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Millimeter and Submillimeter Wave Applications

MERRILL I. SKOLNIK

Radar Division

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NAVAL RESEARCH LABORATORY
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Merrill I. Skolnik
Radar Division
Naval Research Laboratory

ABSTRACT

Many applications of millimeter and submillimeter wave systems have been suggested in the literature but, in general, they have not yet been employed in practice to any significant degree. This report discusses the advantages and limitations of this frequency region and reviews the potential applications under the categories of radar, communications, radiometry and instrumentation. One of the problems of operating in this frequency range is that some of the advantages can also be considered as limitations. Even if transmitter powers and receiver sensitivities were the same as those obtained at microwaves, it would be unlikely that millimeter and submillimeter wave systems could compete with most of the major applications of microwaves. Successful applications of the shorter wavelengths will probably utilize characteristics that are distinct from those of microwaves. The special attributes of millimeter and submillimeter waves are narrow beamwidth with reasonably-sized apertures, wide bandwidth, and interactions with the constituents of the atmosphere and other gases. The more likely candidates for applications unique to this frequency range include remote sensing of the environment, interference-free communications and radar, low-angle radar tracking, high-resolution and imaging radar, extremely wideband communications, plasma diagnostics, and spectroscopy. If systems applications occur it seems more likely that they would be found initially at frequencies below 50 GHz rather than at the higher frequencies. At the present time, there does not seem to be imminent major systems applications of these wavelengths. The search for quick "riches" in practical millimeter wave systems applications probably should be minimized, and more emphasis should be placed on exploring the science and technology of this region for their own sake.

TABLE OF CONTENTS

INTRODUCTION	1
USEFUL CHARACTERISTICS OF THE MILLIMETER WAVE REGION	2
LIMITATIONS OF MILLIMETER WAVES	4
A LISTING OF APPLICATIONS	5
RADAR SYSTEMS AT MILLIMETER WAVELENGTHS	7
COMMUNICATIONS	13
RADIOMETRY	17
INSTRUMENTATION	22
COMPARISON WITH OPTICAL AND INFRARED	24
THE FUTURE	26
REFERENCES	28
APPENDIX	35

MILLIMETER AND SUBMILLIMETER WAVE APPLICATIONS *

INTRODUCTION

The millimeter and submillimeter wave region that lies between microwaves and the far infrared is intriguing to the laboratory researcher looking for new challenges, but to the practical systems designer it generally has been a source of frustration. The microwave region adjacent to the lower portion of the millimeter region has been fairly well exploited up to about K_a band (35 GHz). Practical applications have been made of the infrared and the optical portions of the electromagnetic spectrum but there have been few, if any, major applications in the region between the far infrared and microwaves. This report will attempt to show what is both attractive and unattractive about millimeter and submillimeter frequencies for systems applications. These systems are divided into the four categories of radar, communications, radiometry, and instrumentation. Since the emphasis will be on systems rather than components, an underlying assumption is that the hopes and promises made for millimeter and submillimeter components and devices will indeed be true; if not now, then sometime in the future. The question to be explored is what practical applications can be made with the best of the foreseeable components and techniques.

Before proceeding it is necessary to make some statements defining the wavelength range under consideration. From a strict definition of the terms, the millimeter region extends from 1.0 cm to 1.0 mm (30 GHz to 300 GHz)** and the decimillimeter region from 1.0 mm to 0.1 mm (100 μm). The far infrared may be considered to extend from 100 μm to 10 μm and the infrared from 10 μm to the visible region. It is not clear whether the term submillimeter is meant to be synonymous with decimillimeter or whether it also includes wavelengths less than 0.1 mm, with the lower wavelength limit only vaguely defined. Heroic attempts to make general definitions are sometimes of little avail since usage in applications tends to have little respect for academically defined boundaries. A microwave systems engineer, for example, generally ~~considers~~ his domain to extend up to K_a band where the wavelength is 8mm. This band is considered by others as belonging to the millimeter region. However, the components, techniques, and propagation conditions at K_a band are not that different from those at the lower microwave frequencies to say that K_a band belongs to the millimeter wave technology rather than microwave technology.

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** In this report, the wavelength will be used at times and at other times the frequency will be used with no apparent reason for selecting one term rather than the other, as is the habit in most of the technical literature.

(A possible exception would be those systems to be discussed later in this report that operate at or near the water absorption spectral line at 22 GHz). As the microwave engineer tries to extend his frequency beyond K_a band, there is quite a difference in technology and in the environment in which he must operate. Components become too small to be fabricated by conventional microwave methods and atmospheric losses can limit system performance. Therefore, a distinction is sometimes made between the millimeter waves that lie in K_a band and those lying above K_a band. The crossover between the two regions might even be defined as high as 50 GHz, since the atmospheric loss at frequencies below 50 GHz, is generally less than the atmospheric propagation loss in the 94 GHz (3.2 mm) "window". The fact that most research work that belongs uniquely to millimeter waves is done at frequencies greater than K_a band lends further support to separating K_a band from the rest of the millimeter wave region. It is realized that such a separation is arbitrary and is not universally agreed to.

The upper frequency end of the submillimeter range is harder to specify than the lower end. Wavelengths as short as $10\ \mu\text{m}$ would seem to lie outside the province of submillimeters, but gas laser techniques at $10\ \mu\text{m}$ are not too different from gas laser techniques at wavelengths of $100\ \mu\text{m}$ or longer. Fortunately, for purposes of this report it does not seem necessary to be precise about the upper frequency.

For convenience, the term millimeter wave will be used here to mean both millimeter and submillimeter waves. Unless otherwise noted the lower frequency limit is taken as 50 GHz (6 mm) and the upper frequency limit is undefined, but is less than 30 THz ($10\ \mu\text{m}$).

If there has been a lack in the millimeter wave region, it has not been a lack of review papers¹⁻¹⁰ and papers with promises for systems applications. This is another of the many reviews that will discuss systems and describe some of those applications that might be better performed at millimeter waves than at other frequencies. It will also discuss why millimeter waves are fundamentally not competitive for most of those particular applications already performed at microwave frequencies.

USEFUL CHARACTERISTICS OF THE MILLIMETER WAVE REGION

Since the millimeter wave region is seldom considered to be a part of either the microwave or the optics regions, it must have some obviously different characteristics when compared to the portions of the spectrum that lie above and below it. In order to be more specific, the comparison in this paper will generally be with the microwave region unless otherwise stated. It is easier to compare millimeter waves with microwaves since millimeter waves lie closer to microwaves within the electromagnetic spectrum than to the optical region.

The three principal characteristics of millimeter waves relative to microwaves are (1) smaller wavelengths, (2) greater bandwidth, and (3) greater interactions with the atmospheric constituents and other gases. The smaller wavelengths allow smaller size antennas to be used to achieve a given beamwidth. Since the scattering properties of objects are wavelength dependent, the smaller wavelengths mean that information can be obtained about the nature of certain objects better than at the lower frequencies. This would be especially important for objects comparable in size to the millimeter wavelengths, as for example the particles that make up clouds. The smaller wavelengths might also result in smaller RF devices.

It has been pointed out many times in the literature that the entire microwave region can be encompassed within any one of the usual millimeter wave bands, where the bands are defined as those corresponding to the atmospheric propagation windows. For example, the bandwidth at the 94 GHz window is approximately 23 GHz. The available bandwidth is so large that it probably would be difficult to take full advantage of its potential with existing techniques. This is a problem, however, that would most likely disappear if sufficient effort were applied to it.

The greater bandwidth means that more information can be transmitted per unit time in a communications system, that greater range resolution is possible in radar and that greater sensitivity can be obtained in a radiometer. Greater bandwidth also should reduce the mutual interference between the users of the spectrum.

In the millimeter wave region, electromagnetic energy interacts with the atmospheric constituents considerably more than at the lower microwave frequencies. The resonances of the atmospheric gases cause frequency selective absorption and scattering. The small wavelengths that are comparable in size to rain and fog cause similar effects without exciting molecular resonances. The frequency selective interaction with gases can be utilized to remotely sense the atmospheric constituents. The attenuation of the signal that results from scattering and absorption can also be taken advantage of when it is desired to limit the range of active transmissions as for the reduction of mutual interference or for "secure" communications and radar.

These three major characteristics of millimeter waves -- smaller wavelengths, larger bandwidths and greater atmospheric interactions than microwaves -- are the basis for most of the applications that have been proposed for millimeter waves. Unfortunately, two of the three are also among the major factors that can limit the ability of millimeter wave systems to compete for microwave applications. The smaller wavelengths and the greater atmospheric interactions can be utilized to advantage in some applications but they can be serious limitations in others.

