Interstellar Beamer Engineering

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Abstract. The fundamental differences between solar sails and interstellar beam Riders are presented. Design requirements and design considerations are developed for an interstellar beamer phased array of gigantic proportions for photon pushing beam riding spacecraft to significant fractions of the speed of light. Considerations for beam safety and beamer security are discussed. A suggested asteroid is selected for providing raw materials and a construction base. Means for financing and the economics of the beamer are presented, along with comparisons of the World's energy production and some rate of asset growth histories for putting such a large endeavor into perspective.

INTRODUCTION

Interstellar travel has been a long sought goal. For missions whose length is less than a human lifetime, the only current means using known physics involves photon pressure pushing reflective sail spacecraft. The projectors of the beams of photons to push the sails are giant apertures with powerful transmitters. Their engineering is awesome as regards the scale and economics of such devices.

There is a fundamental difference between solar sails and the beam riding spacecraft discussed here. This difference impacts the Beamer engineering. The distribution of energy across the photon reflectors is the major change. Solar sails use incident sunlight that is uniform across their aperture, whereas the energy distribution from a Beamer is more Gaussian like. The power flux density is peaked in the center and falls off continuously away from the beam axis. This fundamental contrast leads to different "sail" or spacecraft configurations. To reflect that difference the "sail" pushed by the beam from an interstellar Beamer will be referred to as a Rider.

Solar pressure will not suffice to push the spacecraft to interstellar distances in reasonable times and thus very large, coherent electromagnetic systems are required for the power Beamers. We will present the engineering of a System consisting of a Beamer and a Rider for conducting interstellar missions. The emphasis will be on the Beamer as a phased array consisting of reflective optics elements and solar powered electromagnetic converters. Such arrays will have commercial applications in the future for exploiting as well as exploring space and its assets.

We will discuss the underlying concepts for the engineering of giant phased arrays. They are so huge; they must be based in space, and for reasons of economy, constructed in situ of asteroid materials. The design requirements and operating environment will be developed based on an Alpha-Centauri flyby mission proposed by Dr. Robert Forward (1984) and downsized by Landis (1995) both of which proposed using a Fresnel Lens aperture illuminated by a laser array at its focus. However, we will assume a planar phased array Beamer system.

BEAMER REQUIREMENTS

Ordinary sunlight pushing typical thermal limited light sails is inadequate due to the $1/R^2$ diminution of power flux density that reduces the achievable acceleration rapidly beyond the orbit of Earth. The basic physics laws of diffraction also produce in the interstellar Beamer a limited range of efficient power transfer before significant 1/R2 spreading of even the coherent beam takes place. Thus, in order to yield Rider velocities that are a significant fraction of the speed of light, c, the Beamer diameter must be quite large, (of order hundreds of km). This is due to the vast distances to the nearest stars (4.3 Light Years to Alpha Centauri) and the desire to reach there in the lifetime of a principal investigator.

In order to project a coherent beam for the long distances (a few to hundreds of AU) that allow the near continuous acceleration (order of a g to hundreds) to build up the Rider velocity to the desired fraction of the speed (of order greater than10%) of light, without thermally (< 2000K depending on the material) overloading the Rider material, a large diameter, variable focus Beamer is required, to be operated for fractions of a day to days, depending on the mission detail design.

At the end of the beaming period, the round trip light time (RTLT) from Beamer to Rider may be 10s to 100s of days. Thus, at some time into the power-beaming period, it is not possible to receive telemetry from the Rider and to then effect any meaningful changes in Beamer parameters with that time lag. Therefore, the Rider must be able to take care of itself and keep itself nearly centered on the beam. The Rider follows the beam. Move the beam and the Rider should follow if the displacement rate is slow and smooth. The capture range of the beam centroid projected on the Rider is probably less than half the diameter of the Rider. We will discuss how such accurate beam pointing may be accomplished in a subsequent section.

Aperture Taper

Throughout the beaming and in particular near the end of the beaming period, the Rider should intercept a significant fraction of the beamed power, as the acceleration is directly proportional to power intercepted.

A detail in this regard, results in the requirement that the Beamer phased array have an amplitude taper across its aperture. For example, if there were no taper (uniform in amplitude), then only 84 % of the total transmitted power is enclosed within the first nulls, about 2.5 times the half power beamwidth, (only 48% of the transmitted power is within the half power beamwidth). The rest of the energy is in sidelobes. To try to capture more energy would take a larger diameter Rider, whose mass would be much more, thus reducing the effective acceleration.

