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Millimeter Wave Propagation Over an Aircraft Carrier Deck

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CONTENTS

ABSTRACT

A study has been performed to assess the magnitude of multipath interference effects on the transmission of millimeter waves in an aircraft carrier deck environment. The results indicate that although serious interference potential exists, the magnitude of the interference can be greatly reduced by appropriate antenna beam shaping. The interference nulls could be eliminated by using diversity techniques; the use of spaced transmitting antennas is especially promising.

PROBLEM STATUS

This is an interim report; work continues on other phases of the problem.

AUTHORIZATION

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MILLIMETER WAVE PROPAGATION OVER AN AIRCRAFT CARRIER DECK

INTRODUCTION

The use of millimeter waves to provide a line-of-sight data link between the island and the aircraft on the flight deck of an aircraft carrier is under consideration. This system would be used to transfer data from the ship's inertial navigation system (SINS) to the carrier aircraft inertial navigation system (CAINS). By operating at 60 GHz, where the atmospheric absorption approaches 30 dB per nautical mile, very secure operation can be achieved. Furthermore in this frequency region, extremely high data rates are feasible. A general study of the propagation problems that would be encountered at EHF and their effect on the signal transmission in a representative case has been performed. The effect of deck reflections and antenna patterns on the received signal, the use of diversity schemes, and the resulting complications of using such schemes are discussed in this report.

REFLECTION

In the absence of reflections the relative signal power arriving at the receiver would depend on the transmitter-to-receiver range, the antenna patterns, the frequency of the signal, and the absorption loss. Table 1 gives some calculated values of these various factors. The largest of the various losses is the normal free-space loss, which for a range of 500 feet is about 112 dB. The loss due to atmospheric absorption for a range of 500 feet is only 2.4 dB.

In the presence of reflections the received signal would be modified by the interaction of the reflected wave with the direct wave. The magnitude of the reflected wave depends on the surface material, the surface roughness, the grazing angle, and the frequency and polarization of the incident wave. The reflection coefficient (a complex number whose magnitude is the fraction of the incident wave that is reflected) for a smooth surface is given by Fresnel's (1) equations in terms of the surface dielectric constant and conductivity. For vertical polarization

$$R_V = \rho_V e^{-j\phi_V} = \frac{\epsilon_c \sin\psi - \sqrt{\epsilon_c - \cos^2\psi}}{\epsilon_c \sin\psi + \sqrt{\epsilon_c - \cos^2\psi}},$$

and for horizontal polarization

$$R_H = \rho_H e^{-j\phi_H} = \frac{\sin\psi - \sqrt{\epsilon_c - \cos^2\psi}}{\sin\psi + \sqrt{\epsilon_c - \cos^2\psi}},$$

where R_V and R_H are the complex reflection coefficients for vertical and horizontal polarization respectively. ψ is the grazing angle and ρ_V and ρ_H are the magnitudes of the respective reflection coefficients. The incident wave would change in phase by the angle ϕ

Table 1

Signal Loss Without Reflections for the Following Parameters: Frequency, 60 GHz; Absorption Coefficient, 29 dB/naut mi; Maximum Gains, 20 dB for the Transmitting Antenna and 5 dB for the Receiving Antenna; Heights Above the Deck, 30 feet for the Transmitting Antenna and 15 feet for the Receiving Antenna; Transmission Gain, $(2 + \csc \theta)/30$ for the Transmitting Antenna and $(\sin 3\theta)/\theta$ for the Receiving Antenna, where θ is the vertical angle; Antenna Pointing Directions, 2 degrees Downward for the Transmitting Antenna and 20 degrees Upward for the Receiving Antenna

