# The Beamed Power Microwave Transmitting Antenna

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*Abstract*—**The potential applications, resulting hazards, safety considerations, and alternate options for high-power microwave beam transmission functions are discussed. Existing and projected beamed power control techniques are presented, and the differences between existing and proposed high-power conventional antennas and phased arrays are described.**

## I. Introduction

THE PURPOSE of this article is to raise and discuss some issues for microwave component and system designers relative to beamed microwave power transmission and its safety considerations, and to consider the effects of these issues on high-power beamed microwave transmitting antenna design. Beamed power refers to radiation techniques employing directional antennas (rather than transmission lines) for purposes of transferring energy in microwave form from one place to another.

Beamed power concepts have been standard fare in science fiction literature for various probes, transportation systems, offensive and defensive weapons, etc., for many years, although earth's society has exploited mainly communications and navigation concepts of beamed power to date. However, the technology potential in real life is now such that other applications are beginning to be seriously advocated [1]. This article addresses principally the peaceful uses of beamed power as applied to electric utilities functions and transportation concepts. Recent advances in microwave converter efficiency [2], small scale model systems efficiency achievements [3], and high-power long-range wireless transmission demonstrations [4], coupled with our society's desire to investigate alternate electrical power schemes such as the satellite power systems [5], are hastening the day when antenna designers and other microwave component designers will have to consider in greater detail the capabilities, limitations, and consequences of their designs. In these designs for very-high-power beamed energy systems, whose outputs can and do interface directly with society, the interfaces may be much more frequent and lasting and potentially more hazardous than in today's fledgling systems.

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There is no question that such high-power systems or schemes can be hazardous, as any interface between personnel and other forms of energy transport are characteristically dangerous. Consider, as examples, railway crossings, rivers and water falls, high-voltage lines, automobiles, gas pipelines, and even sunbathing! However, society in general, over the years has accommodated to the energy transport schemes even with their casualties, given adaptation, utility practices, education, acceptance, and first-hand experience. High-intensity microwave beams, on the other hand, are a fairly recent phenomenon. Humans are not adapted to remotely perceive microwave power beams. Thus there exists the danger of entering unknowingly, a high-power microwave beam. Induced sound perception of pulsed microwaves is possible during immersion in the beam, however [6].

The thermal heating effects of intense microwaves are becoming well known (as demonstrated by the consumer microwave oven sales), whereas low-level microwave radiation effects are quite controversial [7]. Because of the potential high-level dangers combined with the low-level effects uncertainties, it may be concluded that the allowable "safe" microwave flux densities and absorbed dose permissible for interfacing beamed power with the populace will be arbitrarily set quite low. Additionally, sensible engineering design practice will prudently allow a margin of safety. For example, with electromagnetic radiation of decimeter wavelengths, it is relatively easy in and among the works of man (as contrasted to those of nature) to obtain "effective" corner reflector antennas with gains in power flux density greater than 10 dB [8].

Therefore, we examine whether there are design approaches and techniques, existing or projected to be available in the future, for use by the microwave component engineer to render beamed power systems potentially safe for humans and other biota. We shall attempt to present objective considerations for both protagonist and antagonist: first, the promises of beamed power systems, then the problems, and finally, potential transmitting antenna design techniques and considerations for promoting beam safety. Alternatives to beamed power will also be considered.

## II. Beamed Power Potential Promises

High-power microwave transmission antennas, or "trantennas," are proposed for beaming power from earth-orbiting satellites to "rectennas" on the earth as a

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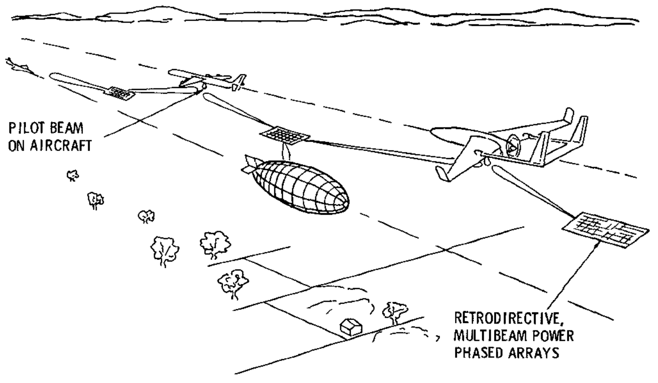


Fig. 1. Electric aircraft microwave skyway.

