Space Propulsion and Power Beaming Using Millimeter Systems*

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ABSTRACT

Past schemes for using beamed microwave power for space propulsion and providing power to space platforms have used microwaves below 10 GHz. Recent expansions of the high power microwave technology domain offer fundamental reassessment of the following missions: 1)location of orbital debris, 2) supplying power to loitering high-altitude airplanes, 3) satellite battery recharging, 4) imaging of asteroids, 5) orbit raising and transfer, 6) interplanetary probe launch to the outer planets and comets, and ultimately 7) launch into Earth orbit. This group of applications may be done by a ground-based system. The system would start small, being built for the near Earth missions, and be enlarged incrementally as the technology matures and confidence develops. Of particular interest are sources in the millimeter range where there are low loss atmospheric windows and MJ pulses are available in quasi-CW operation. A development scenario for these missions using millimeter wave technology is described.

INTRODUCTION

Two factors dominate space development: the cost of transportation to and in space and the availability of operating power once there. We advocate here that propulsion and power can both be done with the same technology: beaming power from ground based stations. Moreover, there is a technology growth path which leads naturally through a series of mission capabilities with common hardware. The goal is substantial cost savings by using the same technology to perform different functions. The early applications are potentially commercial so that technology can be transferred to the private sector, in the spirit of current policy trends.

This work can be summarized in two quite independent propositions:

1) Space propulsion and power beaming applications-which vary over several orders of magnitude in required power aperture product or effective radiated power (ERP)-can be met by building up a system using increasing numbers of modules, starting from a single module for identification of orbital debris to

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hundreds of modules for imaging and deep space probes and culminating in 3,000 module system for launch of 30 kg payloads into low Earth orbit (LEO).

2) The optimum frequency for such power beaming applications is likely in the millimeter wave regime rather than in the ~10 cm regime of most previous studies.

Several means for using microwave beams for space propulsion and power applications were proposed in the past. In the last 15 years the technology base has been expanded, allowing new power beaming missions and offering innovative improvements to existing missions. Generically known as "high power microwaves" (HPM), this new technology produces very high CW and peak powers over an extensive frequency range.

Of particular interest for space applications are powerful sources now available at wavelengths in the millimeter range. Twenty-five years ago such sources were available at average powers of a watt. Now these powers have reached megawatt levels for quasi-continuous operation[5]. There are now commercial varieties used in fusion research which deliver megajoule pulses at frequencies above 100 GHz (3 millimeters). They do so by tapping the enormous power and energy reservoirs of modern intense relativistic electron beam technology.

HISTORY

The first high power microwave beaming experimental work was performed by Dickinson in 1975[4]. This test was conducted at Goldstone over a range of 1.5 km. A 25 m^2 array of elements collected the microwave beam at a conversion efficiency above 80% at 30 kW transmitted average power. The frequency was 2.4 GHz, using technology of the 1950's.

The new HPM technologies have not been applied to NASA missions because, in the 1960-1975 era, when the concept work by Bob Forward[2] and Martin Willinsky[3] and William Brown was done, the only technologies available at high average powers were in the centimeter wave region below 10 GHz.

Recently a concept for the most difficult of missions, direct launch into Earth orbit, was advanced by Benford and Myrabo[1]. Costs reductions of two orders of magnitude were estimated. The capital investment required for such a large facility, not to mention the development program, raised the question of a development path with accompanying economies. This led to the present work.

POWER BEAMING MISSION CLASSES

The missions fall into general classes divided according to the average power required. Therefore they provide a path for technology growth, allowing near term applications with present day satellites at moderate power levels and extrapolating to long range missions requiring much higher power. In this paper we describe a development path leading to LEO launch at 30 MW power level. For completeness we list applications of greater power as well.

The first power mission class requires average power levels up to 100 kW:

1) Location of orbital debris
2) Supplying electric power to loitering high altitude airplanes or aerostats (powered balloons)

The second mission class requires average powers of order 1 MW:

3) Spacecraft battery recharge in low Earth orbit and geostationary orbit.
4) Earth-crossing asteroid imaging. Mapping of asteroids both for

resource assessment and because of concerns about collisions with Earth.

The third mission class uses powers of the order of tens of MW:

5) Interplanetary probe launch, particularly to the outer solar system, using microwave radiation pressure broadcast from the ground to spacecraft in Earth orbit (as in the solar sail concept, but at much higher power densities) with low mass scientific payloads. This technology may be compatible with NASA's New Millennium spacecraft program. Of particular interest are outer planet flyby and Oort cloud missions, where high velocity is required.

6) Orbit raising and maneuver, such as moving satellites within a given orbit to a different plane, and raising satellites to geosynchronous orbit (GEO).

7) Launch to low Earth orbit using a combination of air breathing pulse jet and terminal phase rocket. The cost to orbit can be lowered by perhaps two orders of magnitude

These missions are now more feasible because of HPM technology advances. The fourth mission class demands powers of order 100 MW to 1 GW, but are beyond the scope of this paper:

8) Solar Power Station- providing large scale power to Earth from huge orbiting platforms.

9) Lunar Power System- like SPS, but on the moon and built from lunar materials.

10) Earth-to-Moon power beaming during the two week dark period. This has been shown to have advantages over large area solar cells, battery storage and nuclear generators because of the high cost of space transportation.

11) Interstellar launch-like outer planet launch, but with very low mass payloads and much higher power.

GROUND BASED HPM TRANSMITTER

Power beaming through the atmosphere depends upon two principal factors, the power of the available sources and the attenuation through the atmosphere. At the 1-10 GHz frequencies chosen for previous beaming studies, attenuation is not a factor and the highest peak powers are produced. There are advantages to going to much higher frequencies: Technology development for fusion has produced high power sources at very high frequencies. Relative to low frequency microwaves, high frequencies offer smaller broadcasting and receiving antennas and rectennas. In general real estate gets smaller. Relative to lasers, higher microwave frequencies are less expensive and of much higher efficiency.

