerostats have been actively applied to various problems. These include aerial imaging [1]–[3], remote sensing [4], radar [5] visual and infrared monitoring of international borders [6], [7], airspace and movement on the ground , traffic monitoring and control [8], synthetic aperture astronomical telescopes [9]–[11], relaying electromagnetic signals [12], generation of wind power [13] from the jet stream, and collection of solar power from above the cloud layer. Williams [14] proposes power generation from aerodynamic kites, but many of the application lessons may be applied and scaled up to use aerostats which can guarantee liftoff from the ground and endurance regardless of ground-level or upper-level winds.

B. Relevance to Retail Power Beaming

When the issues in power beaming are examined, two things become clear. The first is that diffraction-limited antenna size becomes unacceptably large for rural receivers, at frequencies below 100GHz. Where low frequencies are used, antennae are sized to receive no more than the central main lobe of the beam, thus losing roughly 14 % of the arriving power just through spillage. The second point is that above 10GHz, horizontal power beaming at low altitudes incurs extreme losses, and is impractical beyond 1 or 2 kilometers. For these reasons, Ref. [15] argues for adoption of the 200-225GHz band for beaming vertically through the atmosphere and a couple of thousand kilometers into Space, with a lower waveband such as 100GHz for horizontal transmission over short distances. In their proposed architecture for rural power beaming in

India, local wired grids would be used within a village and its immediate surroundings. Lower-frequency wireless beaming would be used over short distances where the antenna size and transmission loss are not prohibitive, if justified by a tradeoff with the immediate costs and the opportunity costs of installing a wired grid for that purpose. They argue that a wired grid will follow, dictated by the economics of power cost, once the local economy picks up using wireless power for the startup phase. To deliver power over distances of several tens of kilometers, they propose high-altitude (stratospheric) platforms, accompanied by lower-altitude aerostats. These enable the power to be beamed vertically up and down, minimizing distance transmitted through the moist, dense, lower troposphere, and then horizontal line-of-sight beaming through the clear, dry, low-density upper atmosphere using 220GHz beaming. Their interest stems from considering the retail power beaming end of a comprehensive Space Power Grid architecture, enabling renewable power plants around the world to exchange power through and between Space satellites [16] to reach across the planet. They have considered several of the difficult issues in millimeter wave power beaming in earlier work [17].
Dessanti et al [18]have recently considered the startup phase of a space solar power (SSP) using the Space Power Grid, with India and the USA as the first participating nations. While there are obviously difficult obstacles in making millimeter wave power generators and receivers for such high-power applications, and in transmitting such power efficiency, the conversation in power beaming and Space Solar Power has clearly shifted to the regime of millimeter waves. As pointed out above, LTA platforms at several levels provide key enablers for power beaming. The rest of this paper accordingly considers the issues in building and applying such an approach to the Indian rural electrification problem.

II. Program on Airship Design and Development in India

Around a decade ago, studies related to operation and design and development of airships for India were initiated at IIT Bombay through the launch of a Program on Airship Design and Development (PADD). The principal mandate of PADD was to generate a detailed project definition report for design and development of airships to transportat goods and passengers over mountainous terrains, while operating under hot-and-high conditions. Another mandate was to establish the techno-economic feasibility for leasing some airships and gaining operational experience in India [19].

As part of this project, the baseline specifications of a Demo Airship (with payload capacity of 100 kg) and a PaxCargo Airship (with payload capacity of 1500 kg) for operation at an altitude of 3500 m AMSL under ISA+15 deg. conditions were obtained through conceptual design and sizing studies. These studies involved development of a methodology for initial sizing and sensitivity analysis [20], estimation of stresses on the envelope material, estimation of aerodynamic, stability and control characteristics, and dynamic modeling of these airships. Through these studies, the key sizing parameters and their sensitivities to the payload available and/or the envelope size were established, and critical design features, work packages and major tasks were identified. Some design features that could greatly enhance the operational capability and safety of airships over mountainous terrain were also identified and studied.