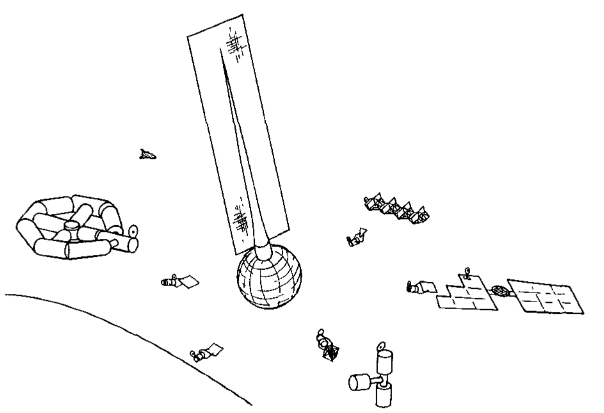

Fig. 2. Orbiting central power distribution station for space industrialization.

scheme for providing electric power in the future. Other applications include beaming power to run helicopters [9] (demonstrated by W. C. Brown of Raytheon in 1964), airplanes, and aerostats equipped with rectennas [10] (Fig. 1). The aeronautic applications allow fuelless, on-board electric-powered propulsion without tethers. Future space-power transfer [11] and distribution [12] applications are also possible (Fig. 2). Lasers, too, can beam power, but for the above applications, wherein the power beam transits the Earth's atmosphere, microwaves are superior in efficiency because the atmosphere is nearly transparent to the long-wavelength radiation. The more diffuse nature of microwave beams occasioned by fundamental physical focusing limitations, and the unique electronically swift beam shape control possible in phased arrays are additional attractive features compared to lasers. Laser beam systems also currently suffer from the lack of a highly efficient reconversion scheme that will yield convenient electric power output. *S*-band rectennas at 91-percent collection-conversion efficiency [2] from RF to dc have been demonstrated.

The satellite power system (SPS) application has the highest total power in a beam, yet it also has a very low level of received peak flux density due to the range from geosynchronous orbit, which spreads the beam. Current SPS systems designs [13] have 2.45-GHz beams of about 6.5-GW beam power launched from 1-km-diameter power arrays in orbit, with Gaussian tapers in the aperture amplitude distribution. The beam is intercepted on the ground with an average 10- by 14-km ellipse rectenna to yield 5-GW electric power output to a utility grid. The nearly continuous output of clean electric power appears attractive when compared to the problems of stored energy, ground-based solar power, or conventional coal and nuclear baseload electric power systems.

The electric-powered, station-kept balloon at about 20-km altitude is a potential low-altitude "stationary satellite" that can be used effectively as a platform for communication broadcast, relay, navigation, data collection, and earth or space observation by small states or regions of larger states. The balloon would receive its power from a power station on earth via a microwave beam, to its rectenna located in the balloon or on its outer fabric.

The electric airplane may be used in the future as an airborne, electric-powered wireless trolley in high-density dedicated air routes for personnel and cargo transfer. The bottom surfaces of the airplane would be covered with rectennas. Hence, when portable fuels become scarce in the future, the ground-based, coal-fired, powered airplane is possible via intermediate electric power and microwave conversions.

High-density space industrialization may use beamed microwave power transfer from a central solar-powered station. This would free individual users from having to carry around their own large solar collectors, thus promoting productivity through increased maneuverability.

Additional beamed power energy transport applications may be possible, but the system detriments as well as the attributes must be considered.

## III. Potential Problems

The potential problems of beamed microwave power may be put into focus by asking the following questions: 1) What is a "safe" level of microwave absorption for humans and other biota, given various flux densities and exposure times (i.e., are microwave effects transitory or cumulative?), wavelengths, polarizations, and polarization orientations? 2) Do the legal concepts of eminent domain or easements extend to microwave beam crossings?

The known effects of high-level microwave radiation (greater than 10 mW/cm$^2$) on personnel and property are thermal for long-term exposure (i.e., dehydration, cataract formation, and at very high intensities "steam" explosions in trapped fluid situations, steel wool ignition, and other combustions and carbonizations). Near-perfect reflectors such as aluminum sheets are unaffected, at least up to flux densities as high as kilowatts per square centimeter, as in Cassegrainian antenna subreflectors.