Horizontal Range (ft)	Path Length (ft)	Free-Space Loss (dB)	Absorption Loss (dB)	Total Loss (dB)	Effective Loss (dB)
10	18.0	82.8	0.09	82.9	83.4
20	25.0	85.6	0.12	85.8	80.2
30	33.5	88.2	0.16	88.4	80.5
50	52.2	92.0	0.25	92.3	82.1
100	101.1	97.8	0.48	98.3	84.5
150	150.7	101.3	0.72	102.0	85.7
200	200.6	103.7	0.96	104.7	86.5
250	250.4	105.7	1.20	106.9	87.1
300	300.4	107.2	1.43	108.7	87.6
350	350.3	108.6	1.67	110.3	88.0
400	400.3	109.7	1.91	111.6	88.3
450	450.2	110.8	2.15	112.9	89.4
500	500.2	111.7	2.39	114.1	91.3
550	550.2	112.5	2.63	115.1	92.9
600	600.2	113.3	2.87	116.1	94.4

on reflection. The complex dielectric constant ϵ_c of the reflecting surface may be expressed as

$$\epsilon_c = \epsilon - j \frac{18\sigma}{F},$$

where ϵ is the relative dielectric constant, σ is the conductivity in mhos/per meter, and F is the frequency of the incident wave in gigahertz.

Curves calculated from the above equations (Figs. 1 through 4) show how the reflection coefficient changes with grazing angle for both horizontal and vertical polarizations for various values of dielectric constant and conductivity. For vertical polarization the reflection coefficient becomes a minimum at some value of grazing angle which is commonly known as the Brewster angle.

The above calculations were made for a smooth surface, which under actual field conditions would not be present. Using Rayleigh's (2) criterion, a surface is considered to be smooth when the vertical irregularities Δh satisfy the expression $\Delta h \sin \psi < \lambda/8$, where ψ is the grazing angle and λ is the wavelength of the incident wave. The preceding expression gives only a qualitative measure of the grazing angle at which the reflected wave becomes mainly diffuse instead of specular. There is no sharp dividing line in going from a smooth to a rough surface. The reflected wave contains both components,

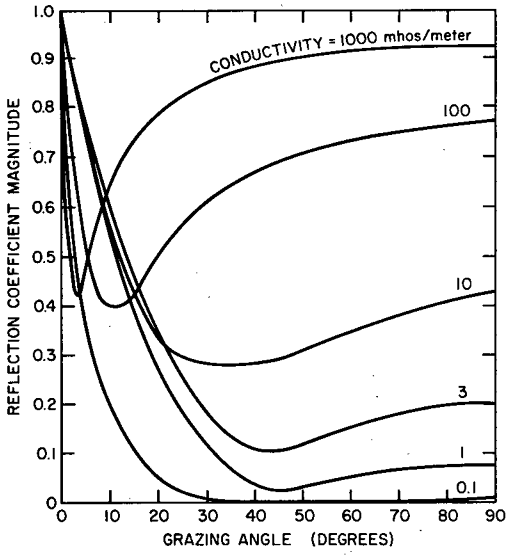


Fig. 1 - Reflection coefficient for a dielectric constant of 1, a smooth surface, and vertical polarization

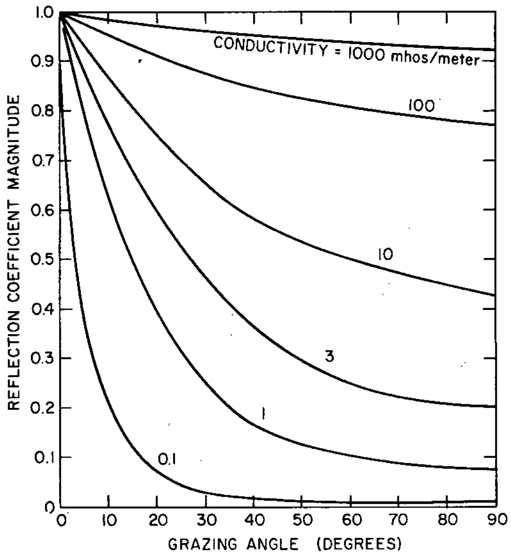


Fig. 2 - Reflection coefficient for a dielectric constant of 1, a smooth surface, and horizontal polarization

and for a surface of given roughness the relative mixture gradually changes from predominantly specular to predominantly diffuse as ψ is increased.

