

MICROWAVE POWERED MICRO-RPV

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INTRODUCTION

One important application of small RPVs, or micro-remotely piloted vehicles (MRPV), is the video surveillance of the inside of a building. Very long mission duration may be required, but the mission ranges can be short and external support systems are allowable. For long mission duration and very small vehicle size (on the order of two to three inches), it may be necessary to utilize off-board energy sources. Furthermore, the need to operate through building walls favors wireless power transmission in the microwave region.

This paper summarizes the design and development of a microwave powered micro-RPV. A ground station antenna radiates microwave energy to the MRPV where it is received and rectified. The resulting dc signal is used to power the rotor and other onboard systems. The second harmonic signal, which is a by-product of the diode rectification process, is used as a source to transmit telemetry and other data between the MRPV and ground station. The research included design and analysis of the microwave link, design of the MRPV antenna, evaluation of potential safety hazards, and the development of several critical components. A computer simulation was performed to provide confidence that a system based on the specified design parameters will be capable of performing as required. In some cases, for example the antenna and rectifier circuits, components were breadboarded to demonstrate that the essential technology for lightweight, compact microwave rectifiers is obtainable.

The deployment of the MRPV system is depicted in Figure 1. A major design issue is the optimum number of ground stations and the configurations that should be used. A single ground station with a physically large, high gain antenna has both advantages and disadvantages. The primary disadvantage is that the maximum MRPV range is extremely sensitive to the path loss. Thus, if the beam passes through a wall with 6 dB of loss (which is not uncommon for an exterior wall in the 1-5 GHz frequency band) the maximum MRPV range is reduced to 1/2 of that without the wall. Also, it will be shown that a single large antenna limits the operational flexibility needed in deploying a MRPV system.

OVERVIEW OF THE MRPV SYSTEM

Figure 2 shows a block diagram of the ground based portion of the microwave link, which consists of a transmitter, antenna, receiver, and beam control and processing units. A single large ground station can be used, or several smaller low-power stations can be synchronized to provide the required power density at the MRPV.

The MRPV segment of the microwave link, shown in Figure 3, includes the receive antenna and rectifier circuit. The combination is frequently referred to as a rectenna. The second harmonic from the diode will be used to transmit telemetry and surveillance data. The telemetry signal is received by the ground antenna, which also operates at the second harmonic frequency.

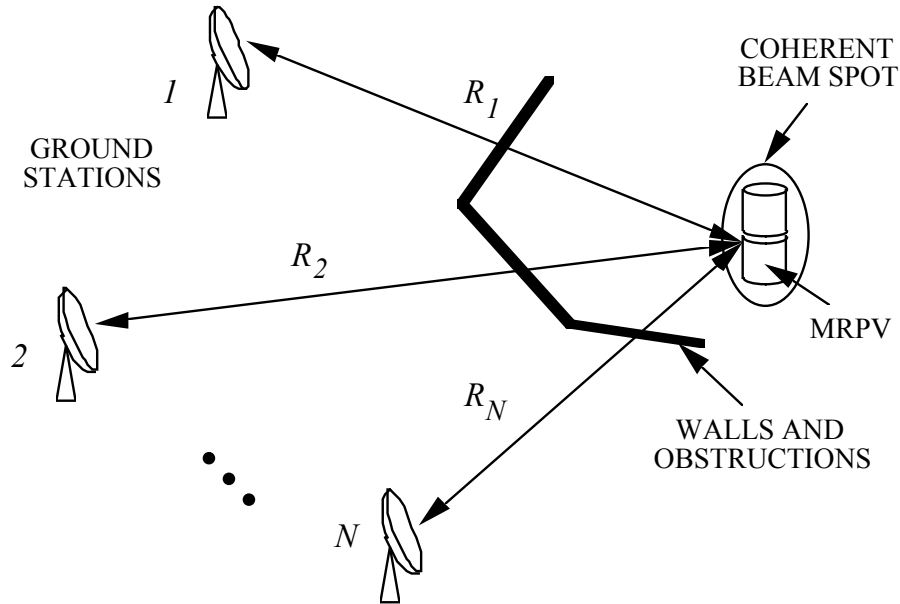


Figure 1: MRPV microwave link geometry.