LIMITATIONS OF MILLIMETER WAVES

The relatively poor status of components and devices presently found in the millimeter region has been widely documented. The methods successfully used for generating high power in the microwave region are generally inefficient when applied to millimeter waves. Although the laser has shown some success in the sub-millimeter region and shows promise of being an economical power source, available powers have not been as great as achieved with lasers in the far infrared region (10 μm or so). Thus high power sources are found at higher and lower frequencies but are lacking at millimeter waves. Receiver techniques are in a similar state. The sensitive superheterodyne microwave receiver is less sensitive when extended to the millimeter wave region. Also the quantum-type detectors that are successfully used at shorter wavelengths are not better than the superheterodyne receivers at millimeter waves.

Thus, there are limitations in available millimeter wave components compared to those found at both lower and higher frequencies. However, no one has yet proved that the lack of high-power transmitters and sensitive receivers is due to some fundamental irrefutable limitation of Nature, so that in time these component limitations hopefully will be overcome.

It has sometimes been implied, especially by editorial writers, that when component capabilities are improved the millimeter wave millennium will be heralded and it will take its true competitive place in the electromagnetic spectrum. Even if better and more capable components were available, other more basic factors enter to limit the types of applications that will prove useful. Undoubtedly, more efficient high-power transmitters and more sensitive receivers will result in more applications of millimeter waves than at present. However, there appear to be some basic considerations that make it difficult for millimeter wave systems to successfully compete with present microwave or optics applications. These considerations will be discussed further in later sections under the specific applications.

The atmospheric interactions that offer attractive possibilities for the remote sensing of the environment unfortunately limit the range of millimeter wave radar, communications and radiometry applications in the lower atmosphere. Not only are the fair-weather propagation losses high, but rain can cause even greater, almost prohibitive, attenuation. This results in a loss of the "all-weather capability" so attractive for many of the applications of microwaves. If millimeter wave applications must be confined to short ranges, they have to compete economically with already established short-range applications at other frequencies. Atmospheric effects in the millimeter wave regions also cause refraction and fading

of signals. The system designer often can account for such propagation effects, but it is difficult to overcome the signal attenuation resulting from the propagation loss.

The small wavelength that results in narrow-beamwidth antennas with physically small-sized apertures is often said to be an advantage of millimeter waves; but in applications where sensitivity is important, the small physical aperture of the receiving antenna results in less energy collected. Small receiving apertures are a direct consequence of the small wavelength and represent a fundamental limitation to the range that can be achieved with millimeter waves. The above assumes that the millimeter wave antenna is gain-limited rather than aperture-limited. If the aperture is limited in size as it might well be in some applications, then it is often desirable to operate the aperture at as high a frequency as possible in order to maximize the gain. This would be especially useful in tracking radar, point-to-point communications, and radiometry. At microwaves, the wavelengths are such that waveguides, waveguide components and active devices are of reasonable size for ease of construction and handling. Millimeter wavelengths are of such a small size that present manufacturing techniques are quite difficult and costly. Even if the precision manufacturing techniques can be mastered, the higher losses and less power handling capability of the small-size components presently used add further practical limits to millimeter wave applications.

Thus, even if the limitations of the available millimeter wave components are overcome in future years, there will still remain the fundamental limitations imposed by the physically small antenna apertures and the losses when propagating within the atmosphere. This is a strange situation, since as discussed in the previous section, these two limitations are also the same reasons for considering millimeter waves in some applications. Another example of the same characteristic acting both for and against is the doppler frequency shift. In CW millimeter wave radar, the large doppler frequency shift can provide a more accurate measurement of relative velocity than at lower frequencies but for earth-to-spacecraft transmissions the large doppler shift can result in the signal being outside the receiver bandwidth so that the doppler shift must be known and compensated. It is one of the frustrating characteristics of this wavelength region that many of its good points are also its weaknesses.

A LISTING OF APPLICATIONS

Tables 1 to 4 list most of the applications of millimeter waves that have been suggested in the literature. Items marked with an asterisk are those for which the writer believes millimeter waves may offer some special or unique attraction as compared with microwave frequencies. The references indicated are where the application is either suggested or described.

Table 1 SUGGESTED RADAR APPLICATIONS

Low-angle tracking* 11-13	Remote sensing of the environment ⁸
"Secure" military radar* 15	Surveillance ¹²
Interference-free radar*	Target acquisition ¹²
Cloud-sensing radar* 14	Missile guidance ¹²
High resolution radar* 15	Navigation ¹²
Imaging radar 61,62	Obstacle detection ⁹
Ground mapping ^{3,8,20,22}	Clutter suppression ¹⁸
Map matching ¹⁸	Fuzes ⁷
Space object identification ¹⁶	Harbor surveillance radar ⁶³
Lunar radar astronomy ^{6,17,56}	Airport surface detection radar ⁶³
Target characteristics ⁸	Landing aids ⁷
Weather radar ¹⁴	Air traffic control beacons ¹⁵
Clear-air turbulence sensor ^{6,8,15}	Jet engine exhaust and cannon blast ¹⁹

Table 2 SUGGESTED COMMUNICATIONS APPLICATIONS

"Secure" military communications* 8
Point-to-point extremely wide-band communications* 8,24,30
Spacecraft communications during blackout* 8
Interference-free communications* 23
Satellite-to-satellite communications 8,35
Intersatellite relays 8,67
Earth-to-space communications 8,21
Retroreflector communications 55

Table 3 SUGGESTED RADIOMETRY APPLICATIONS

Remote sensing of the environment* 8,14,40-42
Radio astronomy 42,57,58
Radio sextant ¹⁰
Ship detection 9,18
Ground target detection 12,13
Missile detection
Missile guidance 18
Clear air turbulence sensor 66

Table 4 SUGGESTED INSTRUMENTATION APPLICATIONS

Plasma diagnostics* 47-50,60
Rocket exhaust plume measurements*
Spectroscopy* 51,52
Remote vibration sensor
Prediction of blast focusing ¹²
Model radar cross measurements ¹³
Classroom demonstrations of optics ⁵⁴

There is some overlap in this catalog of applications and some of the topics appear redundant. Remote sensing of the environment is listed under both radar and radiometry since both devices are useful in such applications. Not everyone, including the writer, would agree to all of these topics in a listing of applications, but they are given here since they have been proposed somewhere in the literature of millimeter waves. In the remainder of this report each of the four major areas of application will be briefly reviewed.

RADAR SYSTEMS AT MILLIMETER WAVELENGTHS

Microwave radar has been widely used for surveillance, tracking and navigation. Important applications are found at frequencies as high as K_a band (8 mm wavelength). The higher microwave frequencies are used in applications where good angular resolution is required with small aperture antennas (as in airborne fire control radars) and where high-resolution target imaging is desired (as in airborne ground-mapping radars). Significant radar applications have not progressed as yet to higher frequencies than K_a band because of decreasing power capability, poorer receiver sensitivity, higher component losses, greater atmospheric attenuation, and smaller apertures as the frequency is increased. This section will consider the fundamental limitations (other than components) to the use of millimeter waves for radar and discuss the likelihood of particular radar applications.

An important use of radar is for the surveillance of aircraft, as in air traffic control. The radar range equation for this situation is

$$R_s^4 = \frac{P_{av} A_e \sigma t_s}{4\pi k T_s (S/N) \Omega_0} = K_s \frac{P_{av} A_e c}{T_s} \quad (1)$$

where R_s = range, P_{av} = average power, A_e = antenna aperture area, σ = target cross section, t_s = time to scan the angular region Ω_0 , k = Boltzmann's constant, T_s = system noise temperature and S/N = signal-to-noise ratio required for detection. Note that the frequency does not appear explicitly in this equation. A closer examination of the frequency-dependent parameters of the equation must be made to determine the effect of frequency on the range. The constants in the equation and those parameters given as system constraints are lumped into the constant K_s . This leaves P_{av} , A_e , σ and T_s as possible contributors to the implicit frequency dependence. The limitations of transmitter power, P_{av} , and the receiver sensitivity, T_s , have been well documented in the literature and need not be elaborated upon except to note that the decrease in available power and receiver sensitivity with increasing frequency re-enforce the conclusion to be made.

The cross section σ for most targets is relatively independent of frequency in the microwave range. Few measurements have been made in the millimeter wave region. For some targets the cross section actually decreases with increasing frequency (the cone-sphere is the most notable example), but for most targets it is essentially constant. Thus it will be assumed here that the cross section σ is not frequency dependent.