After completion of this study, an LTA Systems laboratory was set-up at IIT Bombay, where many subsequent studies and projects were carried out to further the design and development of LTA systems for various applications in India. These studies include design development and field prototype testing of indoor remotely controlled airships for neural network control hardware implementation [20], aerostats as platforms for low-cost re-locatable wireless communications systems [21], [22], outdoor remotely controlled airships for product promotion [1], aerial river ferry using superheated steam-filled balloons [23], and aerostats for snow cover evaluation [24].

III. Aerostats for last mile wireless communications

Figure 1 is a conceptual sketch of a low-cost re-locatable wireless communications system, from [21], in which a fixed tower is replaced by a tethered aerostat on which a communications antenna is mounted. Such a system can bring the rural areas in India into the mainstream by providing them last mile connectivity, especially when other modes of communications are severely hampered.

The technical feasibility of this system for voice and data communication over a radius of 7.5 km was established by the design, fabrication and field trials of two working prototypes [21]. A recent study [22] concluded that the total cost of this innovative solution for providing internet access to rural areas is nearly half of the tower based system, over a life cycle of three years. An additional advantage of this system is that it is easily be re-furbished and re-located, which makes it more adaptable to changes in technology and needs.

IV. Sizing of Prototype and Full-Scale Airship for Power Generation

The concept of stratospheric airships is still quite novel, and no such system is currently under actual deployment anywhere in the globe. Several authors have considered such systems. Brown [25] considered such platforms as part of his exploration of options for wireless beaming. Djuknic [26] cited wind velocity profile data acquired and transmitted by the US National Aeronautics and Space Administration High Resolution Doppler Imager (HRDI) using a high-altitude platform. Rehmet et al. [27] provided sizing methodology for high altitude platforms. Thornton et al [28] described the European HeliNet program to use high-altitude platforms in wireless broadband communications.

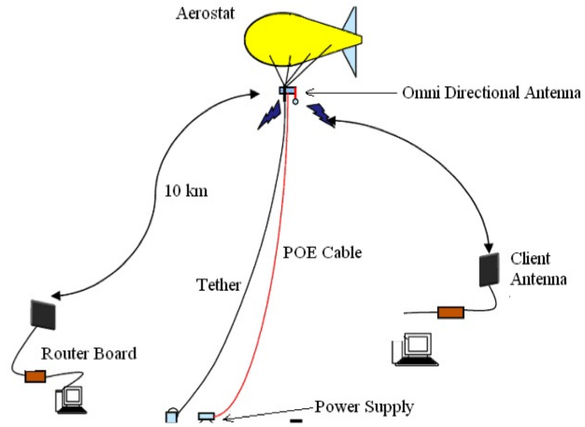

Fig. 1. Aerostat based wireless communications system. From [21]

Tozer and Grace [29] considered such platforms for wireless communications. They cited commercial high altitude platform programs, and the PWI tethered aerostat program in Brazil as examples of contemporary programs (in 2001). Advances in solar-powered airplanes such as the NASA Solar Pathfinder, and in the area of solar-augmented ship power, indicate growing interest in solutions that will enable substantial solar power generation from high-altitude platforms that are immune to clouds and rain. On-station endurance as long as 5 years is being advertised by developers. The reliability of wireless links may not live up to the 99.99 % availability criterion, however, unlike spacecraft, these platforms can be brought to the ground for repair and maintenance. They cite energy storage as a likely issue. Antonini [30] describe stratospheric relays for communications from and to satellites. They consider two HAP-satellite integrated concept for both radio and optical links. One of the advantages cited is in helping to augment the terrestrial telephone infrastructure.

For the power-beaming application, it will be necessary to first create a model-scale prototype airship to prove the concept, and then to develop a full scale version of the same. The airship to be used for power generation purposes would be positioned in stratosphere, in an altitude band of 17-21 km AMSL, in which the ambient wind direction undergoes an inversion and thus a zero-gradient region, thus reducing the onboard power required for station-keeping. A methodology for sizing of an airship of ellipsoid envelope shape given the set of operating requirements was developed by Gawale and Pant [31], based on the general scheme suggested by Rehmet et al [27]. Sizing of an airship was carried out for the operating requirements specified in Table I.

As mentioned by Tozer [29], not all the parameters scale linearly, and hence it will be necessary to build some full-scale prototypes to understand all the issues of full-scale operations.