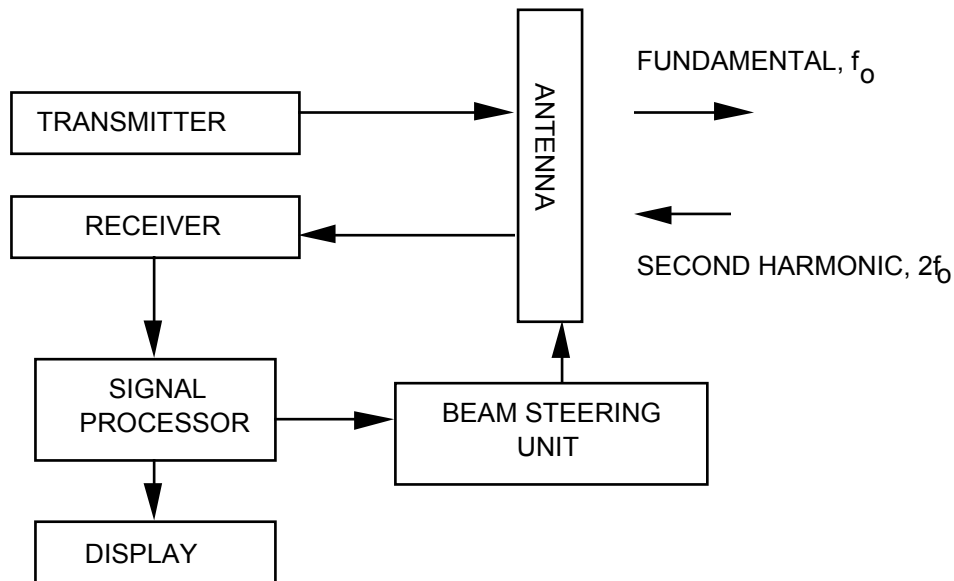


Figure 2: Block diagram of the ground station.

GROUND STATION DESIGN

The MRPV system has many military and civilian applications that cover a wide range of operational environments. The most demanding scenarios occur when the MRPV must operate inside of buildings. The insertion loss of walls (i.e., reflection and absorption) can be extremely large (20 dB or more). If a single ground station is used, the only way to maintain the power density at the MRPV spot is to increase the transmitter power to compensate for the additional amount of loss incurred. Obviously there is a limit to increasing power because of:

1. transmitter size and prime power requirements,

2. antenna power handling capability and breakdown, and
3. extreme heating and arcing hazards to personnel and objects in or near the beam.

All of these limitations are mitigated somewhat by using multiple ground stations that are dispersed in a convenient geometrical arrangement around the MRPV surveillance space. The number, ranges, and angular separations are arbitrary. They would be determined primarily by the conditions at the surveillance site. For cost considerations the ground station hardware would probably be standardized (same antenna size, transmitter power, etc.), although the components would be adjustable to some extent.

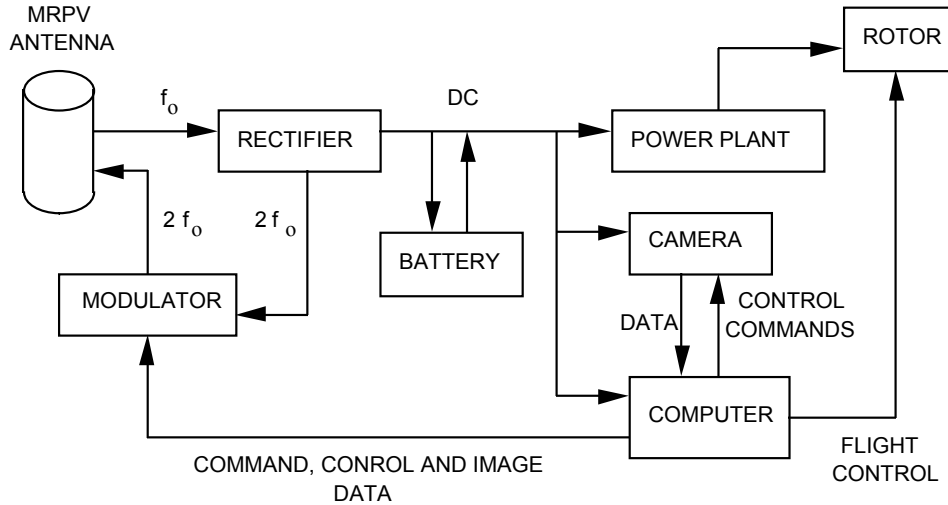


Figure 3: Block diagram of the MRPV systems.

The measurement and prediction of wall loss in the frequency range of 1-5 GHz is discussed in detail in [1]. An analytical model based on geometrical optics was used to predict the transmission loss between two antennas. Measurements were taken on four walls as described in [1]. A typical plot of loss in decibels (dB) vs frequency is shown in Figure 4. The loss increases with frequency, and therefore the reduction of wall loss favors low frequencies. However, this must be traded off with increase in antenna size.

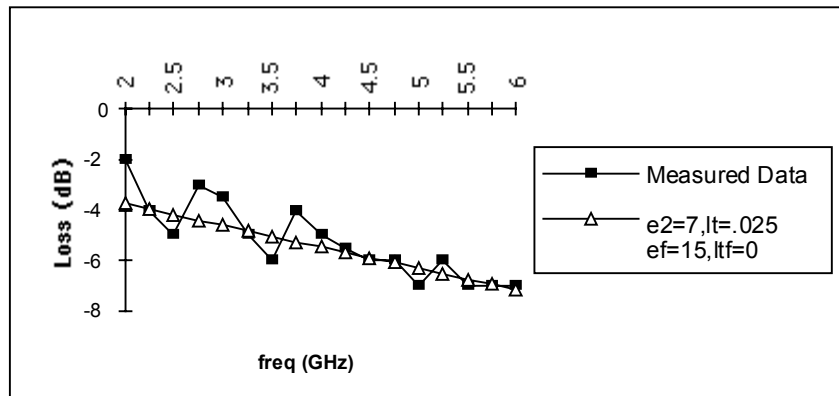


Figure 4: Measured wall insertion loss (from [1]).