Therefore, in order to place most of the power in the main beam, it is necessary to taper the amplitude across the aperture. For example, in order to capture 97 % of the transmitted power at the end of the beaming period, the aperture should have about a 14 dB taper according to the Goubau- Schwering (1964) criteria for maximum energy coupling between circular outline apertures.

This means that the power flux density at the edge of the Beamer aperture is $1/25^{th}$ that in the center. Since a lot of structure is associated with the reflector aperture of phased array elements out at the edge, but so little power is radiated, per unit of area, one has to ask if this is cost effective? It may be efficient, but at the expense of optimum economics.

If data were available on the incremental cost of producing the amplitude taper and the Rider mass as a function of radius and the captured energy as a function of radius, beaming time to achieve the desired velocity, etc, one could economically optimize the system for the best beam shape and aperture taper and the allowed spillover at the Rider. A trade study needs to be done to determine the optimum aperture taper.

Because the interstellar Beamer produces a beam shape that results in a Gaussian shaped beam nose, the particular configuration of solar sails with attitude control flaps at the edges of the sails are rendered ineffective due to the low power flux density at the edges of the coherent beam.

A flat-topped beam could be produced if the Beamer has an Airy pattern distribution across its aperture, with the requisite multiple phase reversals and amplitude nulls and peaks. However, the Beamer diameter would need to be nearly three times larger than the Gaussian truncated tapered Beamer for the same –3 dB beamwidth. A 10-times the area Beamer would be very costly indeed.

Beamer System Elements

The System Beamer is composed of the power source, the transmitters or energy converters and the phased array. The prime power source is assumed to be the Sun, thus the System power source subsystem consists of the solar collectors/ reflectors, their support structure, attitude control, and monitor and control equipment.

The phased array includes the beam expanders or antennas, their support and intertie structures, an attitude control system, wavelength or frequency diplexing filters, receivers, signal processing, telemetry and controls and the beam pointing calibration subsystem. The phased array elements of the array aperture should tile the plane as closely as possible. The array aperture efficiency is proportional to the filled to available area. The lost power goes into grating lobes that do not fall on the Rider.

The transmitters include the power conversion devices (for example, solar pumped lasers), their waste heat radiating subsystem, the coherent frequency or wavelength reference driver, its distribution system (fiber optics for example) and monitor and control instrumentation.

We would like to know how best from an economic sense to determine the aperture size and the transmitter power level for effective engineering of an interstellar Beamer.

Beamer Cost Optimization

We can model the cost of an interstellar beamer as the cost of aperture with an areal cost coefficient of A_o-\$/m2, plus the cost of power with coefficient B_0-\$/W. We seek the value of diameter D and power P that minimizes the cost for accelerating a mass m, in kg to a fraction, k of the speed of light, c. We use a wavelength λ, and r is the ratio of Beamer diameter D, to the diameter of the Rider, d.

First, we find the relation between power P and diameter D through the acceleration a, which is 2P/mc, by noting that at maximum useful beaming range, R, the sail diameter d, is approximately $R\lambda/D$. The maximum accelerating time t, is equal to the square root of 2R/a. Substituting kc for the velocity, v leads to the value of P in terms of D:

$$P = \frac{mc^3k^2r\lambda}{4D^2} \;\&\; P = qD^{-2} \tag{1}$$

Thus, the total beamer cost $Ct = A_o D^2 + B_o q D^{-2}$. Differentiating with respect to D, equating the results to zero and solving for Dopt, yields:

$$D_{opt} = \sqrt[4]{\frac{mrc^3k^2\lambda B_o}{4A_o}} \;\&\; P_{opt} = \frac{kc^{3/2}}{2}\sqrt{mr\lambda A_o / B_o} \tag{2}$$

The minimum cost for this two-parameter model occurs when the cost of power is equal to the cost of aperture. The optimum beamer diameter is proportional to the fourth root of mass to be accelerated, whereas the optimum power is proportional to the square root of mass.

Table one shows the parameters for Beamer designs at three different wavelengths, with different estimates for the key cost coefficient parameters. The three systems are designed for accelerating 1000 kg of combined Rider and payload mass to 11% of the speed of light and assuming a ratio of Beamer to Rider diameter of 275.