TABLE I
OPERATING REQUIREMENTS OF AIRSHIP FOR POWER GENERATION

Parameter	Units	Value
Floating Altitude	km	20
Mission Speed	m/s	25
Envelope Slenderness ratio [Length/Diameter]	N/A	7.64
Off standard Temperature	degrees C	ISA+20
Discharging time	hours	8
Average Irradiance	W/m^2	213.76
Solar Cell Efficiency	%	20
Energy Density of Regenerative Fuel Cells	W.h/kg	429

TABLE II
KEY PARAMETERS AND MASS BREAKDOWN FOR PROTOTYPE AND FULL SCALE AIRSHIP

Parameter	Units	Prototype	Full Scale	%change
Envelope Volume	m^3	38939	97538	150
Envelope Area	m^2	8822	16271	84
Envelope Length	m	161	219	36
Envelope Diameter	m	21	29	36
Net Disposable Lift	kg	2920	7316	150
Surface for Solar Cells	m2	1417	2495	76
Thrust Required	N	1093	1924	76
Power Required	kW	28	73	158
Propulsion mass	kg	633	1128	78
Structure Mass	kg	2237	4187	87
Take Off Empty Mass	kg	2870	5316	85

It is assumed that the prototype airship would be required to hover at an altitude of 20 km AMSL and beam a small amount of power to a ground based receiver. Assuming an antenna of 25 m diameter weighing 0.1 per m^2, and approximately 20 kg weight of other on-board equipment, the required payload capacity is approximately 50 kg. It is also assumed that a solar regenerative fuel cell system would be installed on the airship to meet its own power requirements, and an excess capacity of 1 kW. For the full scale system however, an antenna of 150 m diameter and 225 kg weight of other on-board equipment and excess power generation capability of 25 kW is assumed. The last four parameters listed in Table 1 are related to solar power system; the values of these parameters are appropriate for operating conditions in India, which are quoted in [32]. Table II lists the key output parameters and the mass breakdown for the two airships, with Hydrogen as the LTA gas. It can be seen that the percentage change in airship dimensions, power required, and component weights is much smaller in proportion to the change in payload and excess power generation capability of the airship, which illustrates the fact that airships become much more efficient as their size is increased. On the issue of whether ground antenna need be steerable, Tozer [29] points out that if the circular position error due to airship drift is less than the antenna beamwidth, steerable antennae may not be necessary, and communications could be maintained by increasing gain. This is not an acceptable solution for power beaming as it will entail large losses. Whether the right solution is to require every receiving antenna on the ground to be steerable, or to build some pointing capability into the platform, must be considered

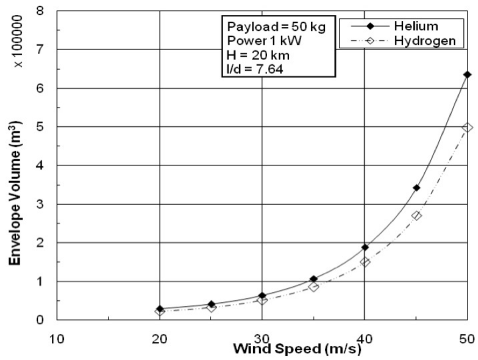

Fig. 2. Sensitivity of envelope volume to ambient wind speeds

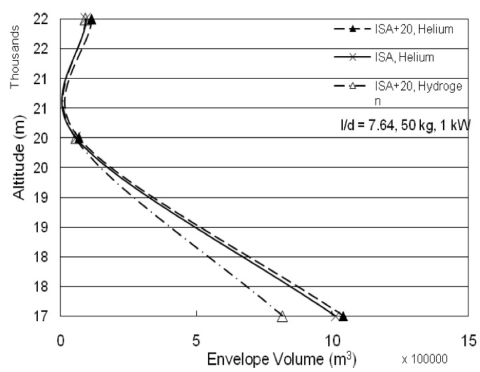

Fig. 3. Sensitivity of envelope volume to operating altitude

in detail later as part of the architecture design.