The antenna aperture is not in theory frequency dependent, but there are some practical considerations in the construction of antennas that set constraints on the frequency. Equation (1) shows that the aperture should be large for long range surveillance. Since it is easier to construct a large antenna at the lower frequencies, long-range surveillance radars are rarely found at the higher microwave frequencies, say above 4 GHz. This conclusion is even stronger for the millimeter wavelengths and for optical frequencies and is one of the chief reasons why lasers are not likely to be used for surveillance. There are also other factors favoring the lower frequencies for surveillance. These include better moving-target-indication and less weather effects. However, the large antenna sizes available at the lower frequencies is one of the more important factors, if not the most important one, governing the choice of frequency for long range radar surveillance.

In tracking radar a slightly different form of the radar equation applies and slightly different conclusions result. Lumping the non-frequency-dependent terms into a constant K_t gives

$$R_t^4 = K_t \frac{P_{av} G A_e}{T_s} \quad (2)$$

where G is the antenna gain. The frequency does not appear explicitly but the antenna gain depends on frequency as given by the relation $G = 4\pi A_e / \lambda^2$, where λ = wavelength. Thus for a given size antenna aperture the wavelength should be small if the range is to be large. In a tracking radar, range is but one measure of performance. Tracking accuracy is another. Fortunately, maximizing the tracking range gives the same result (large GA_e product) as that obtained for minimizing the angle-error measurement when receiver noise is the major limitation.

Because of the ever-present errors that exist in any mechanically constructed antenna, there is a practical upper limit to the gain. (Similar limitations occur in the accuracy of the amplitudes and phases of the element currents in a phased array antenna.) With microwave reflector antennas the limit can be expressed in terms of the relative precision $\eta = D/\epsilon$, where D is the largest antenna dimension and ϵ is the rms error of its surface contour. (The best microwave antennas seem to be limited to an η of about 3×10^4 .)

It can be shown³² that the wavelength that produces the maximum gain for a given error ϵ is $\lambda_m = 4 \pi \epsilon$, hence, the maximum gain for a circular aperture of dimension D is $G_{\max} = (\rho/43) (D/\epsilon)^2 = (\rho/43) \eta^2$, where ρ = aperture efficiency. If the relative precision η is independent of wavelength, as it appears to be at microwave frequencies, the largest size antenna should be used and again, as in the case of surveillance, the lowest frequency should be used. Since tracking ranges are generally not as great as surveillance ranges, and since there are generally limits on how big the beamwidth can be for accurate angle tracking, tracking radar frequencies are not as low as surveillance radar frequencies. Also, the higher frequencies make the problem of mechanically positioning the antenna easier. Surface-based tracking radars are generally found at frequencies above 5 GHz, and airborne radars at frequencies in the vicinity of 10 and 35 GHz. Millimeter wavelengths might have some utility for tracking radars where both the aperture and the beamwidth must be small. However, requirements generally can be readily met at frequencies lower than 35 GHz (K_a band), so that millimeter wavelength tracking radar does not look too attractive for most applications, except for low angle tracking as described later.

The above was based on the assumption that $\eta = D/\epsilon$ is essentially independent of frequency. At microwaves this is approximately true with present technology, with the limiting value being of the order of 10^4 . Reflectors at optical wavelengths can be considerably better than this by several orders of magnitude. (The physical sizes of typical optical telescopes may be several orders of magnitude smaller than large microwave antennas). Thus it is not certain how much better η can be in the millimeter wave region than the value of about 10^4 characteristic of the microwave region. In the submillimeter region where the antennas look more like optical devices rather than microwave devices, the value of η will no doubt be greater than that achieved at lower frequencies. However, the size of the aperture at the higher frequencies will be considerably smaller so that it is unlikely that it is necessary to change the conclusion regarding the superiority of microwaves for tracking.

Figure 1 shows the maximum antenna size (diameter) as a function of the wavelength for several values of D/ϵ . This figure assumes that the particular value of D/ϵ is independent of frequency and that $\lambda = 4 \pi \epsilon$. Also shown in the figure are several examples of large antennas. The best of the large-size microwave and millimeter wave antennas have a relative accuracy of about 1 part in 3×10^4 . At optical frequencies, the relative accuracies might be 1 part in 10^6 or 10^7 for lens and mirrors. (This is an estimate with uncertain confidence since the writer was not able to extract precise data from the sources available,^{68, 69} although such information undoubtedly exists.) There has been little experience in precision antennas in the submillimeter region, but it appears that precision apertures greater than a few meters in diameter will be very hard to achieve and maintain.

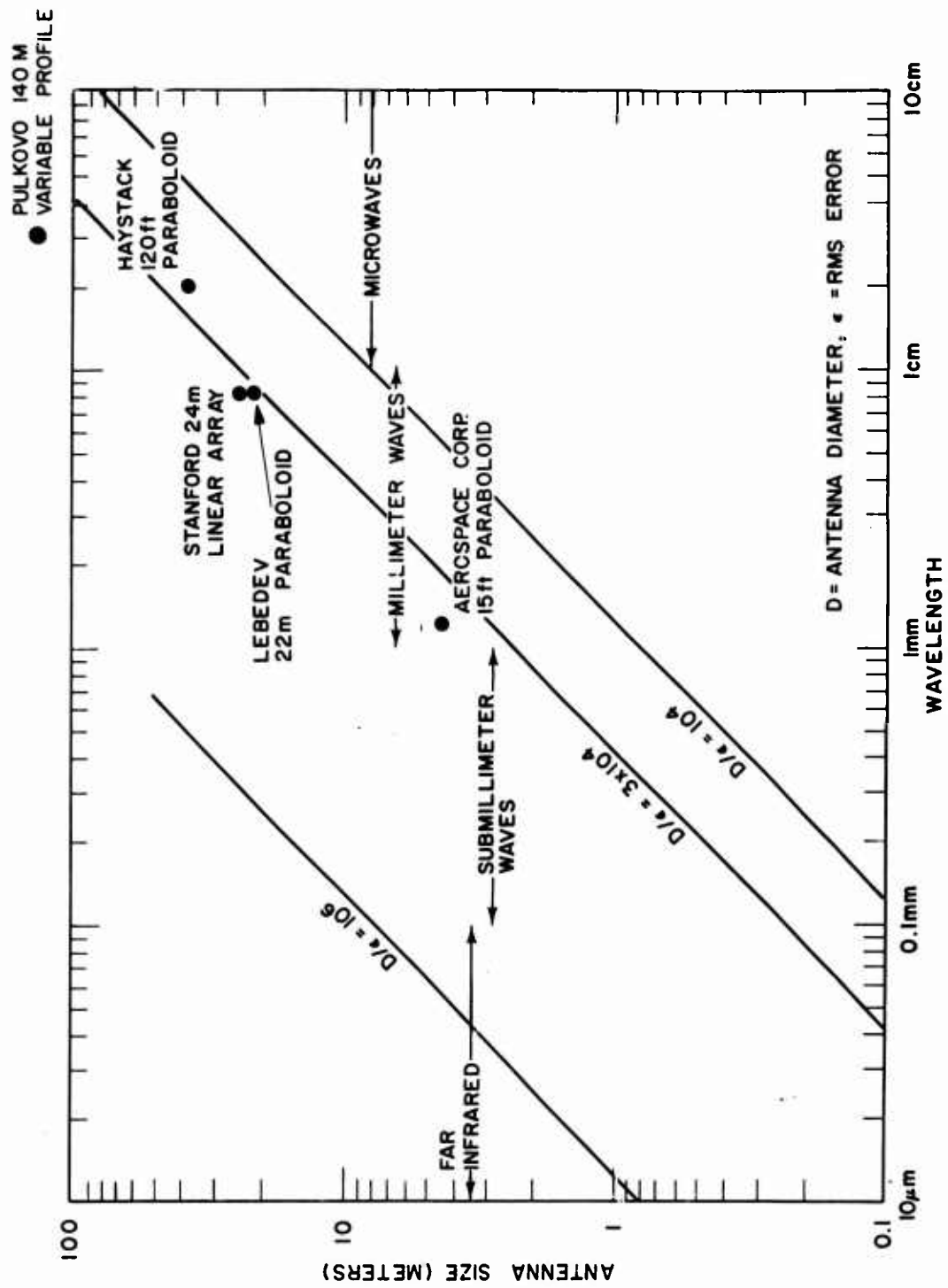


Fig. 1 - Maximum antenna size as a function of wavelength for various values of D/ϵ

A serious fundamental problem with long range radar in the millimeter range is illustrated by Fig. 1. Assuming that the manufacturing tolerance determines the limit to the gain, the maximum antenna size that can be employed is proportional to the wavelength. Any reduction in sensitivity due to the smaller antenna aperture at smaller wavelengths must be compensated by increased transmitter power or improved receiver sensitivity. Even if large apertures could be used, the beamwidths would be very small and beam pointing would be a problem.