There are atmospheric windows at 95 GHz and around 220 GHz where attenuation, due to water molecule absorption, is high at the surface but is slight at high altitudes. For example, transmission efficiency for vertical beaming around 220 GHz from a 4 kilometer altitude site is 95% compared with 45% at sea level. Considering the added cost of construction at high altitude, high desert locations at intermediate altitudes may be preferred.

The problem of air breakdown at high altitudes is eliminated because the breakdown fluence ϕ in W/cm^2 scales as

$$\phi=2.39\ p^2\left(1+\frac{\omega^2}{\nu^2}\right)$$

where p is the pressure in Torr., ω is the angular frequency,of the emitted radiation and $\nu = 5.3 \times 10^9$ p (s^{-1}) is the molecular collision frequency of the air at that pressure. At high frequencies the second term dominates and the problem of breakdown at high altitudes is bypassed. Therefore, the optimum window when one considers the size of the radiating antenna is at much higher frequencies than have been studied previously . A good frequency is 245 GHz because government allocation for radiation is unrestricted; we will use 245 GHz in our calculations.

New sources are available with high power and high energy capabilities. The HPM devices we describe in this paper are very different from lower frequency microwave devices such as magnetrons, klystrons and traveling wave tubes, which typically use rectangular waveguides in fundamental modes for extraction. Many of the HPM devices employ altogether new interaction mechanisms. This emerging technology includes not only sources but overmoded transmission waveguides, phase shifters, rectennas and other components.

The appropriate sources for producing radiation around 220 -250 GHz are free electron lasers, the gyrotron family (especially Cyclotron Auto- Resonant Masers, CARMs), and the Cerenkov source family, which has powerful members at high frequencies. All can be operated as amplifiers, as preferred for the phased array antenna. Oscillators are not excluded, however. Recent experiments reported in this conference,[Ref. D.J. Hoppe, et al, "Phase Locking of a Second Harmonic Gyrotron Using a Quasi-Optical Circulator," paper 2557-54, this Session], show phase control of high frequency gyrotron occollators. Master oscillators can drive, i.e., control the phase of, both oscillator arrays and amplfier areays.

Not all the above devices have been developed at frequencies higher than 120 GHz, but there is no fundamental reason why they cannot be. Substantial peak and average microwave powers at such high frequencies have not been the subject of investigation by the HPM community. At 120 GHz the peak power per source of Cerenkov generators and CARMs is about 10 MW, whereas FELs have operated at powers of several GW at 120 GHz. Internal breakdown will not be a problem at these short wavelengths; all the candidates operate highly overmoded and one can reasonably expect that they can be developed to suit this requirement.

High average power at high frequency has advanced significantly in recent years due to the needs of the magnetic fusion program for plasma heaters. Gyrotrons are currently being used for development of tubes in the megawatt class at frequencies from 100-280 GHz, producing microwave energy at the MJ level. They have reached the domain required for power beaming applications. For example, Varian now produces a 110 GHz gyrotron that produces a 0.5 MW pulse for 2 seconds, giving 1 MJ/pulse. The built-in quasi-optical mode converter produces a Gaussian transverse intensity distribution. Such beams are suitable for transportation with small losses via oversized or mirror transmission lines. These techniques are necessary in order to propagate large amounts of power in waveguide structures that are easy to build. Thus the power limitations of conventional waveguide techniques have been circumvented in the millimeter wave region. Present development programs call for 1 MW, 280 GHz CW gyrotrons, quite sufficient for the applications discussed in this paper.

The key technology issues for such high power sources are largely independent of source type. Issues for high power gyrotrons at high frequency are described in detail by Felch et.al.[6] and Goldenberg and Litvac. The key issues are 1) power dissipation in the cavities: the power density on the wall can be ~ 4 kW/cm^2 using present technology, which allows 1 MW devices with 250 cm^2 collector area, 2) magnets: superconducting magnets are essential for the large fields and cost is determined by bore size, 3) output coupler: optical techniques such as the Vlasov coupler have produced 95% transmission, 4) extraction windows: cryogenically-cooled single-disk sapphire windows look attractive due to lower RF losses and significantly higher conductivity of sapphire at high temperature.

ARRAY MODULE

.The proposed array module shown in Figure 1 consists of a thermally controlled elevation over azimuth (AZ-EL), beam waveguide (BWG) parabolic antenna about 9 m in diameter. The optimum size will be determined by an economic analysis to conform to Dickinson's Law [Ref. R.M. Dickinson, "Cost Effectiveness of Spacecraft Pointing Antenna," JPL Technical Memorandum 33-390 (1968)] wherein for a given effective isotropic radiated power (EIRP) requirement, the minimum system cost is achieved when the cost of antenna gain (including the cost of pointing, acquisition and tracking) is equal to the cost of transmitter power (including the raw power, power supply, cooling and exciter).

The gyrotron transmitter and the low noise amplifier (LNA) receiver are housed in the antenna pedestal and are duplexed to the BWG feed system via a flip-mirror arrangement. The array operating frequency is proposed to be in the radio spectrum segment allocated to the Industrial, Scientific and Medical (ISM) band at 244-246 GHz [Ref. United States Frequency Allocations, U.S. Dept. of Commerce, National Telecommunications and Information Administration, Office of Spectrum Management].

Commanded phase steering of the array power beam will be done by supplying each transmitter with a common frequency reference distributed by buried fiber optic lines and applying to its phase shifter the sum of the calculated geometrical path length phase difference and the transmitting equipment phase conjugate determined from periodically receiving with a common receiver sequentially all of the transmitters returned pulses from a piece of orbital debris or one of the numerous radar calibration spheres in orbit such as the Lincoln Calibration Sphere Object #90D in the U.S. Space Command Satellite Catalog (SAT CAT), or LCS-1 [Ref. M. I. Skolnik, "Radar Handbook", McGraw-Hill, 33-4, 1970.]. Similarly, determining the receiving array equipment phase calibration conjugate values will be accomplished by periodically receiving one transmitted pulse simultaneously at all of the receivers, before applying the computed beam steering commands required for the desired geometrical pointing direction.