MICROWAVE LINK EQUATIONS

There are two microwave links operating simultaneously between the ground station and MRPV. The primary link operates at a frequency f_o and provides power for flight and onboard systems. A second link operates at the second harmonic of the first link, $2f_o$, and is used to transmit command, control, and image data back to the ground station. These are referred to as the primary and secondary links, respectively. Based mainly on wall losses, but also the commercially availability of transmitters and antennas, power handling capability, size, and frequency availability, among other factors, f_o has tentatively been chosen as 1 GHz.

There are two fundamentally different approaches to providing power to the MRPV: (1) a single ground station with a large high gain antenna, and (2) multiple ground stations with smaller antennas that are synchronized to provide a coherent high-power illumination spot. In general, the power received by the MRPV from N transmitters is given by

$$P_r = \frac{A_{er} e_{dc}}{4\pi} \left| \sum_{n=1}^N \frac{\sqrt{P_{tn} G_{tn} L_{wn}}}{R_n} \right|^2 \quad (1)$$

where P_{tn} , G_{tn} , L_{wn} , and R_n are the transmitter power, antenna gain, wall loss, and range for station n , as illustrated in Figure 1. It is assumed that the signals from all stations are converted to dc with an efficiency e_{dc} . A_{er} is the effective receiving area of the MRPV antenna, which is approximately independent of direction and therefore is independent of station.

For convenience it will be assumed that all of the N ground stations are identical. By adjusting the phases of the individual transmitters, the electric fields at the MRPV can be made to add (i.e., coherent summation). Coherence implies compensation for any phase differences that may occur in the individual links due to path differences, hardware insertion phase differences, etc., in which case

$$P_r = \frac{P_o G_o A_{er} e_{dc}}{4\pi} \left| \sum_{n=1}^N \frac{\sqrt{L_{wn}}}{R_n} \right|^2 \quad (2)$$

where:

- A_{er} = effective area of the vehicle antenna ($A_{er} \approx 0.17 \lambda_o^2$)
- λ_o = wavelength at the fundamental frequency f_o ($\lambda_o = c / f_o$)
- $P_o G_o$ = effective radiated power of each ground station

The assumption of identical ground stations is not a real limitation of the design, but simply a mathematical convenience. In fact, a major advantage of multiple ground stations is that the transmit power of one or more stations could be increased to compensate for the failure or loss of another station. This adaptivity is not possible with a single station design. Note that a single ground station is simply the special case of $N = 1$ in Eq. (2).

Based on the current state of technology, it is estimated that between 7 and 10 W of dc power must be available at the output of the rectifier to support the systems onboard the MRPV. From this requirement it is possible to determine the allowable range of each system parameter.

To increase the effective radiated power of a ground station either the transmitter power or antenna gain can be increased. There is a practical upper limit to the size of the antenna. If the largest acceptable antenna is one that could be mounted on a semi-trailer, then the dimensions could be up to 15 m in length and 2 m in height. For multiple ground stations the ranges and wall losses will be different for each ground station in a multiple transmitter configuration. For convenience, let all of the ground station parameters be identical, except for range and wall loss, and therefore Eq. (2) holds. Solving for the required transmit power gives. Figures 5 and 6 compare required transmitter powers for various numbers of ground stations. Wall 0 is no wall present while wall 1 is a 5.5 inch interior wall of

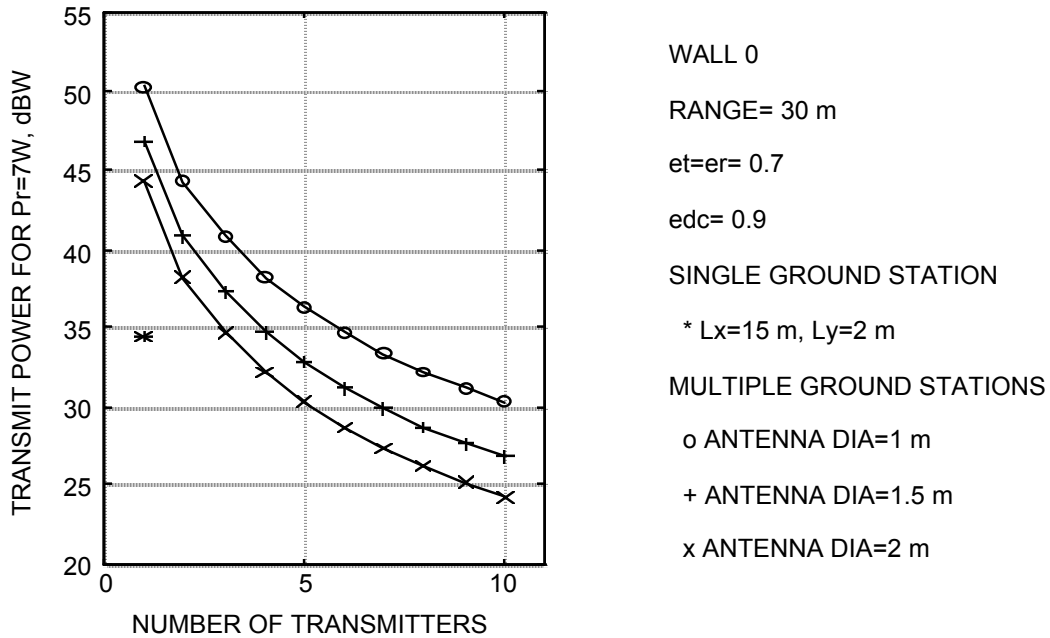


Figure 5: Transmit power required to provide 7 W at the MRPV, single vs multiple ground stations, no wall.