This, then, is one of the dilemmas of operating radar in the millimeter wave region. The small wavelength results in small apertures but small apertures result in less sensitive reception.

Although millimeter wave radar cannot compete economically with microwave radar for most applications, there are several special cases where the millimeter wave region might be preferred. One such application is low angle tracking.¹¹⁻¹³ When a radar must track a target at elevation angles comparable to or less than the antenna beamwidth, the ground reflection produces a signal that causes an erroneous measurement of elevation angle. The lower angle limit will vary depending on the criterion used for the angle accuracy that can be tolerated. The error can be quite severe and can degrade tracking performance. Thus an antenna with a 0.5° beamwidth cannot accurately track targets at angles less than 0.5° or so. A 0.5° beamwidth at X band requires an antenna approximately 12 ft in diameter. This is a large but not impractical antenna for X band. At 94 GHz, however, the antenna diameter need only be 1.2 ft. A narrow-beam antenna such as might be obtained at millimeter wavelengths permits low-angle tracking as well as offer improved performance in other multipath situations or where multiple targets must be resolved in angle.

Although the low-angle tracking capability can be improved with narrow-beam antennas at millimeter wavelengths, atmospheric absorption and refraction sometimes can negate the benefits, especially at long range. At short range (less than a few kilometers) the effects of the atmosphere and weather on the range are claimed to be not prohibitive.¹² One study¹¹ has shown that for a particular low-altitude tracking application there was no advantage to operating at 94 GHz with its narrower beamwidth as compared to 35 GHz using the same size aperture when accurate tracking is desired at ranges out to 20 km since atmospheric attenuation limits the performance of the higher frequency radar. In clear weather and with short range, however, radar has a decided advantage over lower frequency radars. For example the 94 GHz radar in a particular¹¹ situation will be capable of accurate tracking out to about 4 km while a K_a band radar with the same size aperture can track to 2 km and a C-band radar to only 0.9 km.

Atmospheric refraction effects can result in measurement errors at low angles and can contribute to amplitude variations (fading). Peak-to-peak variations of 20 db have been observed over a 18.95 km one-way path at 94 GHz on dry, windy days.²⁸ Under more humid conditions the fluctuations are of less magnitude. Over water, multipath can produce fluctuations.⁶⁴ The low-lying evaporation duct over water can trap electromagnetic radiation and result in considerably longer ranges when both the antenna and the target are at low elevations.⁶⁵ This propagation in the duct is said to be better the higher the frequency, but measurements at millimeter waves do not seem to be available.

Another reason for considering millimeter waves for radar is when the spectrum crowding of the lower frequencies is intolerable and wide spectrum space is needed. Millimeter wavelengths for radar can alleviate the usual electromagnetic compatibility problems found at lower frequencies. The very wide bandwidth in which to hide plus the attenuation of the atmosphere make the radar transmissions more secure from hostile detection and intercept.¹⁵ The shorter the range of the radar and the longer the distance to the intercept receiver, the more secure will be the radar transmissions.

Millimeter wave radar is to be considered when the target dimensions are comparable to the wavelength. Radar probing of clouds thus can be more successful with millimeters than at lower frequencies. With clouds the shortest wavelengths are preferable.¹⁴

The millimeter wave region is also attractive for imaging radars, those that are of high enough resolution to discern the shape and size of the target. The wide bandwidths result in good resolution in range and the narrow beamwidths result in good angle resolution. A radar with good range resolution can provide the target size and determine the highlights of the target that contribute to the echo. Resolution in both angle and range is employed in airborne ground-mapping radars. Synthetic aperture processing can be used to improve the angle resolution for ground-mapping radars, but the real-aperture conventional radar at millimeter wavelengths can be made with a beamwidth sufficiently narrow for some applications. High resolution airborne imaging radar at K_a band has demonstrated its capability to discover geologic features not found with optical photography, to make surveys of vegetation of various sorts, to map cultural regions and to map ice.²⁰ Higher frequencies might also have potential in such applications.

The imaging or high resolution properties of millimeter wave radar are of interest for the identification of target characteristics and, in particular, for space object identification.¹⁶ As with the mapping radar, the wide bandwidth for range resolution is a desirable property and the high carrier frequency makes synthetic aperture methods attractive for higher resolution

in angle. The high doppler sensitivity at millimeter waves should permit a precise measurement of the spin rate for spinning satellites.

Another application of the imaging properties of millimeter wave radar is for harbor surveillance and airport surface detection equipment. Frequencies at K_a band or less are more attractive at present than higher frequencies. Millimeter waves can penetrate fog or haze while optical frequencies cannot. Other weather effects however, would limit imaging (surveillance) radars to short range.

Since the doppler frequency $f_d = 2v_r/\lambda$, where v_r = relative velocity and λ = wavelength, a given accuracy in measuring the doppler frequency results in a greater accuracy in measuring velocity the shorter the wavelength of the radar. For example, if the doppler shift can be measured to an accuracy of 10 Hz, accuracy with which a target could be measured at $\lambda = 3.2$ cm (X band) is 0.3 knot and at $\lambda = 3.2$ mm (94 GHz) is 0.03 knot. The accuracy with which the doppler frequency can be measured depends only on the time duration of the measurement and not on the frequency, so that more accurate velocity measurements can be made at the high frequencies, as indicated by the doppler equation above. Just as with several other useful characteristics of millimeter waves, the high doppler frequency shifts, however, can cause a problem. If the doppler frequency shift is great enough, the received signal may be sufficiently far in frequency from the transmitted frequency that the receiver must be tuned to that of the expected doppler-frequency-shifted echo signal. In some cases, the amount of doppler shift is unknown and the receiver must be swept in frequency to find that of the echo, or a bank of overlapping receivers must be used to simultaneously cover the expected band in which the echo signal may be found. Thus, the large doppler shift is another of those characteristics of the millimeter wave region with the strange property that it can be both good and bad at the same time.

The few illustrations given above indicate that potential advantages can accrue in some applications from the use of millimeter waves for radar. The crucial question is whether or not the advantages outweigh the disadvantages. In the appendix is given a brief description of a millimeter wave radar designed for surveillance to illustrate what performance might be possible.

COMMUNICATIONS

The directive nature of conventional millimeter wave antennas of even small physical size requires that communications at these wavelengths generally be point-to-point.²⁴⁻³¹ Two types of millimeter-wave point-to-point ground communications systems have been proposed. In one, propagation is by "free-space" radiation as in conventional microwave relay links and in the

other, propagation is via transmission lines. Point-to-point radio communications propagating in "free space" require large transmitting gains and large antenna apertures for achieving long distances. (This is similar to the requirements for the tracking radar discussed previously and similar conclusions apply). The need for large gain favors the high frequencies but the large aperture favors the low frequencies. Taking account of the maximum antenna size due to mechanical tolerances sets a limit to the upper frequency. This limit, with current practice, seems to lie within the microwave region. Consequently, millimeter waves do not hold much attraction over microwaves for long-range point-to-point communications. Adding further weight to this conclusion is the attenuation of millimeter radiation by rain. Thus, millimeter-wave point-to-point communications in "free space", if used, would generally be of short distance. One study²⁶ shows that at 35 GHz, path lengths of 8 to 12 km are feasible with reasonably low outage times even in bad weather. In fair weather, distances can be greater. In the 94 GHz band the distance between terminals might be but several kilometers for high reliability in all weather,²⁹ but in fair weather it is claimed that path lengths can be of the order of 50 km with transmitting powers under a watt.²⁸ For comparison, the distance between line-of-sight microwave links is typically 40 to 50 km.

Heavy rain that severely affects millimeter wave propagation is generally localized. Therefore, it has been suggested²⁹ that the rain attenuation problem at millimeter wavelengths can be reduced by a diversity network of short-range communication links with redundant paths to reach the same point. With geographical diversity via alternate routes it is unlikely that all paths connecting two points will be affected simultaneously by heavy rain. This approach might reduce the severe effects of rain, but its utility must be justified economically as compared to other methods that are not affected by rain.

It has been suggested²⁴ that short range millimeter wave links if operated within an absorption band, such as the oxygen absorption region around 5 mm wavelength, can provide satisfactory short-range propagation with little interference to other stations. By changing frequency so as to move up and down the side of the oxygen absorption spectrum the total path attenuation can be maintained constant when rain attenuation is present.

Although millimeter wave point-to-point communication systems appear technically feasible there does not seem to be a published analysis of the economic feasibility as compared with other point-to-point communications methods. There have been qualitative arguments given in the literature implying that millimeter-wave systems with many short-hop links can compete with the widely used microwave links of fewer sites with longer hops.