The gyrotron can be either an amplifier or a phase-injection-locked oscillator [Ref. D.J. Hoppe, et al, "Phase Locking of a Second Harmonic Gyrotron Using a Quasi-Optical Circulator," paper 2557-54, this Session]. In the former unit the array beam steering is done simply by phase shifting the module drive signal. In the latter case the beam steering must also include means such as a magnetic field strength trim to set the rest frequency of the oscillator.

Figure 2 gives a layout of a 245 GHz, 30 MW ground-based power beaming station which would be the end point of the development program we are discussing. It has a span of 550 m and contains 3,000 gyrotrons at 10 kW power. A single radiating element is the 9 m dish as in Figure 1.

The module in Figure 1 is in fact within the present state-of-the-art. Both the source and antenna technical barriers have already been surmounted. For example, the specific window at 245 can be accessed with gyrotron technology. In Figure 3 we see a commercial 110 GHz device within reach of the specifications we need. Its power is higher and its frequency is lower than the module we describe.

Moreover, the module antenna already exists in the form of large numbers of millimeter wave telescopes scattered around the world. They are used for millimeter and submillimeter wave astronomy. At present there are about 20 such telescopes with diameters typically about 10 meters.but varying up to 100 meters. They have high aperture efficiency in most cases; the Cal Tech Submillimeter Observatory has an aperture efficiency of 75% up to 1 THz. Some are at high altitude sites such as Mauna Kea in Hawaii, some are at lower elevations in high, dry desert such as the Owen's Valley Six Antenna Submillimeter Array.

Beamed Power Safety: All beamed power systems must have their transmitters interlocked with a safety surveillance radar subsystem. This will be required to protect the wayward aeronaut and his equipment or avian biota even if the array is located in a restricted air space. If the intruder is about to enter the beam, the options are to divert, dim or douse it [R.M. Dickinson, "The Beamed Power Microwave Transmitting Antenna," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-26, No. 5, pp. 335-340, May 1978]. The system must accommodate the resulting electrical transients.

SYSTEMS FOR THE MISSIONS

Table 1 shows rough estimates of the requirements of each mission and the number of 9 meter diameter, 10 kW modules needed. The multi-purpose approach is shown in Figure 4.

Orbital Debris: An early application of one or a few of the array modules is to provide orbital debris mapping [Ref. U.S. Congress, Office of Technology Assessment, "Orbital Debris: A Space Environmental Problem-Background Paper," OTA-BP-ISC-72 (Washington, DC: U.S. Government Printing Office, Sept. 1990)]. By integrating pulses it is estimated that a single 9 m diameter antenna with 50% aperture efficiency (Strehl ratio 0.5) and a 10 kW average power at 245 GHz operating with a 260 K receiver can deliver a 13 dB SNR return from a 1 mm diameter particle (radar cross section, RCS of -58.3 dBsm, dB relative to one square meter) at a range of about 500 km. The phase stability between pulses must be on the order of 10 degrees rms or less. The repeatability within pulses must be of the same order.

Beamed Power to Aerostats: The technology of the modular array could be adapted to supplying electric power to run motors with propellers on airplanes or aerostats (powered balloons) in order to keep them near stationary at high altitude above the array [Ref. J.W. Sinko, "High Altitude Powered Platform Cost and Feasibility Study," SRI Project 5655-502 for NASA HQ. Contract NASW-2926, October 12, 1977]. Such vehicles could function as communications and observations platforms. Rectennas on the airborne vehicles would intercept the RF power beam and convert it to dc voltage for motors and payloads. [Ref. E.B. Graves, "The Feasibility of a High-Altitude Aircraft Platform With Consideration of Technological and Societal Constraints," NASA Technical Memorandum 84508, Langley Research Center, June 1982]. The altitude for minimum flight power to overcome the wind aloft drag is at 70,000 ft. [Ref. T.W. Straganac, "Wind Study for High Altitude Platform Design," NASA Reference Publication 1044, Wallops Flight Center, December 1979]./ The basic array module with its 9 m transmitting dish equipped with variable focus could provide a -3 dB spot size of about 3 m at the 21.3 km altitude. Clouds and rain would provide significant attenuation, however, so a high dry site is desirable. Furthermore, the system and its payloads must accommodate the beam power dimming of propagation impairments.

Spacecraft battery recharge: Commercial communication satellites during periods of solar eclipse must use battery systems to provide on-board power and the lifetime of such batteries limits the operational lifetime of the entire platform. One estimate has shown that a power beaming system from a single ground station providing 25 kW of power could produce direct cost savings to the communication satellite industry of a hundred million dollars per year by extending satellite lifetime. This gives an immediate commercial payoff. Another possible use is for powering electric propulsion systems intended for station keeping or orbital transfer. Some commercial satellites use electric thrusters for station keeping. Power beaming would allow them to operate at higher power levels without having to increase the size of the attached solar arrays.

Asteroid Imaging: Using delay-Doppler imaging techniques [Ref. S. Ostrol], an array of modules can provide images of near Earth asteroids. Assuming a required 20 dB SNR for single pulse operation, approximately 375 modules could image a 10 km 2 RCS asteroid at a range of 0.1 AU. The full array of 3,000 modules could perform similarly at a range of 0.48 AU, which is beyond Mars closest approach (0.38 AU). The desired phase stability and repeatability for imaging applications should be improved over that of simple target detection.

Deep Space Probe Launch: Once the system approaches large numbers of radiators it is possible to begin launching probes using the microwave radiation pressure. This is similar to the solar sail concept, but at much higher power densities on the reflecting, ultra-light vehicle. This concept has been explored by Robert Forward and we will relate this work to his examples. It is necessary, of course, to use very low mass scientific payloads, which is compatible with the direction of NASA toward the New Millennium spacecraft. The most unknown regions of the solar system are the outer planets and and beyond Of special importance are the cometary clouds that reside in the region of the outer planets. The inner region, known as the Kuiper Belt, is beyond Neptune and the outer region, the Oort Cloud, is beyond Pluto). To explore this realm requires very high velocities, in order to have missions occur within reasonable mission time scales and funding cycles, and very low mass in order to get the high velocities.