an industrial building. It is assumed that the wall loss is encountered by the single ground station (denoted by the asterisk in the figures), and by approximately half ($N / 2$) of the multiple stations. For the case of multiple stations, results for three antenna diameters are shown. The figures show if wall losses are present then multiple ground stations can provide higher received power levels than a single station as long as all of the multiple station paths do not suffer a significant wall loss.

GROUND STATION ANTENNA TECHNOLOGY

The two different approaches to ground station design are: (1) a distributed array of antennas each with a separate transmitter, or (2) a single transmitter with a high gain continuous aperture antenna. Available antenna technology related to each of these are discussed in the following paragraphs.

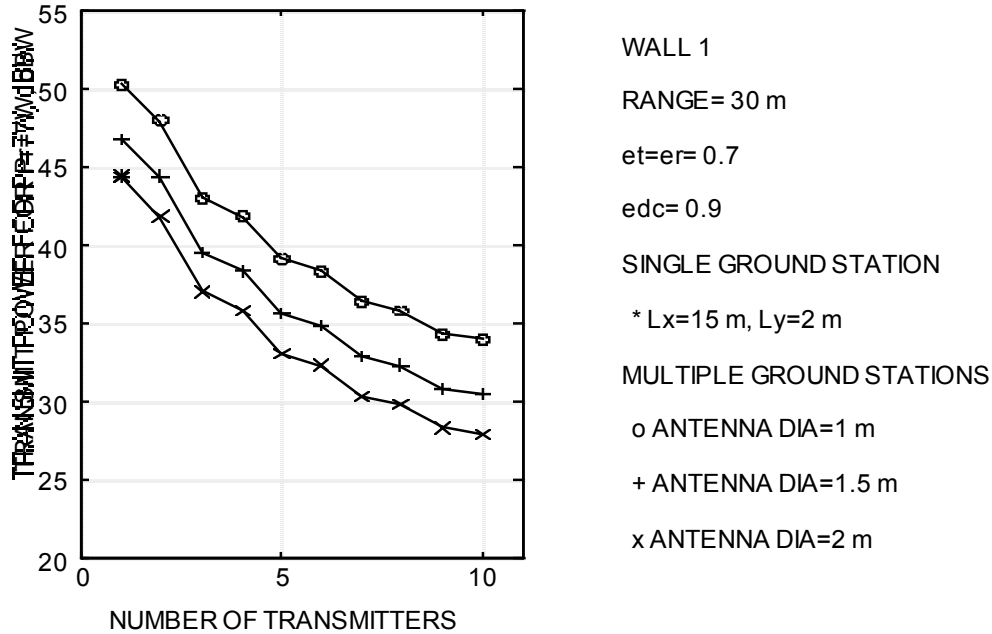


Figure 6: Transmit power required to provide 7 W at the MRPV, single vs multiple ground stations, half of the ground stations encounter wall 1.

In addition to high gain, a single continuous aperture ground station antenna must have the following characteristics:

1. accurate scanning over angles of approximately ± 45 degrees in azimuth (horizontal) and up to 30 degrees in elevation (vertical).
2. near field focusing.
3. transportable, easy to deploy, and low cost.

The primary advantage of single antenna is that no synchronization of multiple sources is necessary. This eliminates the need for path propagation compensation, and the calibration time necessary for multiple antennas. A major disadvantage of a single antenna is that if the MRPV passes behind a metal wall there will be complete power loss. Power to onboard systems can be maintained by a battery, but the specular reflection from the metal could cause a temporary safety hazard in some other direction.

Three candidate designs have been considered and are illustrated in Figure 7: 1) planar lens, 2) reflectarray, and 3) cylindrical paraboloid, all with a phased array feed. Conventional reflectors and lenses are fed at the focus. For the present application, nonfocal point feeds are required. All of these special requirements add to the complexity and cost of a large ground station antenna.

A distributed array of relatively small antennas (1 to 2 meters in diameter) can provide the required power density if the signals from all transmitters add at the MRPV. The fields at the MRPV can be combined coherently or noncoherently. If the sources are phase stabilized and the phase differences due to path lengths and wall insertion phases are compensated for, the total power delivered to the MRPV is given by Eq. (3). For a noncoherent combination of signals the powers rather than the fields add.