There has been no thorough quantitative comparison made however and it would be the writer's guess that the millimeter wave system would not prove competitive in general unless there was some special requirement imposed that could not be readily achieved at microwaves, such as for example the transmission of extremely wide bandwidths.

Point-to-point millimeter wave communications via closed waveguide transmission lines seem to be of more interest than "free space" communications.^{24,25} One of the attractive features of employing the higher frequencies is that the circular electric mode (TE_{01}) of propagation in round waveguide experiences decreasing attenuation with increasing frequency. For example, an ideal circular waveguide with 1" I.D. at 200 GHz has the same theoretical attenuation (2 db/mile) as a 5" I.D. waveguide at 9 GHz.²⁴ The gas within the waveguide can be controlled so that the irregularities of propagation within the earth's atmosphere can be avoided and there is no need to be restricted to the standard propagation windows. Experiments have been conducted in Japan²⁵ with underground waveguide transmission lines 4.2 km long using all solid-state PCM-AM repeaters at a frequency of 47 GHz. The British Post Office Research Department plans field trials by 1972 of a waveguide system using frequencies in the range 30 to 100 GHz and hope to provide for up to one third of a million telephone circuits or 300 two-way television channels.³³

Recently, the Bell Telephone Laboratories announced^{34,70} their intention to build a 20 mile trial link in New Jersey. The all solid-state repeater is supposed to handle 59 one-way channels plus one back-up, over a frequency range of 40 to 110 GHz. Plans are for tests to start in 1974. The experiments planned or now in progress in several countries should provide the basic information needed to determine whether millimeter waveguide transmission is economically competitive. At the present time, insufficient information has been published to permit the writer to judge whether this technique can compete with existing techniques for point-to-point communications. However, the fact that experimental systems will be implemented in three different countries indicates that there is some belief that millimeter waves may be economically justified, especially where extremely wide bandwidths are necessary.

Millimeter waves have been considered for satellite-to-satellite communications.^{8,35} Since propagation is above the atmosphere the absorption encountered within the atmosphere need not be a bother. The long distances, limited spaceborne power and wide information bandwidths result in antenna gains of the order of 60 db for each terminal of a link between synchronous satellites.¹⁸ The narrow beamwidths that accompany the high gain may make beam-pointing between satellites a problem.

If the communication system is operated in the vicinity of the 5 mm absorption line of oxygen it is possible to communicate from satellite-to-satellite without interference from or to ground-based users. It also prevents eavesdropping by a ground-based receiver. (It has previously been mentioned that the large absorption of the 5 mm oxygen line can also be used for short-range point-to-point terrestrial communications when it is desired to limit the range of detection by third parties.) This is a characteristic not available at microwaves.

The extremely wide bandwidth offered by operation at millimeter waves is attractive when attempting to solve the problem of spectrum crowding found at lower frequencies.²³ The atmospheric windows in the millimeter wave region are each wider than the entire microwave spectrum. It has been suggested that the wide bandwidth available at millimeter wavelengths might be used for earth-to-spacecraft communications to relieve the overcrowding of the microwave spectrum.^{9,18,21,36,37} There is considerable interest in exploring the possibility of using frequencies in the vicinity of 15 GHz and 35 GHz and NASA is conducting propagation experiments at these frequencies. Although these frequencies are more like microwaves in their properties, it does represent a significant step towards the millimeter region. The region around 94 GHz is also of interest but the needed technology is not as available as at lower frequencies.

In clear weather, propagation through the atmospheric windows is not exceptionally severe especially for elevation angles greater than about 20 degrees. At 94 GHz, for example, the total absorption loss for signals passing through the entire atmosphere at near-zenith angles is about 1 db. With precipitation, however, the losses can be high enough that reliable communication cannot be readily achieved by adding reasonable power margin in the down-link from the spacecraft. The effect of rain is not only in the propagation path, but rain on the radomes or antennas of millimeter wave systems can increase the loss and is to be avoided. Just as in the case of point-to-point ground communications at millimeter wavelengths, advantage can be taken of the fact that heavy rainfall is generally localized so that a diversity of geographically dispersed sites might be able to insure the requisite reliability of communication. Thus it appears that millimeter wave earth-to-space communications links can be achieved and experimentation now underway should provide the information to tell how well they will work. It is likely however, that such millimeter wave system will have difficulty competing with microwave systems for earth-to-spacecraft systems unless extremely wide bandwidths are necessary. If millimeter systems are used it will probably be because someone is willing to pay the additional price to exploit the wide bandwidths and avoid spectral crowding at lower frequencies.

It should be noted that many consider the 35 GHz region and below to be

more a part of the microwave region than the millimeter region. The microwave region might even be considered as extending up to 50 GHz where the atmospheric attenuation is approximately equal to that in the window at 94 GHz. Thus the millimeter wave community should probably not claim success for earth-to-spacecraft communications until applications appear at 94 GHz.

It is well known that the greater the electron density of a plasma the higher must be the frequency of an electromagnetic wave if it is to penetrate the plasma without significant loss. Re-entering spacecraft can produce plasmas of sufficient density to prevent penetration by microwaves. This is known as blackout. One method of communicating with a re-entering spacecraft surrounded by a plasma is to use a sufficiently high frequency. Millimeter wave systems offer this capability.⁸

The extremely wide bandwidths available at millimeter waves, the freedom from third-party interference possible by operating at the frequencies of maximum absorption, and the ability to penetrate plasmas are characteristics of this portion of the spectrum not found at microwaves. To take advantage of these characteristics, however, the inherent limitations of small apertures and propagation losses found with millimeter waves must be tolerated and competing techniques at other frequencies must not be more attractive alternatives. Competing techniques include exploiting the upper end of the microwave region for wide bandwidth; coded transmissions for reducing third-party interference; and additives or burn-through for communicating through a plasma.

RADIOMETRY (PASSIVE DETECTION)

The radiometer achieves passive detection by measuring the noise temperature viewed by its antenna. The presence of a target is recognized when the noise temperature seen by the antenna differs from that of the background. The temperature of a target (called the brightness temperature) viewed by a microwave or millimeter wave radiometer is not necessarily the same as the thermal, or ambient, temperature but depends on the emissivity of the radiating objects as well as the thermal temperature and on the temperature of radiating objects seen by reflection.³⁸ (It also depends on the magnitude of the radiating objects seen via the antenna sidelobes, if the sidelobes are not sufficiently low.) With microwave and millimeter waves the brightness temperature when viewing the earth is approximately the ambient thermal temperature. When observing metallic targets or the sea surface, the brightness temperature can be much lower than the ambient temperature because the emissivity of such surfaces is low and because these targets reflect the brightness temperature of the cold sky. Four types of objects have been of interest for radiometric detection: (1) "discrete" objects such as ships and vehicles, (2) broad surfaces such as the ground (for mapping) or the sea (sea state measurement), (3) astronomical objects, and (4) atmospheric constituents

including water vapor and precipitation.

Since the undesired background radiation competes with the target radiation, the narrower the antenna beam the less will be the background intercepted and the greater will be the target-to-background contrast. Radiometer sensitivity is proportional to the square root of the predetection bandwidth so that millimeter waves are attractive because of the wide bandwidths that are available. Furthermore, beams can be achieved with physically small antennas. Another advantage of the millimeter wave region is the presence of absorption bands that permits remote sensing of the atmospheric constituents. Unfortunately these advantages are sometimes offset by the poorer receiver sensitivities at the higher frequencies and by undesired atmospheric attenuation, especially in rain.

Millimeter wave radiometers have demonstrated the capability for passively detecting ships^{9,18} and vehicles.^{12,13} Detection ranges of 10 miles on conventional freighters have been achieved with 35 GHz radiometers. These measurements were made viewing the target at low grazing angles. The ships appeared cold against the background of the sea. In other situations ships might appear warmer than the sea.³⁹ Generally the wake generated by a ship is a hotter target than either the ship itself or the surrounding sea. Radiometers at K_u band have been successful for the detection of icebergs.³⁹ Higher frequencies might be attractive for this application because of the improved angular resolution that can be achieved.

Metallic land vehicles such as trucks or tanks are of low emissivity so that the apparent temperature is predominately that of the cold sky reflected by the target.¹² The temperature of the earth background is close to the ambient temperature ($\sim 300^\circ$ K) while that of the sea background is lower ($\sim 240^\circ$ to 280° K at 70 GHz³⁶) because it reflects the sky temperature.