At reduced atmospheric pressures, RF power breakdown levels are significantly lower [14]. For example, at standard temperature and pressure, the RF breakdown levels are theoretically 12 MW/cm$^2$, whereas at about 45-km elevation at 2.45 GHz, the breakdown limit due to ionization is 24 W/cm$^2$. In vacuo, high-field intensity multipacting electron stream breakdown is possible [15].

At lower levels of incident microwave flux density (below 10 $mW/cm^2$) likely to be encountered in sidelobes or grating lobes of beamed power antenna patterns, the thermally induced effects are not as dramatic, but nevertheless constitute a concern for personnel by the antenna designer due to potential standing wave reflection enhancements of the electromagnetic field.

Since one cannot see or hear an approaching microwave beam or high-level sidelobe, personnel must be protected from encounters with microwave radiation of which they cannot sense. Thus system designs must provide for techniques to yield microwave radiation levels that do not under any reasonable circumstances exceed the allowable limits, whatever they may be. The next section will discuss approaches for coping with such a design constraint. Compliance will have to be judged by the individual design, allowable limits applicable, and the safety margins.

## IV. What Can Be Done

First, it will be instructive to review some of the existing techniques employed for protecting the public from microwave illumination [16]. Generally, the high-power beam transmitters are located in access-controlled areas of low population density and away from scheduled air traffic routes. Near the sites, safety techniques include fences with posted signs, flashing warning lights, public address loudspeaker warnings, and klaxtons. Search radars are used to look for and monitor air traffic. Intrusion detectors, TV, and visual surveillance, along with limit switches on antennas to prohibit beam turn-on or to shut off the beam at potentially hazardous elevation angles or elevation-azimuth angle combinations, and fixed RF detection monitors, are employed to protect personnel on the ground around a site. Transmitter interlocks are placed on potentially dangerous intrusion accessways. Cooperative forewarnings of scheduled power beam operations are made available to other operations most likely to be affected, such as nearby aircraft maneuvers that may accidentally intrude into the restricted air space near a high-power beam site. In summary, existing beam safety systems, while employing surveillance with fixed detectors, visual and radar means, attempt to avoid problems by spatially separating personnel and beams via remote locations and barriers or by time-sharing of beam space.

The beamed power technology being considered in the future will tend to bring together more people and higher-power beams as well as long-lasting low-power beams. Thus the strategy of separation will be less effective as the population of aircraft, beams, and personnel increases and time sharing must increase for the high-power mobile beams.

If beams are to safely move among the populace, or vice versa, only a finite number of responses to potential hazard situations are available to the trantenna designer. The first is beam design, which refers to those techniques for producing tightly focused, low-sidelobe, accurately pointed beams, such as those required by SPS, that are pilot beam steered via retrodirective arrays with accurately maintained, filled apertures with high aperture amplitude tapers.

Second are beam diversion tactics for repointing the beam from its present or projected pointing direction to another direction determined to be nonhazardous.

Third are fixed or self-adaptive beam shaping techniques that yield a noncircular or other contour so as to exclude the hazard region or spot. These techniques would be similar to the null tracking techniques for sidelobe nulling in today's adaptive arrays [17].

Fourth are the beam dimming strategies obtained by dephasing or defocusing and turning down, or selectively turning off, converters momentarily.

The fifth and final response is dousing the beam totally and restoring it after the hazard has passed.

For instances of beamed power transfer activities wherein it may also be hazardous to be without the beam power, the systems must be equipped with sufficient on-line reserve energy storage to carry the load through the maximum credible beam outage. Obviously, the load subsystem as well as the trantenna and its prime power supply must be engineered to tolerate the transients associated with the fourth and fifth hazard safety responses. In fact, the power interrupters themselves will require a high level of engineering design to be reliable and long-lived.

The viability of beam space, time sharing, and the credibility of the above responses to potential hazard situations rests not only on the ability to accurately form controlled, low-sidelobe-level beams but also, and principally, on the potential threat surveillance detection system. The power beam trantenna should fail-safe contingent upon the outcomes of a continuous effectiveness assessment of the detecting system, for example. Thus beam position, shape, and quality monitors for fixed beam applications, along with active beam penetration testers of known scattering cross section, should be structured as integral parts of the trantenna control system. The beam tester scattering device size, movement or apparent movement rates, and quantities are functions of the detection system threshold testing.