V. Sensitivity Analyses

Sensitivity analyses were carried out to understand the interdependency of key design parameters and to identify the design drivers i.e., the parameters to which the airship performance at the required operating conditions is most sensitive. Figure 2 illustrates the exponential increase in the envelope volume with increase in ambient wind speed that the airship is expected to handle. The increase in size of the envelope if Helium is used instead of Hydrogen is also quite apparent.

Figure 3 illustrates the sensitivity of envelope volume to the operating altitude. It can be seen that the optimum operating altitude in India is around 21km AMSL. The envelope volume is larger at lower altitudes than this due to higher ambient wind velocities, which increase the powerplant size and weight. Envelope volume is also larger at higher altitude than this, due to loss in buoyancy of the LTA gas.

VI. Sizing of an Aerostat for Power Beaming

It is not enough to generate the power using a stratospheric airship; it is also required to beam this power down to the ground. A tethered aerostat deployed at an altitude of 5 km AMSL could be used for this purpose; this operating height will ensure that the size and weight of the onboard equipment needed for this purpose will be quite manageable. The aerostat altitude may be brought down to 4 km to 5 km with tethered aerostats. The mass per unit length of the tether would probably dictate the optimum altitude in this case.

A methodology for sizing of a tethered aerostat system for high altitude applications has been developed by Raina et al. [24]. Using this methodology, an aerostat system was sized for the operating requirements listed in Table III. The aerostat envelope was assumed to be of GNVR profile with three inflatable fins in inverter Y layout. It was assumed that a total on-board payload carrying capacity of 200 kg would suffice to meet the weight of the power beaming equipment. It was also assumed that the aerostat would be required to stay afloat for a continuous deployment period of 4 months in a year before the need to top up the gas that would have leaked out from the envelope.

TABLE III
Operating requirements of an Aerostat for power beaming

Parameter	Units	Value
Onboard payload mass	kg	200
Floating Altitude	km	5
Ambient wind Speed	m/s	15
Envelope Slenderness ratio [Length/Diameter]	NA	3.05
Off standard Temperature	degrees	ISA+20
Diurnal temperature variation	degrees	+/- 10
Time on station before envelope top-up	months	4
Envelope material specific mass	kg/m2	0.21
Helium leakage rate	lit/ m^2 / day	2.5
Tether specific Mass	kg/m	0.25

TABLE IV
Key parameters and mass breakdown of an Aerostat for power beaming

Parameter	Units	Value
Envelope Volume	m^3	4111
Envelope Surface Area	m^2	1413
Envelope Length	m	43
Envelope Diameter	m	14
Net Disposable Lift	kg	2596
Tether length	m	5500
Envelope group Mass	kg	353
Elastic Strip mass	kg	98
Fin Assembly Mass	kg	141
Tether Mass	kg	1545
Gross Take Off Empty Mass	kg	2137

VII. Millimeter Waveguide Requirements and Sizing

Given that modern tethers have diameter well over 25 mm and already convey small amounts of electrical power and communication signals, one could consider whether a tether could be made, that incorporates a waveguide for Megawatt-level transmission of millimeter wave power.

Below we consider some sizing numbers when using waveguides to transfer power between aerostats and ground stations. For 220 GHz frequency, the wavelength is 1.36 mm. A waveguide of length/breadth ratio 2 is assumed. The length 'a' of the rectangular hollow waveguide cross-section corresponding to half the wavelength is then 0.68 mm, and the breadth 0.34 mm. The wall thickness is assumed to be 2 % of the half-breadth, which becomes 34 microns for each waveguide duct. These parameters give a wall mass of 0.5 grams per meter of waveguide length. The maximum power that can be transmitted per waveguide without risking air breakdown [33], can be derived for this case to be 4.835 kW. With a safety factor of 2, transmission is limited to 2.42 kW. Higher power density and hence lower system mass may be achieved by using rare gases or vacuum rather than low-density, dry air as the waveguide medium. This and other refinements are left to detailed design. Above, we have assumed 1-atmosphere air as the medium in calculating the breakdown power level. By evacuating the waveguide down to a very low pressure, the breakdown power level could be substantially increased, however the waveguide mass and operational complexity may increase due to the evacuation requirement.