One of the limitations of millimeter wavelengths is its absorption by atmospheric constituents. This limitation to radar and communication systems can be turned to advantage for the remote sensing of the atmosphere (meteorological measurements). Radiometric measurements can determine the temperature-pressure profile of the atmosphere and the distribution of water vapor and ozone.

The determination of the atmospheric temperature profile utilizes the absorption of 60 GHz radiation by the oxygen molecule. This absorption can be quite large. The total vertical attenuation at 60.8 GHz is 130 db.⁴⁰ The spectrum of oxygen in the vicinity of 60 GHz contains a number of individual lines that completely overlap at sea level, but are resolved at altitudes of 30 km. At intermediate altitudes the spectral lines partly overlap. Thus the attenuation in the atmosphere depends on the altitude and the frequency. Because of the correlation between absorption and emission of energy,

the brightness temperature measured by a radiometer in the vicinity of the 60 GHz oxygen lines will also depend on the frequency and the ambient temperature distribution with altitude. The frequency selective nature of the absorption by oxygen causes each frequency to be effectively able to penetrate to a different altitude of the atmosphere. The temperature profile is found by an inversion technique that, in essence, finds the profile that best fits the measured brightness temperature data. This requires an accurate knowledge of the absorption characteristics of oxygen as a function of the altitude. Details of the method may be found in the references.⁴⁰⁻⁴² Such measurements may be able to give the average temperature in a layer of the atmosphere roughly 10 km thick.⁴⁰ The bandwidth of the radiometer must be smaller than the bandwidth of radiometers generally used for target-detection purposes or for radio astronomy. The bandwidth should be increasingly narrow to determine the temperatures at increasingly high altitudes.⁴⁰ The narrow bandwidths mean the sensitivity will be reduced compared to a wide band radiometer.

Unlike similar measurements with infrared, the effects of clouds on millimeter wave radiometer measurements are generally negligible. Ground based measurements can be used to probe the temperature structure of the lower troposphere, a region in which temperature inversions are likely to form that can trap city smog.⁸ Measurement from satellites and balloons can provide temperature profiles of the upper atmosphere where it is difficult to obtain meteorological information with radiosondes. The radiometric method for obtaining temperature profiles provides a technique for studying time-dependent changes in the atmosphere. It has been said that if the temperature profile can be measured to an accuracy of 2 to 3° K on a global scale, it would be very useful for the collection of synoptic meteorological data.⁴¹ The use of the 60 GHz absorption band has also been suggested for possible detection of clear air turbulence.⁶⁶ The temperature profile in a horizontal path forward of an aircraft would be sensed with a multichannel radiometer. Assuming that temperature discontinuities are associated with clear air turbulence, it is calculated that the presence of such a region might be detected approximately 5 to 6 minutes before penetration by an aircraft at a speed of 600 mph.

Measurements of the atmospheric distribution of H₂O are usually made in semitransparent regions of the spectrum where the spectrum is more sensitive to the distribution of absorbers in the atmosphere than to the temperature profile.^{41,42} The composition profile is found from the measurement of a spectral line in absorption using the sun or the brightness temperatures from space or using the ground as the source for the absorption measurement. Measurements of the water vapor content have been made at 22 GHz by the inversion of solar absorption measurements, at 20 and 22 GHz by ground-based observations at zenith and at a number of frequencies from 22 to 64.5 GHz by observations from space over the smooth ocean.⁴¹ It is because the

water vapor resonance line at 22 GHz is not completely opaque that the content can be measured. At higher frequencies where the water vapor resonances are more lossy, the measurement of content is more difficult. (The 22 GHz region at which most of the observations have been made is not within the millimeter-wave region in the strict sense, but the principle on which the measurement is based is more familiar to the millimeter rather than to the microwave technologist.) It should also be possible to make similar composition-profile measurements of ozone and stratospheric water vapor.

Millimeter waves might be used for the remote measurement of the water content of clouds,⁴¹ ground mapping, ice mapping and the detection of forest fires.³⁸

The millimeter wave region is an important part of the spectrum that cannot be excluded from a complete study of radio astronomy.^{43,57,58} The radiometer is the basic measurement tool of radio astronomy. The part of the sun viewed by a radiometer depends on the wavelength of observation because the absorption of electromagnetic energy by the solar constituents is frequency dependent and the depth of penetration therefore depends on the frequency. Thus, millimeter wave observations should provide information about the sun not practical with observations at other wavelengths. For example,⁴⁴ radiation at K_a band originates primarily from the upper and middle chromospheric regions and high-resolution observations of the sun have been used to provide fundamental data leading to a capability for solar-flare forecasting. A high-resolution radiometric map of the sun can locate the active regions and from this can be determined the probability of a proton-producing flare erupting. Solar flares might also be recognized on the basis of polarization. Solar radiation is generally unpolarized, but that from a flare would tend to be polarized.⁸ Planets apparently appear brighter at millimeter wavelengths than at longer wavelengths and it has been said that probably the most important information concerning the surfaces and atmospheres of the planets will come from millimeter wave observations.⁴³ Millimeter waves have also been used to observe nebulae within the galaxy where it is noted that ionized clouds stand out relative to synchrotron sources. Quasars, which vary with time at millimeter wavelengths, and the general cosmic background (3°K black body temperature) have also been observed. Most of the cosmic background radiation lies in the millimeter region and is thought to be the residue from the explosive early phases of the universe. Extragalactic water vapor has also been detected by the radio astronomers from observations of the absorption line at 22 GHz.

One of the advantages of millimeter waves for radiometry is the narrow beamwidths that can be achieved with reasonable size apertures. The narrow beamwidths provide angular resolution that is needed to enhance the target contrast relative to the background. The narrow beamwidth is described by

the antenna gain G . The greater the gain the smaller the beamwidth. Another advantage of millimeter waves is the wide bandwidth. The wider the bandwidth the greater is the radiometer sensitivity. Since both high gain and wide bandwidth are generally easier to achieve the greater the frequency, the frequency should be as high as possible to enhance these two factors. There are other factors, however, that might preclude too high a frequency. The overall effect of frequencies is described below.

The sensitivity of a radiometer is measured by its ability to detect a temperature change ΔT_{rms} at its input³⁸

$$\Delta T_{\text{rms}} = \frac{\alpha (T_A + T_R)}{\sqrt{B\tau}} \approx \frac{\alpha F_n T_o}{\sqrt{B\tau}} \quad (3)$$

where α is a constant depending on the receiver design and is usually in the range 1 to 3, T_A = antenna temperature (essentially the brightness temperature of the object viewed), T_R = receiver noise temperature, B = bandwidth, τ = integration time, F_n = receiver noise figure and T_o = reference temperature. Equation 3 assumes $T_o \approx T_A$ which is a reasonable approximation when the antenna is looking toward the earth.) The change in antenna temperature ΔT_A is

$$\Delta T_A = \frac{A_T G}{4\pi R^2} \Delta T_T \Gamma \quad (4)$$

where A_T = target area, Γ = atmospheric transmission factor, ΔT_T = temperature difference between target and the background, and R = distance from radiometer to target. Equating the two expressions of Equations 3 and 4 gives

$$R = \left[\frac{A_T G \Delta T_T \Gamma \sqrt{B\tau}}{\alpha F_n T_o} \right]^{\frac{1}{2}} \quad (5a)$$

$$R = K [G \Delta T_T \Gamma \sqrt{B} / F_n]^{\frac{1}{2}} \quad (5b)$$

In Equation 5b, the non-frequency-dependent factors have been lumped into the constant K . Next consider how the range might vary with the frequency.

For a fixed antenna aperture area, the gain $G \sim f^2$. The target contrast ΔT_T is not easy to identify as a function of frequency so it will be assumed constant for present purposes. The transmission factor Γ depends on the range † the attenuation constant, but generally decreases with increasing frequency. In rain the decrease with increasing frequency can be very rapid.

The bandwidth is assumed to be proportional to frequency. For simplicity the noise figure is taken to vary linearly with frequency. Thus, for this particular set of assumptions the range $R \sim f^{\frac{3}{2}}$, in addition to any dependence due to the target contrast ΔT_T and propagation factor Γ , so that higher frequencies would be favored.

If the frequency dependence of Γ were f^{-1} then $R \sim f^{\frac{1}{2}}$. If at any frequency, the maximum gain antenna is used and the frequency dependence of $\Delta T_T \Gamma$ ignored, then $R \sim f^{-\frac{1}{2}}$. It is likely that the frequency dependence of $\Delta T_T \Gamma$ can make the exponent even more negative. Thus under the proper circumstances there might be a slight advantage in using the higher frequencies for radiometers, but realistic propagation conditions and practical receivers might negate any slight advantage of the higher frequencies and result in a frequency dependence that favored lower frequencies. The chief advantage of the millimeter wave region over the microwave region for radiometry applications (exclusive of radio astronomy) is when the target characteristics are unique to the millimeter region, as in the case of molecular resonances used for remote sensing.