Microwaves accelerate payloads at an acceleration

$$a = 2\,\varepsilon P/mc$$

where ε is the efficiency, P the power received and m the mass. The method is to accelerate the sail first in the region out to where the beam spot can be focused to the sail diameter which is given by the diffraction limited distance

$$S = \frac{Dd}{2.44\lambda}.$$

where d is the sail diameter and D is the antenna diameter. Forward has shown that the velocity beyond this point will increase by 40% due to further acceleration with declining efficiency. To achieve a given terminal velocity the power required is given by

$$P = \frac{2.44\ McV_f^2\lambda}{8\ \varepsilon dD}$$

where m is the mass. Detailed analysis shows that the acceleration required to reach a given terminal velocity scales as

$$a \propto \frac{P\lambda}{d^2} \sim \frac{m\lambda^2}{d^3}$$

which shows the extreme importance of going to shorter wavelengths and increasing the diameter without increasing the mass. Clearly the advantage of going to higher frequencies will reduce the power requirement, reduce the acceleration and lengthen the accelerating distance S. This means that the device can be designed for the ~1 g tolerance of contemporary hardware, instead of extreme accelerations at lower frequencies.

As a specific example, in Table 2 we show a comparison of the Forward design and the present calculation. We have chosen a less sporty approach than Forward, using a larger mass, although quite small, and a smaller sail diameter. The effect of the higher frequency is that even with lower radiated power we can accelerate at a low acceleration to a higher terminal velocity over a longer distance. with the full 3000 module system we get ~40km/sec so the outer planets are only about a year away. Deep space probes need only half that. One can drop the velocity by a factor of two in several manners; we choose a higher mass, 120 grams. Since the final velocity is roughly proportional to the power-aperture product (at constant d/D ratio), we could begin interplanetary probe operations when the number of modules is a quarter of the final system, i. e., 750 modules.

Launch into Earth Orbit: The mission is described in reference 1 and in the next paper in these proceedings.

A DEVELOPMENT PROGRAM FOR HPM SPACE APPLICATIONS

The basic argument for such an approach is clear: Power beaming becomes economic only when it can move power from where it is cheap and accessible to places where it is hard to come by. Previous work has shown that it is often more economical to transmit power than to move the equipment to produce power locally. Modern power systems are expensive and complex, but if power for space can be located where it is easily accessible and adjacent to where the required skilled people are located, i.e., on Earth, then it becomes more practical.

If large scale space power beaming is to become a reality it must be broadly attractive. This means that it must provide for a real need, make business sense, attract investment, be environmentally benign, be economically attractive and have major energy or aerospace firms support and lobby for it.

Figures 5 and 6 show a logical development program for achieving missions in sequence by enlarging the facility. The linear relationship between transmitter power and area means that the horizontal axis is also proportional to the number of modules. The antenna area unit used here is easy to visualize: 10^4 square meters is a square 100 meters on a side.

Orbital debris mapping would be the first objective and could be accomplished with a single module. Similarly, recharging of satellite batteries in LEO would take place with a few modules and can reach commercial possibilities with about 90. This gives ten times solar flux, i.e., 13.8 kW/cm^2, on a satellite as it passes overhead. This would be followed by an astroid imaging capability, with an ability to resolve asteroids at a range of 9 million miles. Launch of deep space probes with a mass of 120 grams to a velocity of 20 km/s can achieved with 750 modules (with the full system, the probe mass becomes 3 kg, a more realistic mass for single sensor dedicated probes with aluminized mylar sails made in quantity.

Recharging of satellites in GEO becomes possible at about the 1500 module level. This is a large commercial area and could provide a big payoff.

Finally, at the full 3,000 module capability one can to launch into orbit a small 30 kg objects carrying cargo, launching every few minutes. This makes industrial transport in and out of LEO a reality at cost about two orders of magnitude less than present day and at least an order of magnitude less than rocketry can ever achieve. This facility will also allow imaging of astroids out to 100 million miles, which is all the capability that will ever be needed.

At the top of the figure is a development timeline for the production of the modules. In the early part of the 21st century production could be about one per week moving on to one per day in about 2015. Production of high power sources on this scale is comparable to that already being studied by DOE for the Next Linear Collider (NLC). The NLC tubes operate at about 11 GHz. Nevertheless, there average power is comparable to that needed for this array. DOE is investigating the use of automated production to make such large numbers of tubes at low unit cost; their goal is 50 k$ per tube and the same for the power supply. We can anticipate that such production methods will be in existence in the first decade of the 21st century.

In today's climate it is important for technology development to be coupled to commercial applications. In our view several of the missions we've described are potentially commercial matters. Starting with orbital debris mapping, one can see an incremental commercial development leading first to satellite power recharging. Eventually, as the space market and business confidence grows and capital becomes more available, this development plan leads to the repowering of satellites in GEO and ultimately to launch services with the full system. Investment costs are minimized because the research program leads to many applications.

Therefore, the private sector should be included from the outset in the development of power beaming for space applications . This includes the R&D phase, as it is very important to gain support from industry to maintain a long-term commercial strategy.

Finally, we have to consider the scale of the enterprise we were discussing. Figure 7 shows the Solar System to scale. It is accepted by many that in the next millennium mankind will begin to develop the Solar System. While this is a common opinion, there is no clear view of how it is to be achieved and by what technology we are to make the Solar System readily accessible. This paper has attempted to demonstrate that the technical means are already in hand for a space infrastructure. A unified approach to many missions can be found by looking to the use of millimeter wave beams to provide power and transportation. In a sense this amounts to exploring at the speed of light.

