2011 International Symposium on Electronic System Design
Application of Lighter-Than-Air Platforms for Power Beaming, Generation and Communications
Kochi, Kerala India
December 19-December 21
ISBN: 978-0-7695-4570-7
Rajkumar Pant
Narayanan Komerath
Aravinda Kar

DOI Bookmark: http://doi.ieeecomputersociety.org/10.1109/ISED.2011.51

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 wave guide 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

Citation:
Rajkumar Pant, Narayanan Komerath, Aravinda Kar, "Application of Lighter-Than-Air Platforms for Power Beaming, Generation and Communications," ised, pp.242-247, 2011 International Symposium on Electronic System Design, 2011

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

Rajkumar Pant
Department of Aerospace Engineering
Indian Institute of Technology
Mumbai, Maharashtra, India
Email: rajkumar.pant@iitb.acad.in

Narayanan Komerath
Daniel Guggenheim school of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA, USA
Email: komerath@gatecg.edu

Aravinda Kar
College of Optics
CREOL, University of Central Florida
Orlando, FL, USA
*Email:*akar@creol.ucf.edu

***Abstract*—Retail power beaming using millimeter waves offers a rapid way to bring electric power to areas where the terrestrial wired grid is lagging behind the demand for communications, connectivity and other services, such as rural India. Synergy between infrastructure development for communications and for power allows local, regional and global power exchange, bringing renewable and micro renewable power generation devices 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 in India. Significant experience has already been accumulated in using LTA systems in India for various purposes. The millimeter wave power beaming application still 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.**

***Keywords*-aerostat, airship, LTA, stratospheric platform, optimization, millimeter wave;antenna;retail power beaming; waveguide**

I. Background and Introduction

Lighter-than-Air (LTA) systems belong to a class of aerospace platforms that use buoyancy of a lighter-than-air gas to generate bulk of the lift force to overcome gravity; hence they are able to operate even in the absence of any relative motion between the platform and ambient air. Though LTA systems suffer from operational limitations, they do 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; but since these do not have any worthwhile mechanism to steer them, they are of limited use for most applications. Aerostats and Airships are more capable LTA platforms; Aerostats are aerodynamically shaped tethered balloons mounted with fins for stability. Airships are untethered; and since they have onboard propulsion and control system, they can handle changes in ambient wind much better, and hence can relocate and fly around.

Both Aerostats and Airships can act as high-altitude platforms for several scientific and commercial applications. They have been used all over the globe (and India) for long endurance aerial observation, imaging and communications, as well as an aerial banner for advertisement and product promotion, for which they are uniquely suitable. In fact, LTA systems are most suited to meet the requirement of a slow-moving or nearly stationary aerial platform with very long endurance and low vibration levels, to be deployed in mostly in fair weather and calm ambient conditions. 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], and 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 16 %t of the transmitted 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 perhaps 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]. They have considered several of the difficult issues in millimeter wave power beaming in earlier work [17]. Dessanti et al [18]have recently come out with a paper considering 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 principle mandate of PADD was to generate a program definition and detailed project definition report for design and development of airships for transportation of 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 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 for operation over mountainous terrains 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 testing of prototypes 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, 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 in during natural disasters and calamities, 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

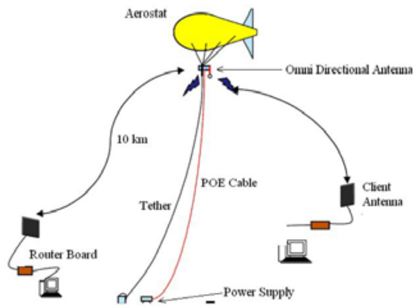

Figure 1. Aerostat based wireless communications system

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. Tozer and Grace [29] considered such platforms for wireless communications. They cite commercial high altitude platform programs, and the PWI tethered aerostat program in Brazil as examples of current 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 to 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

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	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

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, 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 full-scale prototypes to understand all the issues of full-scale operations. 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.

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

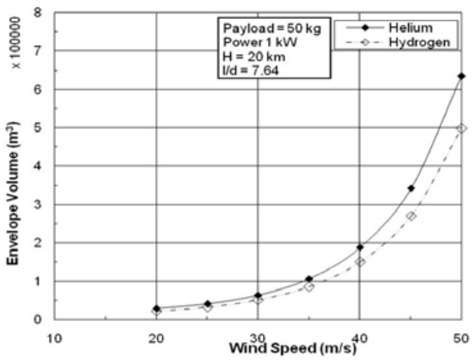

Figure 2. Sensitivity of envelope volume to ambient wind speeds

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 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 reduction in solar cell coverage ratio (i.e., the ratio of area covered by solar cells to the envelope surface area) with increase in the efficiency of solar cells. The effect is illustrated for both the prototype and full-scale airship for two different envelope profiles, viz., the ellipsoidal profile with envelope slenderness ratio (L/D)

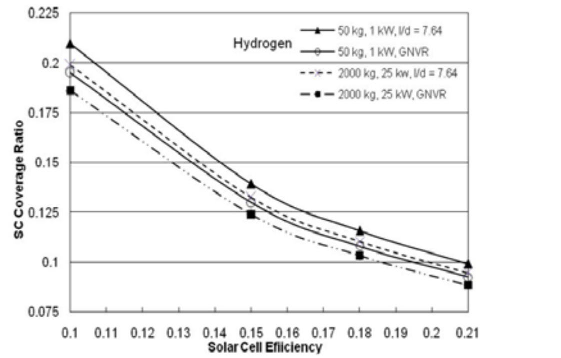

Figure 3. Sensitivity of solar cell coverage ratio with solar cell efficiency

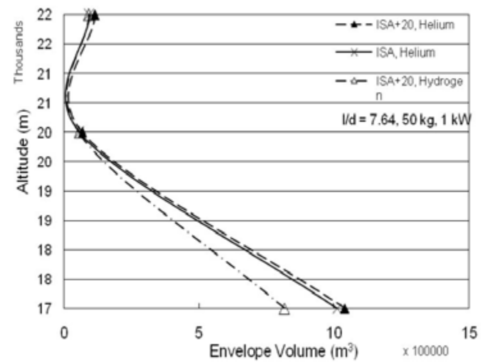

Figure 4. Sensitivity of envelope volume to operating altitude

of 7.54, and the GNVR shape, with L/D of 3.05. Figure 4 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.

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 3. The aerostat envelope was assumed to be of GNVR profile with three inflatable fins in inverter Y layout. It was assume 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

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

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.

VII. 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 5500m 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. Thus to a first approximation we see that the conceptual design for synergistic power beaming and communications using aerostats, is viable.

In the full final paper we expect to provide more detailed estimates. 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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