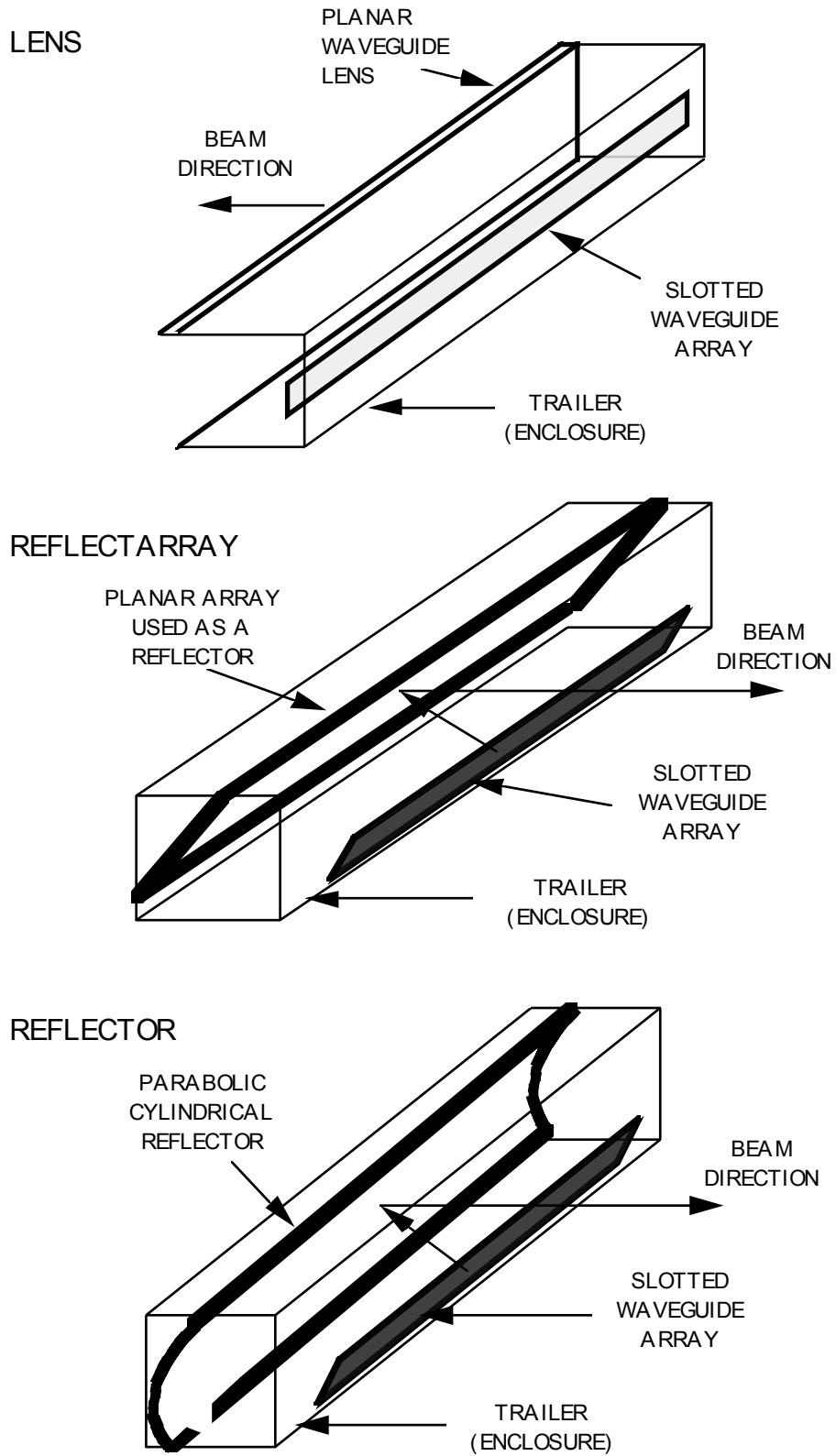


Figure 7: Single ground station continuous aperture antennas that could be mounted on a semi-trailer.

Synchronization of the ground station signals requires adjusting for the unknown phase shifts arising from:

1. phases of the individual transmitter signals
2. differing antenna characteristics
3. distance (range) to the MRPV
4. insertion phase of any obstacles between the ground station and MRPV
5. reflections from the ground and other scatterers (multipath)

Attempting to control the phases of all of these contributors in a typical MRPV scenario would be futile. Thus, any practical beam synchronization technique must be able to adapt to rapid changes without *a priori* knowledge of the propagation path.

The so-called "beam tagging" method [2] can be used to point the individual beams and synchronize their signals to provide a maximum at the MRPV. It is based on the fact that the total received signal can be maximized by adjusting the individual ground station signals sequentially. This is accomplished by vectorially summing the signals from all ground stations with phase-shifted versions of the one being adjusted. A comparison can be used to find the phase necessary to maximize the total signal at the spot.

The beam tagging procedure is completely effective under ideal circumstances; that is, nothing changes during the synchronization. The required synchronization time depends on the number of transmitters and the beamwidths of the ground station antennas. If the number of transmitters is too large or the antenna beamwidths too small (requiring extremely precise pointing), the vehicle motion and velocity may have to be limited. However, if the ground station antennas are 1 to 2 meters in diameter, the beamwidths are 15 to 20 degrees with spot sizes of about 15 feet at 30 meters range. Therefore the beam pointing need not be all that precise.