To put the Beamer engineering and economics into perspective, Fig. 1 shows a comparison of the USA GDP and world annual energy and electric generating capacity, which is to be compared to the Beamers in the table, which all require 1.37 Trillion kWh and whose radiated power varies from 2-150Terawatts.

Such enormous apertures need to be located in space, off the Earth, in order to collect sunlight continuously. Based on conversations with Dr. Steve Ostro, concerning my estimated quantities of materials for the Beamer, he suggested the near Earth Asteroid 1986 DA, which has an orbit-to-orbit closest approach distance to Earth of 0.18607 AU. A beneficiated mass composition estimate by Ostro is 10 Billion Tons of iron, 1 Billion Tons of nickel, 100 thousand Tons of Platinum and 10 thousand Tons of Gold.

The Rider

The Rider is composed of the spacecraft housekeeping function equipment and the science payload distributed across the basic reflecting material. The Rider design is to have the center of pressure always ahead of the center of mass in the direction of flight. The geometrical arrangement of Rider material in connection with the beam are shaped to passively generate restoring forces that drive the Rider toward the beam centerline, stabilize it against excessive rotation rates (the Beamer and Rider may be elliptical in outline) and prevent excessive yawing.

There are limits to the magnitude of beam displacement or Rider translation relative to the beam centroid before a point of no return is reached. The degree of softness or sharpness at this transition boundary is a function of the geometry of the beam and the Rider and the moments of inertia of the Rider. Achieving the highest average efficiency of intercepting a significant fraction of the beamed power with the least mass and with the most robust beam riding stability is a design challenge of importance.

Operating in the vacuum of space with the lack of natural damping means there is not a steady state to the Rider motion relative to the beam, but a region where displacement fluctuations of the Rider about the beam boresight remain within some bounds. There are quasiperiodic fluctuations leading to turbulent solutions but with average results.

The Rider basic housekeeping subsystems functions include the control system, telecom, auxiliary power/ energy storage, thermal control, etc, along with a fabric maintenance subsystem. The function of the later subsystem is to effect repairs to the fabric caused by debris impacts that are structurally significant.

Beamer-Rider Pointing

The beam must be pointed with sufficient accuracy to place the coasting Rider within the desired approach window at the target star system, as the Rider is not capable of large trajectory changes after prime beaming termination when the desired velocity is reached.

The Beamer can be diplexed to allow receiving images from the target star system to aid in determining the beam-lead pointing for the system. Since the Rider is just that, a passenger on the beam, its geometry is designed to passively stay near the peak of the transmitted beam. Ergo, the beam must be placed where one wants the spacecraft to be at any given time, and it must be pointed in the outbound beam direction from the Beamer. A navigational challenge.

We will assume that the pointing must be accurate enough to place the –3 dB half power beamwidth (HPBW) or full width half maximum (FWHM) of the beam (approximately the wavelength divided by the Beamer diameter) within the half diameter of the Rider, a real engineering challenge.

The Beamer must provide the power beam to the Rider nearly continuously for up to a month in some cases, and with no interruption lasting longer than a few hours, for example. This maximum interval should be determined by estimating unmodeled motions of the Rider transverse to the last known beam direction in space at the moment of beam –off. A longer period of interruption would permit the Rider to drift beyond the point of no return. The pointing knowledge capture range may be exceeded and the round trip light time (RTLT) delays may preclude reacquisition. The Rider has no means of finding or getting to the beam; thus the Beamer must place the beam within the capture region of the Rider for reacquisition.

A tracked-fleet of pointing reference microspacecraft that are in the field-of-view (FOV) of the Beamer subarrays can be used to provide a before and after pointing reference for reacquisition. They can also act as the required keys to enable the appropriately interlocked-transmitters to only be turned on when they are pointing in the direction of a Rider. A beam-safety feature. As a matter of fact, the Beamer will require a security system in order that it not be turned into a dangerous weapon. It should be either performing commercial service for space transportation with beamed power, for tourism support and asteroid prospecting assaying, etc, or for interstellar science for radar, imaging, lidar and probe launching.