If each aerostat is to handle 5 MW of power, and be tied with 4 tethers, then each tether must have a bundle of roughly 517 waveguides. These will occupy a cross-section area with an effective diameter of roughly 25.2 millimeters, not inconsistent with the diameter of present-day tethers [34]. We see that aerostats must be spaced no more than 13.35km apart. We will assume nominally that they are spaced 10 km apart. This implies that if each were to deliver 5MW, we could bring essential electric power to a set of perhaps 10 villages. At first sight these numbers look reasonable for a region which has never enjoyed access to the electric power grid.

The waveguide metal mass in the tether is then 0.281 kg per meter of tether, compared to the present day tether technology of roughly 0.3 kg per tether. If the average tether length is 6000 m in order to allow an aerostat altitude above ground level of 5000 meters, then the waveguide mass in each tether is nearly 1700 kg. How these waveguides are to be incorporated into tethers is again a matter for detailed design. The wordwide market for tethered power exchange aerostats may become large enough that waveguide-integrated tethers may become mass-produced commodities. The waveguides themselves can certainly carry some tension, being made of steel. Whether they can support their own weight, and provide extra tensile strength, remains to be calculated.

Requirements for waveguides can be developed from the above considerations. Since the beam path in this case is straight, one absolute upper bound on attenuation is the attenuation of moist air. There is no point in having a waveguide to a tethered aerostat, that achieves less transmission than what a beam through moist air would achieve. A receiving antenna on the aerostat can be designed for substantially less weight penalty than a waveguide through a tether. An evacuated tube waveguide should be able to achieve nearly the propagation effectiveness of the dry upper atmosphere, but the wall thickness required to support 1 atmosphere of pressure difference may pose a large weight penalty. A better alternative may be to fill the waveguide with a suitable dry gas that transmits the specific chosen frequency well. These issues and opportunities remain to be investigated.

The possibility of sending power with minimal losses through tethers opens the way to an aerostat-based rural beamed power architecture and addresses some of the difficulties identified in Komerath et al [15]. The waveguide enables efficient transmission at 220 GHz vertically through moist, dense atmospheric conditions, thus greatly reducing the weather objection to millimeter wave architectures. In addition, the horizontal transmission loss per kilometer is very low above 4000 m, so that there is no need to go down to 100 GHz for this purpose. The entire architecture can then be focused on 220 GHz. By 220 GHz, we imply that the best choice of wavelength around this window will be chosen in detailed design. The antennae and transmitters can then be designed to optimize efficiency for just the one wavelength, enabling resonant architectures with very high efficiency.

VIII. Conclusions

An initial study has been conducted on the parameter values needed to design lighter than air platforms to transfer millimeter wave beamed power between ground stations. Both tethered and self-powered airships have been considered. The initial estimates of the size and mass of tethered aerostats are well within the parameter range of present concepts or operating platforms. An operating altitude of more than 4000 m above mean sea level enables going well above the moist and dense parts of the atmosphere, and above the monsoon cloud layer in India. This permits efficient millimeter wave beaming between aerostats, and stationing these aerostats at substantial distances to serve the rural market.

The possibility of incorporating an evacuated waveguide into the tether of an aerostat has been considered. The geometric size becomes small enough to fit within modern tether cross-section envelopes. With 4 tethers of no more than present tether size, 5 MW could be transmitted to or from an aerostat using waveguide bundles inside each of 4 tethers, even assuming air-filled rather than evacuated tethers.

Thus to a first approximation we see that the conceptual design for synergistic power beaming and communications using aerostats, is viable. Substantial challenges remain in achieving the projected parameters for the design of the antenna system, and in pointing and station-keeping to sufficient accuracy. The attitude control and shaping of the aerostats to optimize the design, taking into account wind forces and antenna shape requirements, remains as one of the important issues to be considered. The issue of heating due to the large amount of power being transacted, as well as the opportunities for gathering solar power using the same aerostats and the proper use for such power, also remain to be considered. However, the paper shows that aerostats can play a viable and vital role in a beamed power architecture.

ACKNOWLEDGMENT

Participation in this conference is enabled by the NASA EXTROVERT initiative to develop resources for cross-disciplinary innovation. Mr. Tony Springer is the technical monitor.

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