If controlled sample testing of the beam safety system is inadequate, a physical barrier hazard alleviation strategy of beam safety must be used. The potentially affected populace must be provided with radiation shielding such as the aluminum screens installed in the U.S. embassy in Moscow, alarm detectors, training, education in avoidance techniques, shelters, radiation-proof suits [18], etc., which are all possible requirements if the beam power benefits are demonstrated to be worth the inconvenience and risks to society.

The microwave beam hazard avoidance provisions must have their threshold limits set rather low because of the threat potential at even low microwave illumination levels. Although modulation could be imposed on the power beam so as to enhance sound perception, such as natural gas is odorized to assist in detecting leaks, the level at which perception occurs is probably already too high. In addition, the populace must be conditioned to recognize the hazard warning and trained in what protective actions to take to minimize the hazard. Just as high-voltage lines are supported on tall towers, pipelines are buried, and railways have crossing gates to separate the public from the energy transport system, so too must the microwave beam system be provided with its unique protective system. However, in considering the reasonable limitations on adequate protective effort, one must obviously consider the untimely but occasional lost kite retriever, the excavation pipeline dig-in, the crossing racer, and the errant aeronaut. Extra effort may consider not only the posted signs and air chart warnings but also the eye-safe laser beam or "Hollywood premiere" searchlight to assist in marking the high-power beams, even though these light devices have limited effectiveness in daylight and certain inclement weather periods. Total power accounting could also be used to detect any power diversion or losses larger than a given threshold. Nonetheless, hazardous situation avoidance depends principally upon beam surveillance techniques.

## V. Beam Surveillance Techniques

Obviously, visual monitoring should always be used where possible, and conventional doppler moving target indicator radars can also be employed for surveillance. The safety system must however also respond to static objects that exist on the arrays at the time of turn-on—flocks of resting birds, for example. Therefore, the appropriate beam surveillance techniques should be intimately related to the type of beam and its dynamics. The quick transient passage through the beam may not be of as great concern as, for example, the leisurely or loitering maneuver.

The SPS beam is approximately fixed in position. The beam used to provide power from the ground to a balloon is slow-moving and has to move only over a small range of angles to intercept the station-keeping aerostat. The airplane beamed power-way also has a restricted angular region to cover, but it is much larger in angular extent than the balloon, and its beams require rapid angular variations.

In all cases, it is desirable to radiate the beam only when required, and then it should be mandatory to require the use of a cooperative pointing system [19], wherein a coded pilot beam is transmitted from the center of the rectenna. Loss of the coded pilot beam at the trantenna should result in the trantenna reverting to a fail-safe condition with the beam either doused or dimmed by automatic random phasing of the subarrays.

The pilot signal illumination of the trantenna could be used to ascertain from the distribution of received power over the diplexed subarray pilot beam receivers, whether the power transmitting array aperture is unobstructed, a necessary condition before transmitting. In a similar fashion, a low-power-level transmit capability should be provided for the trantenna to illuminate the rectenna. A similar survey comparison of the received low-level power beam distribution on rectenna subarrays could be used to verify an unobstructed rectenna aperture before commencing high-power beam operation.

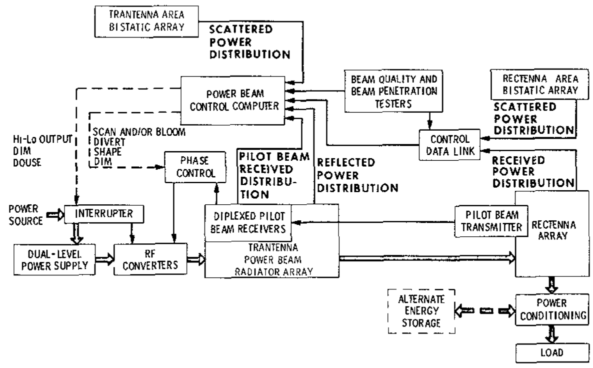


Fig. 3. Microwave power beam safety control system.

An added beam power distribution monitor capable of receiving scattered energy from reflecting objects in the beam near the trantenna could be the array consisting of the reflected power monitors within each trantenna subarray.

More sensitive power distribution monitor arrays could be made up of low-signal-level receivers operating at the power and pilot beam frequencies and located adjacent to each of the terminals of the power beam link (Fig. 3). Computer processing of the power distribution data from the bistatic geometry receiver arrays should be useful in monitoring scatters in the beams as well as the beam focus, sidelobe level, and pointing.