We do not pretend that the module and development path we have described is optimal. Perhaps lasers will be more suited for some applications, as in the SELENE program. We feel that much work must be done to decide whether this method is in fact practical on economic grounds. We urge the technical, and governmental community to support studies of this possible road to our future.

We gratefully acknowledge discussions with Dominic Benford and Dan Greenwood.

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Table 2. Interplanetary Probe Launch By Beam Powered Sails

Parameter	R.L. Forward	Benford & DickInson
Average Radiated Power, MW	100	30
Frequency, GHz	10	245
Mass (g)	3	120
Sail Diameter d(m)	100	10
Acceleration, Earth Gravities	22.7	0.68
Accelerating Range S, km	410	1,760
Acceleration Time, sec	61	760
Final Velocity V_f, km/sec	19	19

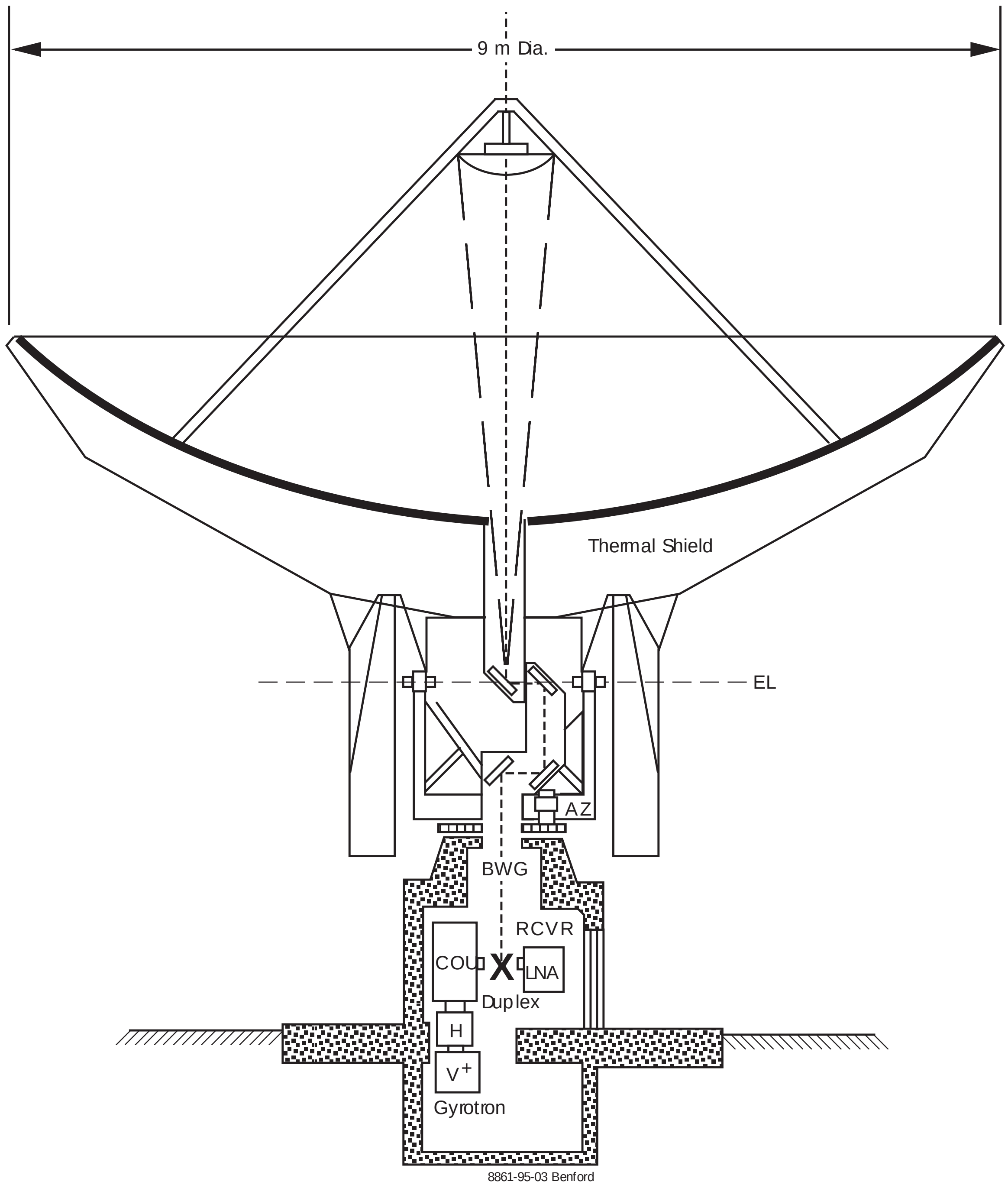

Figure 1. Concept for Module of the Millimeter Wave Phased Array.