The synchronization must be done at the fundamental frequency because, in general, there is no predictable relationship between the propagation path phase at a frequency and its second harmonic. This implies a reduction in the power transmitting portion of the duty cycle. The measurement time consists of the two-way propagation delay between the MRPV and ground station, detector time, and processing time. A summary of issues regarding design of the ground station is given in Table 1.

RADIATION HAZARDS AND SAFETY

Electromagnetic energy is absorbed by the body and deposits energy internally leading to thermal loads and temperature gradients. Since the 1950s the informally accepted tolerance dose in the US has been 10 mW/cm^2 . The American National Standards Institute (ANSI) officially adopted 10 mW/cm^2 as the standard in 1966 for a five year term, and it was reaffirmed again in 1969 and 1974. It was concluded at the time that power densities in excess of 100 mW/cm^2 were needed to produce any significant biological changes (Figure 8). Since the early 1970s electromagnetic energy has been used as means of cancer treatment. The specific absorption rate (SAR) is used in dosimetric applications. It is the time rate at which electromagnetic energy is imparted to an element of mass of a biological body and the common unit is watts per kilogram (W/kg).

Table 1: Summary comparison of candidate ground station antennas.

Approach	Cost	Advantages	Disadvantages
1. Multiple antennas	Low to moderate	Small portable antennas Robust with respect to wall loss	Antennas must be scanned Path phase compensation Coherent transmitters
2. Single lens	Moderate to high	Completely focused beam No synchronization of sources	Safety hazard in the beam Large heavy antenna Susceptible to wall loss
3. Offset reflector	Moderate	Lighter weight than lens No synchronization of sources	Not perfectly focused Oversized feed required Need variable attenuators
4. Reflect-array	Moderate to high	More compact than lens Completely focused beam No synchronization of sources	Safety hazard in the beam Large heavy antenna Susceptible to wall loss

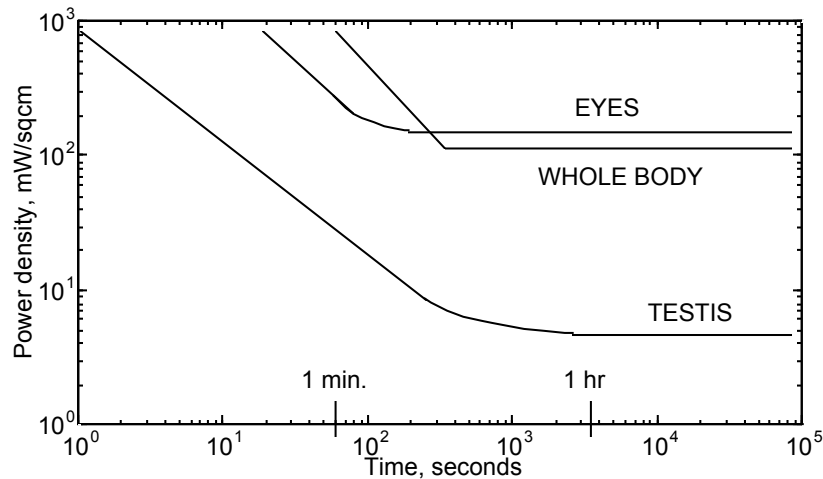


Figure 8: Threshold levels vs time for sensitive organs [8].

Data has shown that a whole-body averaged SAR of 4 W/kg is acceptable, and subsequently the standard was set at 0.4 W/kg to incorporate an order of magnitude safety factor. The standard allows the spatial peak SAR to be greater than the whole-body averaged SAR by a factor of 20 [3-5]. There is still considerable debate as to whether the current standards are sufficiently low. Here we will accept the standards and examine the MRPV system power densities to see if they conform. That is,

- 1) The whole-body averaged SAR should be less than the safe level (4 W/kg),
- 2) The maximum partial-body SAR should be less than 20 times the whole-body averaged SAR (80 W/kg), and
- 3) The power density vs exposure time should remain below the safe values for sensitive organs such as the eyes.

For the MRPV safety calculations a monolithic model of a man is used. A simulation of the MRPV flight was performed on the computer and the effects of various system parameters evaluated. Typical data are plotted in Figure 9. Maintaining the required power to the MRPV is possible in all scenarios investigated, albeit the safety performance is marginal. At 1 GHz there is no problem with the whole- or partial-body SAR limit. The greatest problem is maximum power density at the spot. Note that although the power density limits are exceeded, it is not by much. Furthermore, if the time limit of exposure is short, then these levels are acceptable (see Figure 8).

Multiple ground stations alleviate the safety problem to a great extent. The power density in the beam of each individual ground station is determined by the ERP of the particular station, which is about 1/N of that for a single ground station design. This fact is illustrated in Figure 9, which compares the power densities in the beams of single and multiple ground stations.