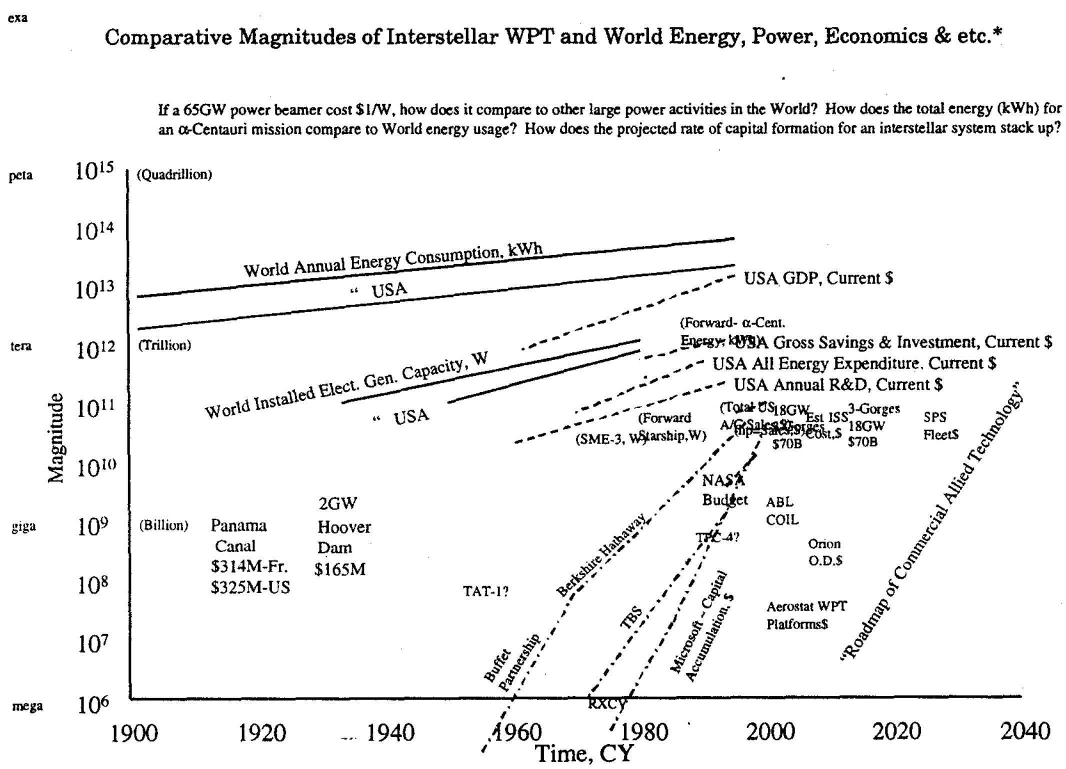

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FIGURE 1. Relative data for placing the interstellar Beamer economics and energy in perspective.

(3)

TABLE 1. Interstellar Beamer System Parameters for Three Different Wavelength Designs

One Micron Wavelength	1.22 mm Wavelength (245GHz)	5.17 cm Wavelength (5.8 GHz)
Aperture Area Cost Coeff. = $1000/m2	50	10
Power Cost Coefficient = $5/W	2	0.5
Optimum Beamer Diameter = 103 km	1023	2758

Optimum Transmit Power =2120 GW	26200	152000
Beamer Cost, Trillion (1e12) $ = 21.2 T	105 T	152T
Beaming Range = 259 AU	20.9 AU	3.6 AU
Beaming Time Period = 648.5 hr	52.4	9
Rider & Payload Acceleration = 1.44 g	17.8	104
RTLT at End of Beaming = 71.4 hrs	5.77	0.99
Rider diameter = 0.374 km	3.72	10
Rider Ave Pwr. Density =19.3 MW/m2	2.41	1.93

CONCLUSIONS

Beamers for driving interstellar photon sails that ride the beam will require huge kilometer apertures and tremendous power (GWs) in the beam. We have developed a cost model and equations to allow determining the optimum aperture diameter and transmitted power level.

Interstellar beamers will probably be space based and manufactured from asteroid materials. In order for such systems to be affordable, the infrastructure that supports them must be parts of a commercial enterprise. The estimated rates of capital formation needed over the next forty years are commensurate with recent commercial enterprises in the USA. Interstellar exploration is difficult and costly, but not impossible in this millennium.

NOMENCLATURE

GDP = Gross Domestic Product ($/annum)
GWs = Gigawatts (10e9 W)
RTLT = Round Trip Light Time
FOV = Field of view

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