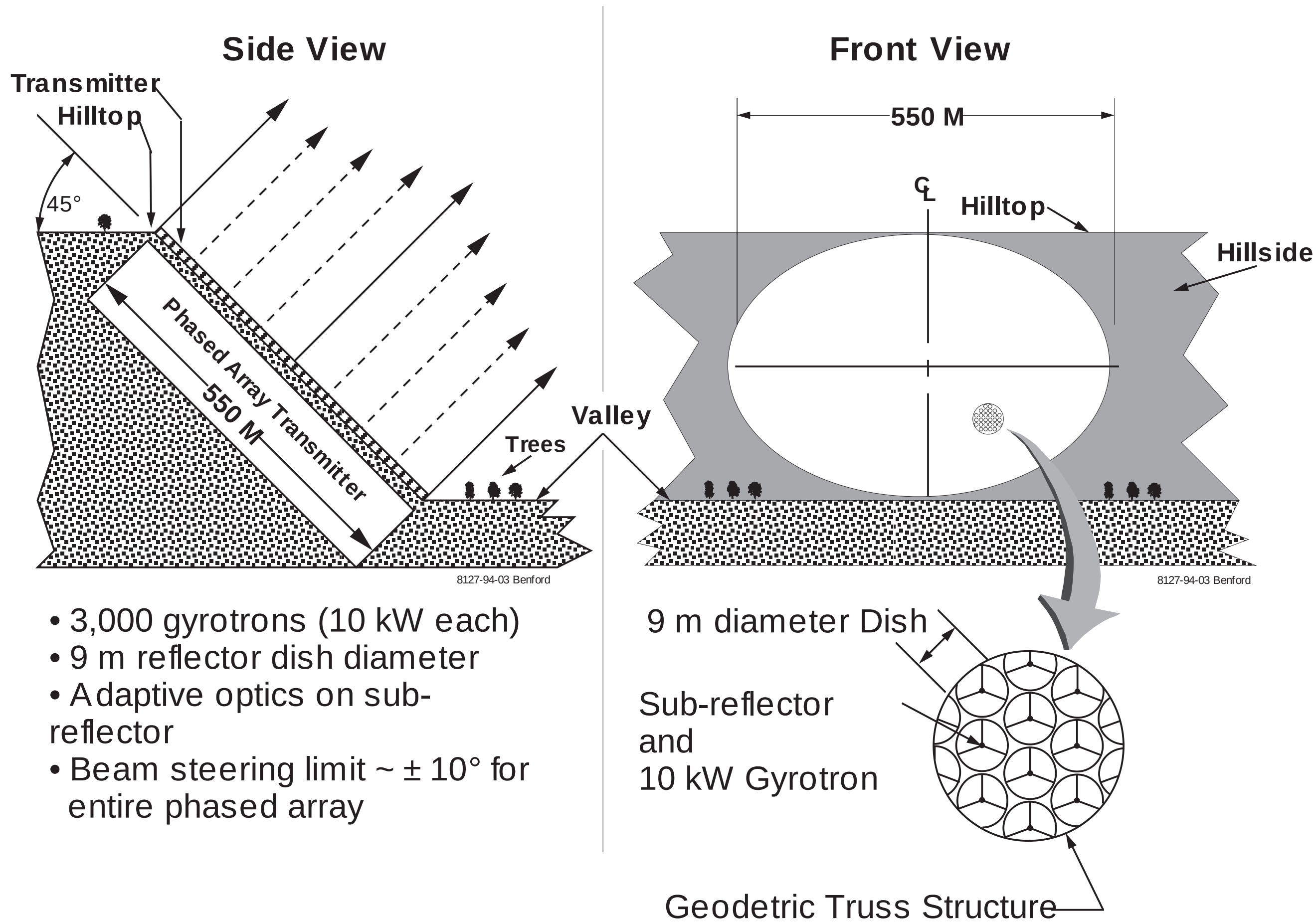

Figure 2. 30 MW Millimeter wave launch station (4 km altitude site).

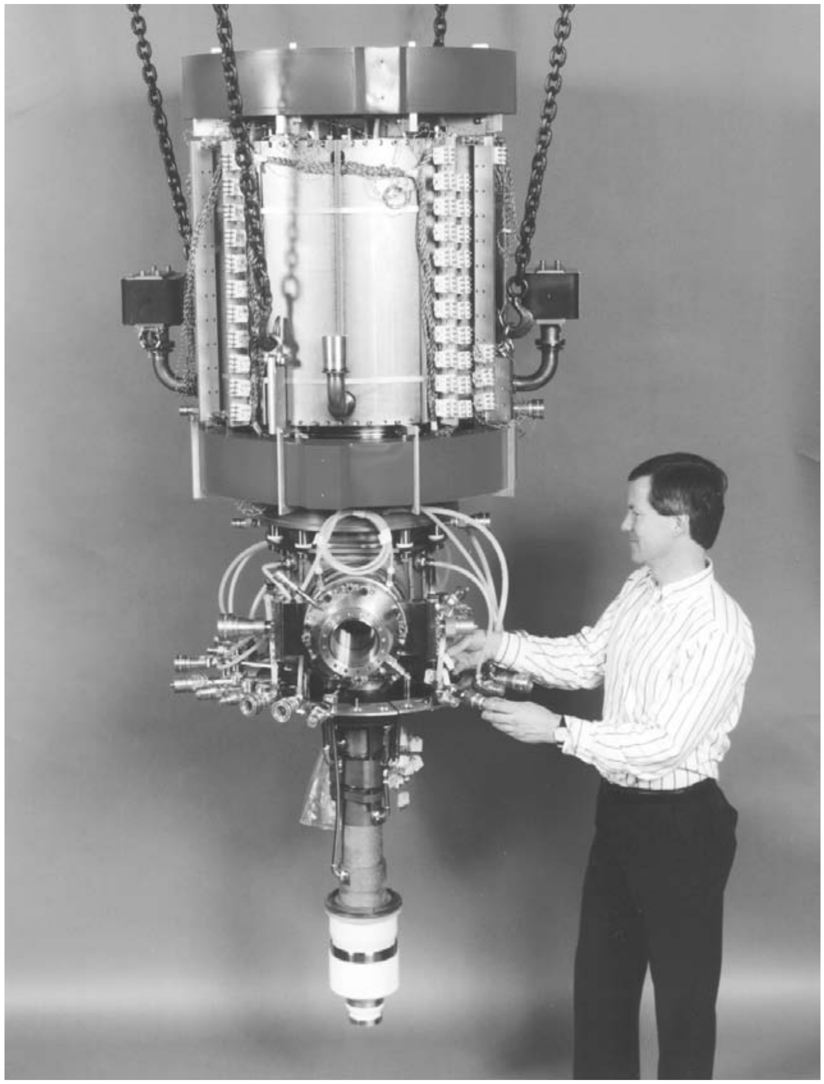

Figure 3. High average power 110 GHz gyrotron produces 350 kW for 10 sec, 500 kW for 2 sec, 1 MW for 2 ms at 30 Hz. Courtesy of Kevin Felch, shown in photo, Varian Associates..