Additionally, if the power beam were time-shared and programmed to scan around the rectenna site momentarily by either preprogrammed conical, spiral, or other scan with the focused beam, or via controlled blooming of the beam to encompass the rectenna and environs, these periodic area illuminations could be used to survey and track approaching potential scatterers in the beam. Arrays of receivers on the ground and/or in the air (more balloons) around the dedicated electric aircraft corridor could be used to acquire and track the accidental aircraft or flock of birds that could be illuminated with the skyway beams. The adequacy of the above self-help safety techniques is affected by the following factors:

1) scatterer radar cross section,
2) irregularities within propagation media (magnetosphere, ionosphere, atmosphere),
3) noisy or inoperative instrumentation,
4) ground clutter levels,
5) bistatic receiver quantities and distribution,
6) trantenna beam stability and repeatability,
7) computer routine, detection thresholds,
8) spacecraft and rectenna RFI,
9) simultaneous events.

Modeling and analysis of the system signal-to-clutter ratio and detection threshold logic must be made to ascertain the minimum detectable hazard, false alarm rates, etc.

The hardware and software necessary for the safety subsystem add to the complexity of the systems.

## VI. Effects on Beamed Power Systems

The hazard-detecting schemes require more land area for the bistatic receivers. The hardware, software, and maintenance of the many arrays of power distribution monitors and the control system devices will be expensive but are probably necessary given the low-level thresholds that must be maintained. Also, the load factor of the beamed power system will be decreased due to turn-on sequence delay and false alarm outages. The system will yield a reduced total load output due to the duty cycle for the area illumination diversion of part of the beam energy. In some cases, energy storage and switching will be required for smoothing the necessary temporary outages occasioned by hazard reduction. Increased RF interference (RFI) from power interruptions will occur; however, the net result should be more positive beamed power control and safety.

The SPS trantenna is different from conventional phased-array antennas and requires some unique conditions to render its performance acceptable from the point of view of both safety and efficiency. The requirement to dissipate about 1 GW of waste heat in the space environment is one of the factors leading to the 1-km-diameter size and the selection of a planar array rather than a clustered or point-source type of feed system. (The resulting heat concentration would be untenable for the converters.) An array of adaptive, phase-controlled subarrays also allows the otherwise continuous surface structure stresses to be relieved periodically. However, in order to avoid large grating lobes, the 1-km aperture must be filled with subarrays that completely tile the plane, each with individual uniform illumination. Overall, the trantenna is designed to have an approximately Gaussian tapered illumination to yield high beam transfer efficiency to a single (rather than multiple) area rectenna. The filled array is unusual in that most large arrays are randomly thinned to phase smear grating lobes and for cost effectiveness. However, a filled, fully packed array is required for beam efficiency in that the loss of energy in the resulting grating lobes (even though randomized in position) cannot be tolerated. The loss in efficiency is in the ratio of the unfilled to the available aperture area.

Grating lobes resulting from electronic steering of the beam off-axis of the trantenna due to spacecraft attitude control errors and trantenna pointing errors can be minimized by employing small subarrays and limited scan ranges. However, the small subarrays are more numerous and thus raise the total system cost for beam steering electronics.

Multipacting breakdown due to the high RF power level is a potential design problem in the waveguide power distribution networks and radiating slots. Large height guide with surface treatments and wide slots may be necessary to prevent breakdown in orbit.

TABLE I
PERFORMANCE PARAMETER VALUES FOR THE PRINCIPAL DIFFERENCES IN SPS VERSUS CONVENTIONAL PHASED ARRAYS

| Parameters | Values |
|---|---|
| Power level | 6.5 GW, CW |
| Filling factor | Nearly 100% |
| Array size | 1-km diameter |
| Phase control tolerances | ~10 deg rms |
| Aperture/beam efficiency | Greater than 95% |
| Operating lifetime | 30 years |
| Limited steering angle | 1 min of arc (for 1% pointing loss) |

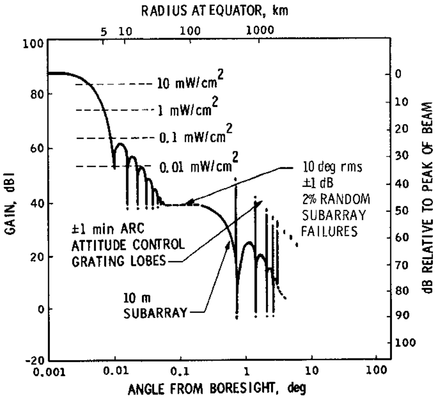


Fig. 4. SPS 10-dB taper array antenna pattern.