Before leaving the subject of radiometry, mention should be made of the combined use of radar and radiometry.^{45,46} In one configuration a Dicke-type superheterodyne radiometer was combined with an FM-CW radar at 3 mm wavelength. The radar and radiometer reception bands were separated in frequency to achieve simultaneous operation. By sharing equipment a savings can be had compared to a separate radar and a separate radiometer. It is claimed⁴⁵ that the combination of the two sensors can provide information as to the type of target being viewed not possible with either sensor alone. Experimental data shows that with a radar alone or a radiometer alone there would be ambiguities in separating metallic from non-metallic targets but the combined use of these sensors allows discrimination since metallic targets will generally either exhibit large radar return or low brightness temperature.

INSTRUMENTATION

This category is meant to include those applications in which millimeter wave systems are used as measurement instruments. Such applications are of more specialized interest than potential applications in the more glamorous areas of radar, communications and passive detection but they have already been utilized to advantage. Applications to instrumentation might not appear spectacular since they have been generally in the area of research rather than in areas with more immediate economic gains. Millimeter waves seem to offer unique advantages in instrumentation because of the interactions with scattering objects that are wavelength dependent. There have been many radar, communications and passive detection systems built in the millimeter wave region and their potential advantages have been highly touted. Their application

to solve some real problem has been, with but few exceptions, almost nonexistent. However, in the area of instrumentation millimeter waves have been used in earnest.

The use of millimeter wave radiometers in radio astronomy has already been discussed. Although it was included under radiometry, it is an important instrumentation application that could just as well have been included in this section. To some extent, the application of the millimeter wave region for remote sensing of the environment also might be thought to be categorized as being more like those in this section. The choice is somewhat arbitrary and the subject could have been included in either listing.

Properties of plasmas, fusion devices, rocket exhausts, ionized flow fields of projectiles and similar ionized media can be determined by examining the propagation of millimeter waves through these media.^{47-50,60} The electron density and its distribution and the collision frequency of the plasma can be determined by measuring the transmission and reflection of an electromagnetic signal. Millimeter waves are useful for plasmas with densities greater than can be measured with microwaves or lower frequencies. (Many of the familiar effects of the interaction of the ionosphere with HF and VHF radiation can be applied to higher density plasmas probed with millimeter waves, e.g. refraction, Faraday rotation, and incoherent scattering). A further advantage of the shorter waves is that the resolution is greater so that the region of the plasma being measured can be better defined.

Spectroscopic measurements of gases have been one of the applications that has not needed high power and consequently has been one of the oldest uses of millimeter waves and is still of significant interest.⁵¹⁻⁵² Although power sources for spectroscopy need not be high (saturation would occur if they were) the power must be of high spectral purity and capable of being tuned over different frequency bands. The principal measurement is the determination of the frequencies (spectral lines) at which electromagnetic energy is absorbed in gases due to molecular rotations. Vibrational spectra in solids, electronic resonances, free radical spectra, cyclotron resonances in solids and gases, and quantum transitions in superconducting solids may also be studied with millimeter waves. Such measurements are used in the evaluation of important physical constants and in the critical testing of basic physical theory.⁵¹ Professor Gordy has made the interesting observation that it is "the measurement of spectral lines of molecules that has been the motivation for development of the millimeter and submillimeter region."⁵³ Another by-product of the study of microwave and millimeter wave spectroscopy is remote sensing of the atmosphere, as mentioned in the previous section, where the understanding of the resonances of the oxygen molecule as a function of pressure led to its application as a means for obtaining the temperature profile of the atmosphere.

The cross section of radar targets is often determined by scaling to a higher frequency where smaller size models can be used. Scaling from the lower microwave frequencies generally is no problem. To scale from the higher microwave frequencies, however, means that the scale frequencies must be in the millimeter wave region.¹³ The scaling is not always easy since the precision of the models must be carefully controlled, but millimeter waves have been used to obtain model measurements that can be applied to the microwave region.

Millimeter waves can be used for classroom and lecture demonstrations of phenomena in physical optics. According to one source,⁵⁴ the best wavelength is about 10 mm. (This is so close to the 3 cm region, presently available in commercial classroom microwave equipment at low cost, that it would seem the 10 mm wavelength region might not be able to compete economically.)

Another possible application is for the remote measurement of small scale vibrations. A millimeter wave signal impinging on a vibrating reflecting object will be modulated by the vibrations. These may be detected and used as an indication of the vibrations as well as determining the vibrating frequency. Since the displacement of the surface must be at least a significant fraction of a wavelength, the smaller the vibration amplitude the shorter must be the wavelength of the electromagnetic probing signal.

COMPARISON WITH OPTICAL AND INFRARED

Most of the relative comparisons of the millimeter wave region in this paper have been with microwaves. Microwaves lie closer to millimeter waves in the spectrum than do optical frequencies and the techniques are, at present, more similar to those at microwaves. Nevertheless, it is necessary to consider the optical and IR frequency range as potential competitors to millimeter waves. Certainly there has been a lot of interest in, and financial support of, lasers in this frequency region and it is legitimate to inquire how this technology compares with millimeter wave capabilities.

Several of the claimed advantages of millimeters relative to microwaves apply even stronger when optical wavelengths are compared to millimeters. Optical wavelengths are considerably smaller and bandwidths are tremendous compared to millimeter waves or to microwaves. Also the characteristic wavelength produces effects and interactions not found at other frequencies. The atmospheric window at optical frequencies allows transmission without prohibitive loss; but rain, fog and haze severely limit the utility of these higher frequencies for sensor or communication applications. Almost all atmospheric effects are transparent to microwaves; millimeters do not penetrate rain well but can penetrate fog; infrared cannot penetrate fog, but can see through haze; but optical frequencies cannot even penetrate haze.⁵ Receiver sensitivities

are generally poorer at infrared and optical frequencies, but high power seems to be available with lasers. The higher the frequency, the more difficult will be the beam-pointing problem. Each of the major categories of applications will be briefly discussed in terms of optical wavelengths vs. millimeter wavelengths.

Laser radar has been demonstrated for range finding, target profiling and imaging. The chief attribute of laser frequencies is the extremely narrow beamwidths that can provide exceptionally good target discrimination in the angle coordinate. All of the basic (non-component) limitations of millimeter wave radar apply as well to laser radar, perhaps more so. Laser powers are higher than presently available at millimeter waves, but there does not seem to be any fundamental reason why the powers of millimeter wave devices cannot be increased. Although available bandwidths at optical wavelengths are high, the full potential of millimeter wave bandwidths -- or even X-band bandwidths -- has probably not been fully exploited. Also, the reduced sensitivity that is characteristic of optical receivers means that the vastly greater bandwidths available in the optical region are useful only at the higher signal levels.⁵ Thus, it would seem that, at least in the near future, the laser radar will be uniquely used primarily for special applications where extremely narrow beamwidths are important and when operation in poor weather is not required.

Similar comments would seem to hold for laser communications. The chief characteristic of IR and optical wavelengths for communications is the extremely wide bandwidth available. Although wider bandwidths than are now used with present communication channels are certainly desirable, it does not seem that there are many services being denied because of the unavailability of the wide optical frequency spectrum. This may be somewhat of an unfair statement since applications not now considered might be uncovered once the wide bandwidths are proven feasible and easily made available.

Passive detection at optical frequencies and IR is a well established art. The sensitivity of receivers at the higher frequencies is less than that of microwave or millimeter waves but the increased thermal energy radiated by targets at the shorter wavelengths and the angular resolution and image qualities are such that there has been little competition from the lower frequencies. The application of these frequencies to measurement instruments has, of course, been far more widespread than at millimeter wavelengths and this dominance is likely to continue. Passive devices at optical and IR wavelengths certainly have proven their practical worth by the many applications that have been made over the years. The apparent "elegance" of the laser, however, does not necessarily mean that active devices at optical wavelengths will dominate those at lower wavelengths. Optical radar was known long before the laser became a reality. The laser provided coherent power not previously available at optical frequencies. Thus, applications of laser radars if they are

to be unique, probably must take advantage of the coherency. Coherent radiation can provide well-collimated narrow beams and large concentrations of power. Laser radar applications that do not take advantage of the inherent coherency, extremely wide bandwidths, or the very narrow beamwidths are probably better accomplished with lower frequencies.

To summarize this section, the conventional applications of passive optical and IR devices will probably not be threatened by millimeter waves (or by microwaves) and there does not seem to be any reason to expect lasers to usurp the classical microwave radar or communication functions except in very special cases. The chief advantage enjoyed by optical and IR lasers over millimeter wave power sources, at present, is their higher power capability.