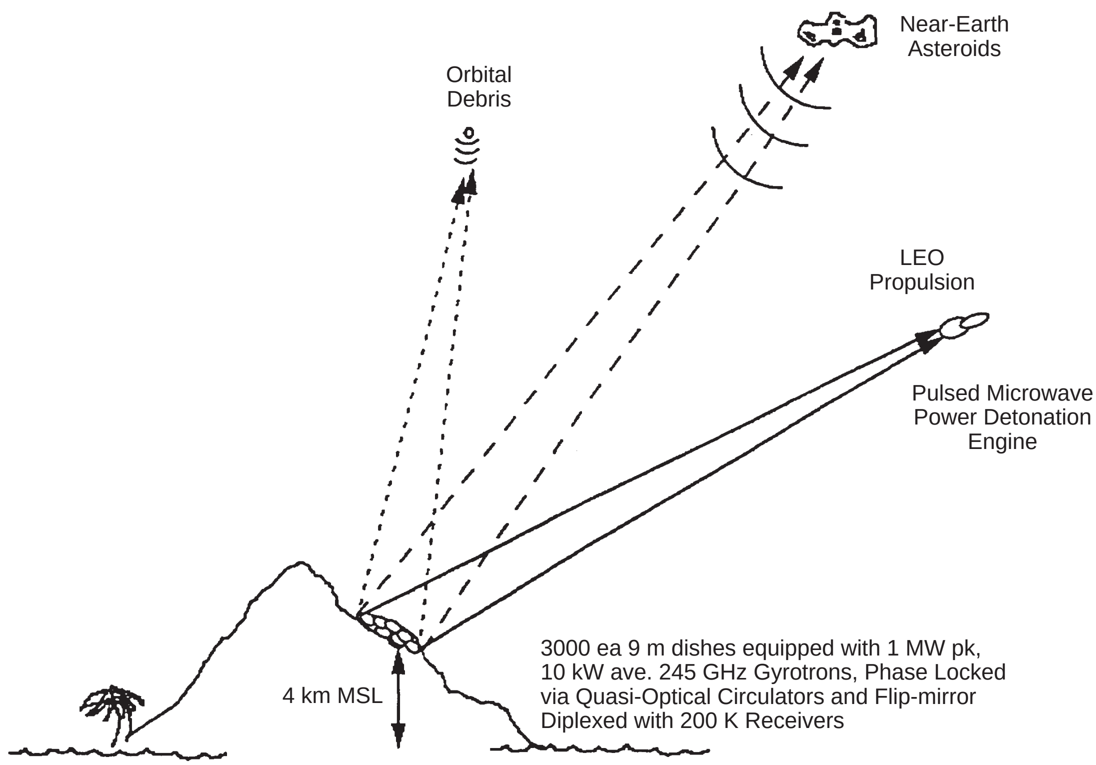

Figure 4. Applications for the millimeter microwave power phased array.

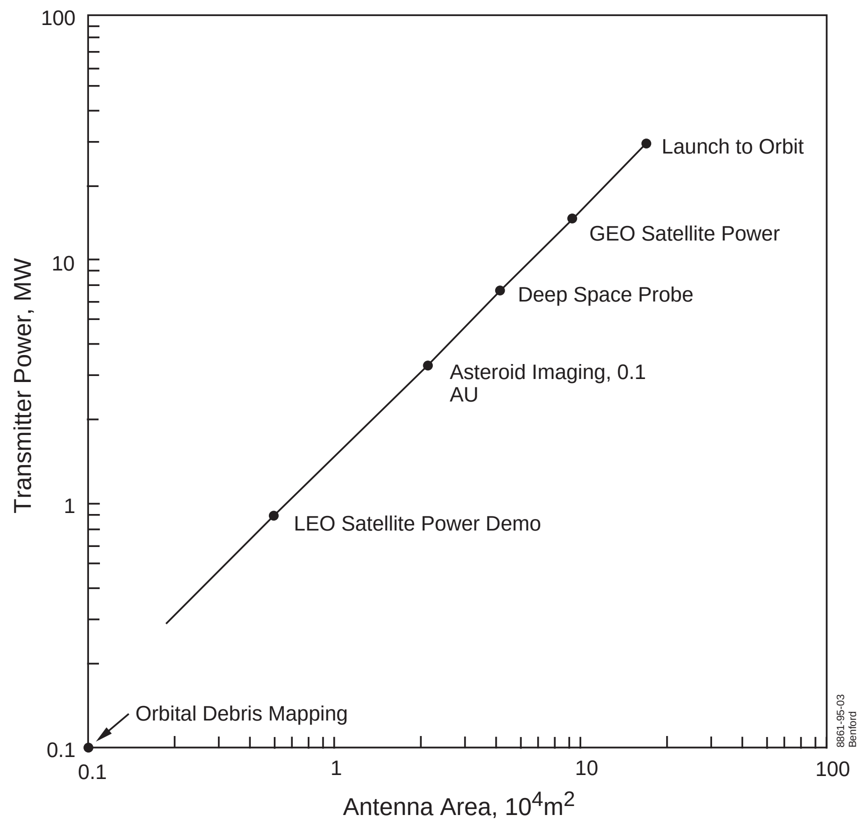

Figure 5. Development Path For Space Power Beaming. Since the basic module of the system is 10 kW, the vertical axis is also proportional to the number of modules, i.e., 375 modules for asteroid imaging. Antenna area unit (10^4 m^2) is a 100 m x 100 m area.