The system's phase control tolerances will be such as to require significant advances in the state of the art in reference phase distribution over long distances for the phase conjugators in each subarray for the retrodirective beam pointing scheme to operate acceptably. Less than 10° rms phase error throughout the array may be necessary.

Finally, the design lifetime of a typical utility, on the order of 30 years, will be difficult to achieve in the geosynchronous orbit environment. Performance parameter values for the major differences from conventional antennas and arrays are listed in Table I.

Because the SPS beam power is so large, the sidelobes, including the grating lobes, represent a low-level radiation source that potentially affects a large region of the hemisphere visible from the satellite (Fig. 4). Consequently, from the RFI standpoint, the details of the antenna pattern many decibels down from the peak of the beam are quite important in order to determine the flux density accurately (Fig. 5). This requires extremely accurate knowledge of RF current distributions and structure details.

The SPS operation uses a low-power density but large area beam whose position is rather stable in time, whereas for aircraft applications, the beam will not be fixed in one direction for long. The aircraft beam power flux density must be many orders of magnitude higher than the SPS beam in order to deliver the required high power (multimegawatts) to the limited surface areas (hundreds of square meters) efficiently. The hazard in the aircraft beam

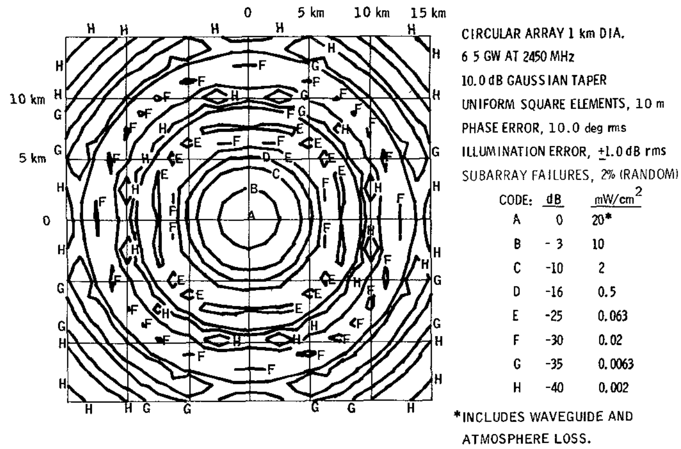


Fig. 5. Microwave power energy distribution on rectenna at equator.

near the ground can be somewhat reduced by the use of a large area trantenna (which also tends to promote high transfer efficiency), but the intensity will be severe in the power beam focusing on the pilot beam transmitter antenna in the center of the rectenna located on the lower surfaces of an aircraft.

## VII. Options

Alternate means of achieving the SPS and aeronautical functions discussed above should continue to be evaluated relative to the potential beamed power hazards and safety system effectiveness. In the electrical power regime, ground-based solar power, cleaner extensions of existing coal and nuclear power, plus the continued promise of fusion should be compared to SPS with its huge engineering and transportation requirements.

After the naturally occurring hydrocarbon portable fuels are nearer exhaustion, methanol- and hydrogen-based liquid fuels may still permit limited air travel.

More efficient, cheaper solar cells and lightweight batteries are potential economic and ecological tradeoffs for the beamed power station-kept balloon system.

## VIII. Summary

The microwave beam transmitting antenna is a high-power component that has a potential direct interface with the public at large. Without careful engineering and system design, it can be very hazardous to humans and other biota. If certain wireless power transmission functions are determined to be useful to society, various acceptable, intermediate states (between off and full on, even temporarily) of the power beam may exist that are appropriate to the potential hazards. The safety system requires an elaborate, highly reliable surveillance and detection scheme to provide the inputs to the trantenna in order to place it in a safe state of beam diversion, shaping, dimming, or dousing appropriate to the hazard. One approach to the problem lies in the use of the power beam itself operated in a bistatic geometric mode to illuminate a wide contiguous area to seek out nearby potential hazards.

Because of dangers of beamed microwave power, optional means of achieving the required functions should continue to be thoroughly evaluated.

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