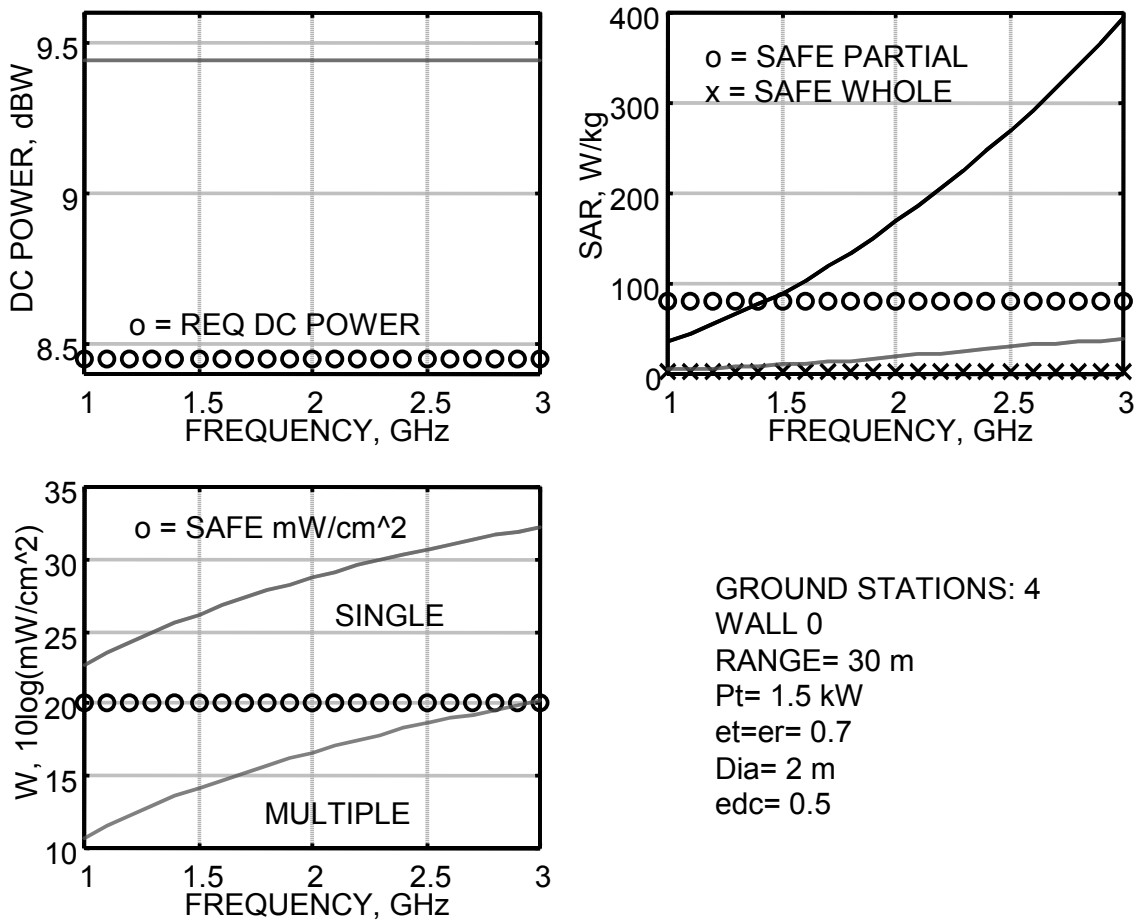


Figure 9: MRPV performance at 30 m, no wall.

MRPV ANTENNA DESIGN AND DEVELOPMENT

The transmission of beamed microwave power to the MRPV must be essentially constant for all vehicle attitudes. A dipole type of pattern, with the nulls along the body axis as shown in Figure 10 satisfies the coverage requirements. To achieve an omnidirectional receive pattern in azimuth (x - y plane), the vehicle structure should be rotationally symmetric. First generation body dimensions are approximately 1.5 inches in diameter and 4 to 5 inches in length. At a frequency of 1 GHz the total body length is less than one third of a wavelength. Therefore, achieving a dipole pattern at both the fundamental and second harmonic frequencies is not a problem. The major challenge is the problem of antenna efficiency.

Figure 11 shows a cut away drawing of a prototype MRPV that was built at the Naval Postgraduate School. A photo of the prototype is shown in Figure 12. The motor was powered via free space propagation. The motor could be turned at about 1000 rpm using approximately 0.25 W of transmit power, the maximum possible from available laboratory equipment. A prototype antenna was built based on an analytical design and simulation using a computational electromagnetics code [1]. As expected, the desired dipole pattern was present at both 1 GHz and 2 GHz as long as the feed point was located on the axis of symmetry of the body (z axis).

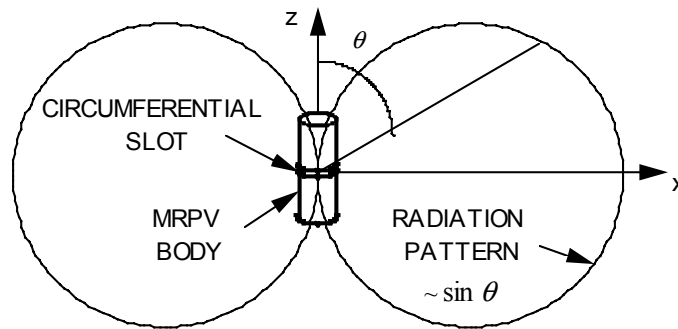


Figure 10: MRPV pattern cut.