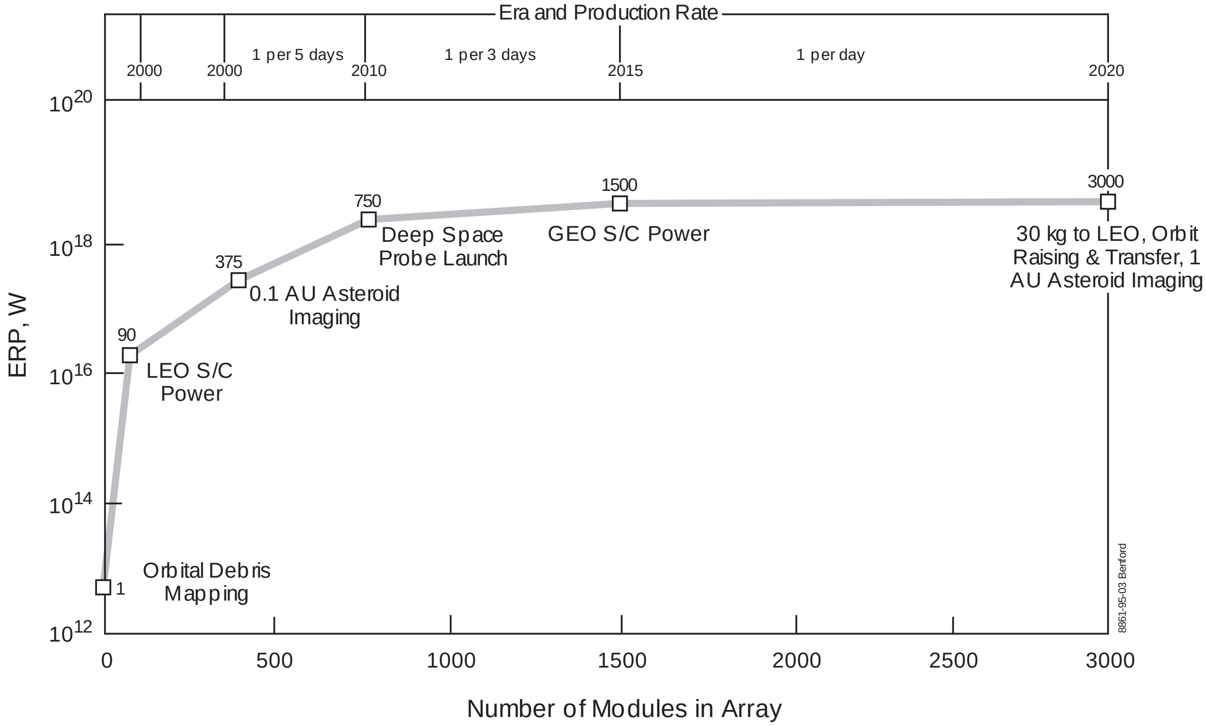

Figure 6. Millimeter power phased array growth capability.

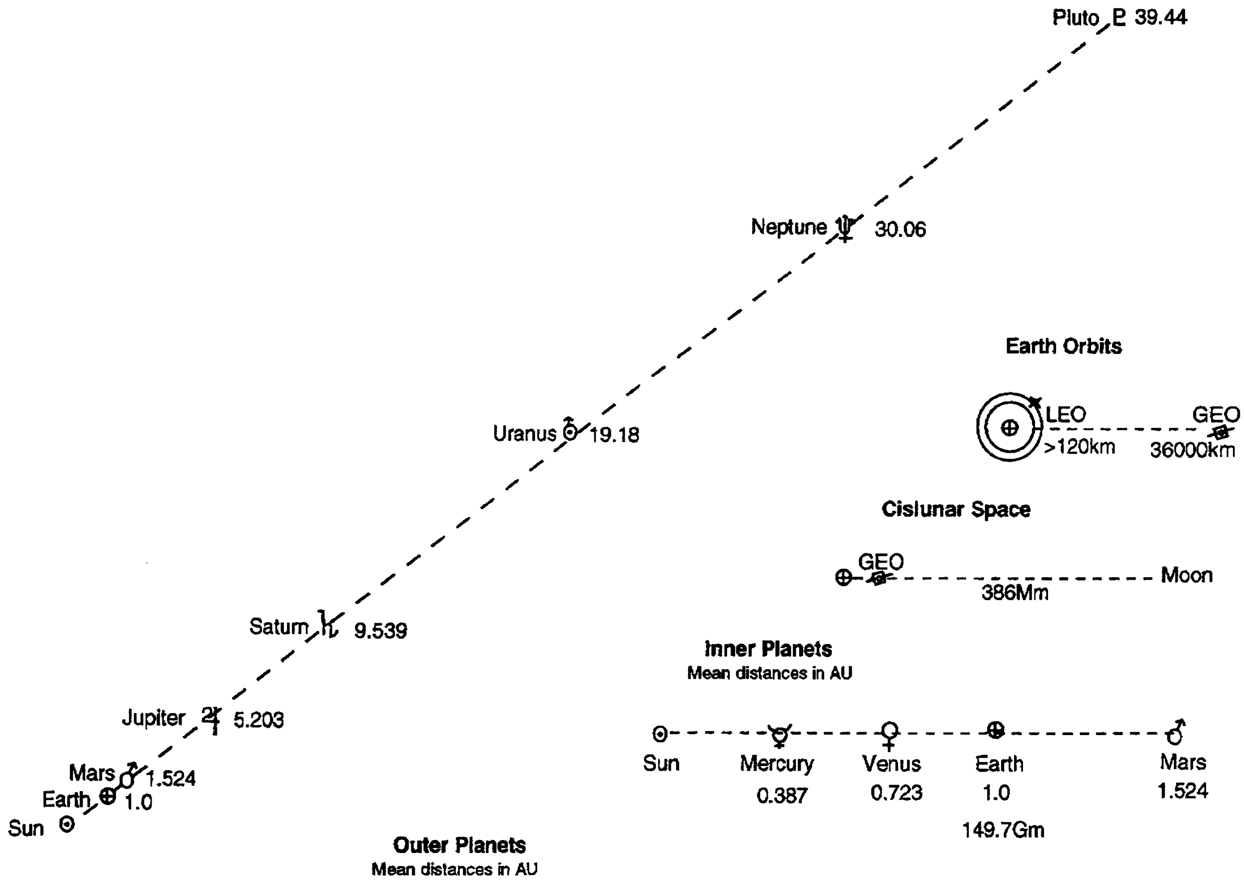

Figure 7. Orbit scales in the Solar System.