THE FUTURE

For the past twenty years predictions have appeared extolling the great future for millimeter waves. This paper presents the observation that the millimeter wave region has important characteristics that are useful for special application but that it is very unlikely that this part of the spectrum will capture any significant part of the approximately \$1.5 billion now spent annually on radar systems and the \$1.8 billion spent annually on communication systems⁵⁹ even if significant improvements in power and sensitivity are made. Important, extensive applications of any technology are seldom obscure. The lack of such obvious applications in the millimeter wave region should be admitted and promises for the future should be made only on a firm foundation of fact.

It is dangerous to try to predict the future in a particular technology and no attempt will be made to do so here regarding millimeter waves. The most foresighted can only view but a few short years ahead for the reason that new inventions usually cannot be predicted and any presently known idea with any prospect of success generally is already being exploited. If someone could really predict what will exist in a particular technology twenty years hence he would be at work now and it would probably be here in five years instead of twenty. This is mentioned to give emphasis that the lack of major applications of millimeter waves is a situation true today and in the near future, but might not be true five years hence. One should not be deceived, however, regarding the utility of millimeter waves today. It follows the classic syndrome of other fields such as information theory, operations research, and lasers which were intriguing to the researcher and which were highly touted for many potential major applications in the future but which have not fully lived up to expectations. It should be noted that over the years the enthusiastic predictions of some proponents of millimeter waves have become more subdued and pessimistic as useful applications failed to materialize.

In pondering the potential and the future of millimeter waves it may be well to recall the early history of microwaves. The early experiments of Hertz in 1886 were at frequencies now considered to be microwaves. A working radar system for the detection of ships was actually demonstrated in Germany in 1904. This work did not materialize into applications since there was no real economic need for radar at that time. Thus, microwaves remained a laboratory curiosity for many years. It wasn't until the maturing of the airplane in the 1930s that a real need for radar existed. With the need for radar came the rapid and extensive advancement of microwave technology, rather than vice versa. Millimeter waves in the laboratory date back almost as far as microwaves, but apparently they must await some now unappreciated major need to reach the economic status enjoyed by other electromagnetic technologies. The technological barriers will undoubtedly be overcome with time, just as were many other technological barriers in the electromagnetic spectrum overcome in the past. (Recall, for example, the difficulty of "breaking the HF barrier" in the thirties until the invention of the microwave magnetron that was brought about by the needs of radar.)

Millimeter waves are of considerable interest to the researcher and should be pursued vigorously in the laboratory. They offer an excellent opportunity for thesis material to those universities that can afford the expense of millimeter wave equipment. (With the continued advancement of laser and quasi-optics techniques costs of experimental equipment may be less in the submillimeter region than in the millimeter region.) At the present time, millimeter waves should be explored for their own sake rather than be tied to finding the "grand" application. This approach may be a bit idealistic since it is sometimes difficult to obtain significant amounts of funding without offering the promise of rich rewards in potentially useful system applications. It is unfortunate that it is seldom possible to obtain large funding to simply stock-pile new knowledge. It seems necessary to promise applications, no matter whether or not they have any competitive potential, just to obtain continued support for the exploration of the technology. This is true of many areas besides millimeter waves. Nevertheless, the investigation of the science and technology of this region of the spectrum should be boldly encouraged for the opportunities available to increase knowledge and capabilities. This part of the spectrum has already been put to good use for scientific endeavors and for some limited applications and its exploration and exploitation should continue.

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APPENDIX

MILLIMETER WAVE SURVEILLANCE RADAR

The purpose of this appendix is to illustrate what the parameters might be of a surveillance radar operating at 94 GHz (3.2 mm) assuming realistic values for the radar characteristics. The equation governing this situation is

$$R_{\max}^4 = \frac{P_{\text{av}} G^2 \lambda^2 \sigma n E_i(n) \exp(-2 \alpha R_{\max})}{(4 \pi)^3 k T_o F_n (B_n \tau) f_r (S/N)_1 L_s}$$

where

- R_{\max} = maximum radar range, m
- P_{av} = transmitter average power, watts
- G = antenna gain
- λ = wavelength, m
- σ = target cross section, m^2 (assumed 1 m^2)
- n = number of hits integrated
- $E_i(n)$ = integration efficiency
- $\exp(-2 \alpha R_{\max})$ = reduction in signal due to attenuation
- α = attenuation constant of the medium
- $k T_o = 4 \times 10^{-21}$ watts /Hz
- $B_n \tau$ = bandwidth-time product ≈ 1
- f_r = pulse repetition frequency, Hz
- $(S/N)_1$ = signal-to-noise ratio required for detection
- L_s = system losses.

At a frequency of 94 GHz, power sources with an average power of 200 watts might be available. Since we know a radar at this frequency will be limited, it is important to use as high an antenna gain as possible. Therefore, we select an antenna with a beamwidth of 0.1° in both azimuth and elevation. The gain is approximately 63 db. Since an elevation beamwidth of 0.1° would give poor coverage, it is assumed that the antenna beam will be spoiled in the vertical plane to give csc^2 coverage and that a loss of gain of 3 db is had. Thus $G = 60$ db. The antenna diameter would be close to 7 ft.

The number of hits integrated is $n = \theta f_r / 6 \omega_m$ where ω_m = the rpm of the antenna. Assuming a rotation rate of 5 rpm (12 sec data rate) and $f_r = 1000$ Hz (about 80 nmi maximum unambiguous range) $n = 0.1 \times 1000 / 6 \times 5 = 3.3$ hits/scan. The product $n E_i(n) \approx 3$.

The attenuation factor will be ignored for the present and will be taken account of later.

The noise figure of a good receiver might be 10 db and 10 db system losses are assumed. A signal-to-noise ratio of 15 db is also assumed.

Substituting into the range equation gives

$$\begin{aligned} R_{\max}^4 &= \frac{2 \times 10^2 \times 10^{12} \times (3.2)^2 \times 10^{-6} \times 1 \times 3}{2 \times 10^3 \times 4 \times 10^{-21} \times 10 \times 1 \times 10^3 \times 3 \times 10} \\ &= 2.5 \times 10^{20} \\ R_{\max} &= 1.26 \times 10^5 \text{ m} = 68 \text{ nmi in free space} \end{aligned}$$

Next, consider the neglected attenuation factor. At sea level, the attenuation rate at 94 GHz is about 0.4 db/km in clear weather. In 4 mm/hr rain the attenuation is 2.5 db/km. The range is reduced to about 16.5 nmi in clear weather and about 4.6 nmi in the rain. These figures are quite low and represent a significant reduction from the 68 nmi free space range.

If 4 such radars were used together as on a "merry-go-round" or some such other coordinated fashion, the theoretical improvement in detectability would be increased by a factor of about 5.5 db. Normally this would increase the range by a factor of 1.37, or to a range of 93 nmi if attenuation is ignored. The atmospheric attenuation will reduce so that the range in clear weather might be about 19 nmi. In rain, the improvement is even smaller so that the expense of employing four radars in unison is not worth the effort.

Thus the best that might be achieved in a millimeter wave surveillance radar is perhaps 15 to 20 nmi in clear weather, reduced to about 4 to 5 nmi in rain.

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<p>Many applications of millimeter and submillimeter wave systems have suggested in the literature but, in general, they have not yet been employed in practice to any significant degree. This report discusses the advantages and limitations of this frequency region and reviews the potential applications under the categories of radar, communications, radiometry and instrumentation. One of the problems of operating in this frequency range is that some of the advantages can also be considered as limitations. Even if transmitter powers and receiver sensitivities were the same as those obtained at microwaves, it would be unlikely that millimeter and submillimeter wave systems could compete with most of the major applications of microwaves. Successful applications of the shorter wavelengths will probably utilize characteristics that are distinct from those of microwaves. The special attributes of millimeter and submillimeter waves are narrow beamwidth with reasonably-sized apertures, wide bandwidth, and interactions with the constituents of the atmosphere and other gases. The more likely candidates for applications unique to this frequency range include remote sensing of the environment, interference-free communications and radar. low-angle radar tracking, high-resolution and imaging radar, extremely wideband communications, plasma diagnostics, and spectroscopy. If systems applications occur it seems more likely that they would be found initially at frequencies below 50 GHz rather than at the higher frequencies. At the present time, there does not seem to be imminent major systems applications of these wavelengths. The search for quick "riches" in practical millimeter wave systems applications probably should be minimized, and more emphasis should be placed on exploring the science and technology of this region for their own sake.</p>			

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37

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