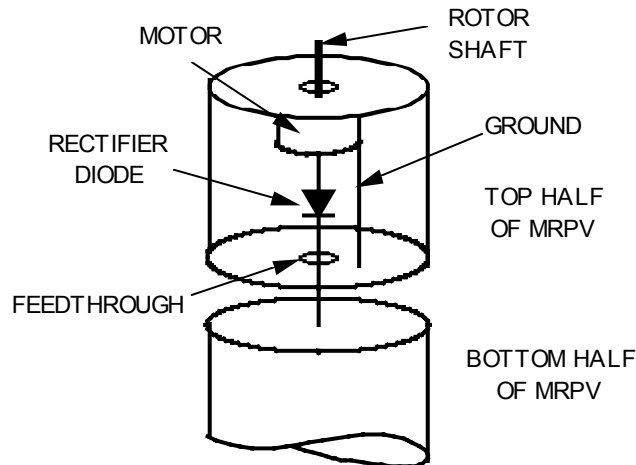


Figure 11: Cut away of the prototype MRPV built to demonstrate rectifier and packaging concepts.



Figure 12: Photo of the full-scale MRPV vehicle powered via free space propagation.

A breadboard rectifier circuit was also build. Passing a cw signal through a diode generates a dc signal and potentially all harmonics. A typical plot of output power vs input power is shown in Figure 12. For power conversion the saturation region could be used but design of the matching network is complicated because the diode impedance is nonlinear in this region. Figure 14 shows the measured efficiency of the breadboard rectifier circuit. The low efficiency is due to operation at the bottom of the diode characteristic as noted in Figure 15. RF to dc efficiencies as high as 90% has been achieved.

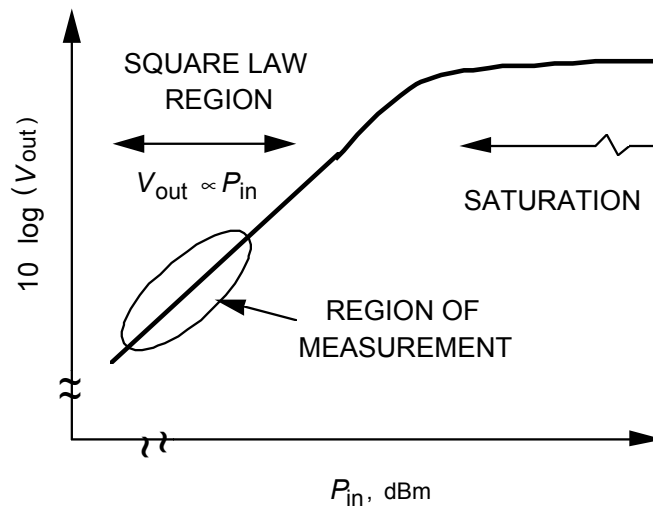


Figure 13: Diode characteristic.

SUMMARY AND CONCLUSIONS

Several approaches to the MRPV system have been examined, the MRPV link and safety equations derived, and the performance shown as a function of vehicle range and operating frequency. Both single and multiple ground station designs are capable of providing sufficient power to the MRPV. However, the multiple ground station approach has the

advantages of more flexibility with regard to deployment, robustness in the presence of large wall losses, and reduced safety hazard outside of the immediate vicinity of the coherent spot. There are no special requirements for the antennas used in the multiple approach, whereas the single station requires a complex, heavy, near-field focusable array or reflector. Therefore, the recommended approach is that of multiple ground stations. Beam pointing and synchronization can be achieved using the tagging method.

The calculated data favors operating at the frequency of 1 GHz, mainly because of the lower wall losses. A wall loss model was developed and verified by measurement. Several critical MRPV components were developed in the laboratory. They include the rectifier circuit and antenna. Generation of the second harmonic was verified and measured. Finally, a full-scale prototype was built and powered by free space transmission.

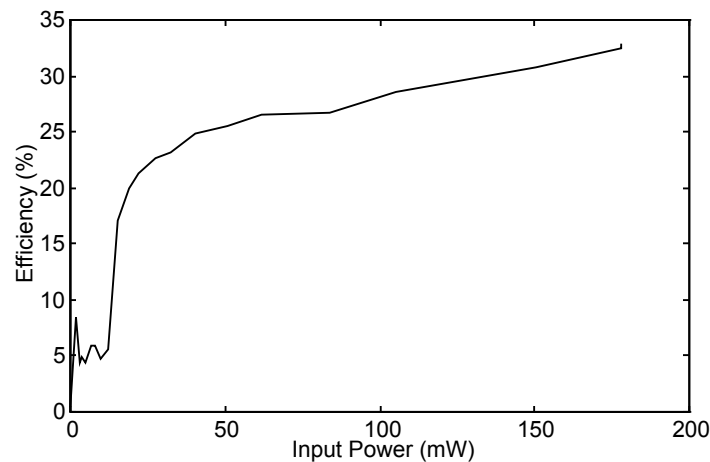


Figure 14: Breadboard MRPV receive circuit's measured efficiency.

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