Assume that in a representative installation the transmitting antenna is placed on the island 30 feet above the deck, with the receiving antenna on the vertical stabilizer of the aircraft 15 feet above the deck. The grazing angles with the deck would then vary from about 5 degrees at a transmitter-to-receiver range of 500 feet to 60 degrees at a range of 26 feet. Using Rayleigh's criterion, the maximum irregularities that the deck could have and still look smooth are shown in Fig. 5. It can be seen that at ranges of 500 feet irregularities of 1/4 inch could be considered a smooth surface, whereas at very close range only a little more than 0.02 inch would be permissible. For a deck of given roughness the specular content of the reflected signal becomes greater as the range is increased.

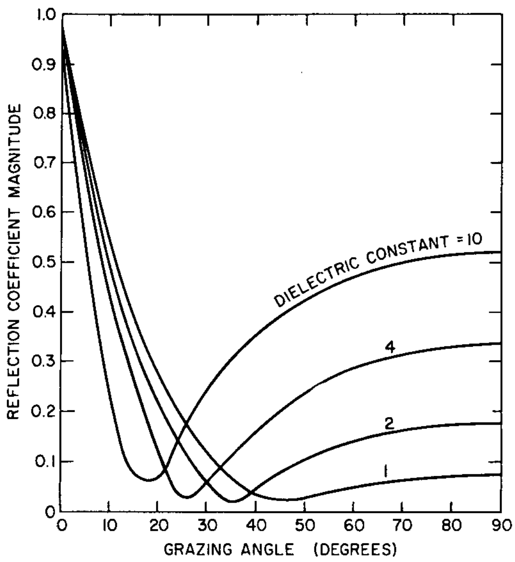


Fig. 3 - Reflection coefficient for a conductivity of 1 mho/meter, a smooth surface, and vertical polarization

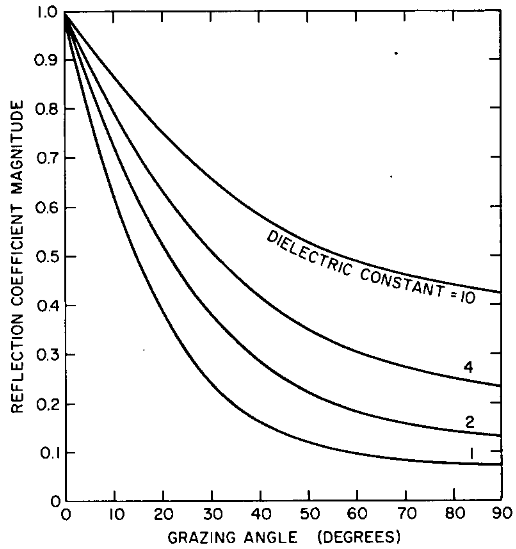


Fig. 4 - Reflection coefficient for a conductivity of 1 mho/meter, a smooth surface, and horizontal polarization

The received signal for this installation would fluctuate as the range is changed due to interference of the direct and reflected waves, which would produce nulls (relative minina). Figure 6 shows how the magnitude of the nulls varies with range for a smooth reflecting surface, when nondirective antennas are used with either horizontal or vertical polarization. This is the worst case, since in practice directive antennas would be used which would reduce the reflected wave and in addition some of the reflected wave would be scattered because of surface roughness. The spacing of the minimums is also shown in Fig. 6 for the preceding representative installation. At a transmitter-to-receiver range of about 400 feet the nulls would be at range intervals of 35 inches. For nondirectional antennas, where the reflecting surface is horizontal and has a dielectric constant of 2 and a conductivity of 3 mhos/meter, the depth of these nulls would be about 15 dB with horizontal polarization or 9 dB with vertical polarization.

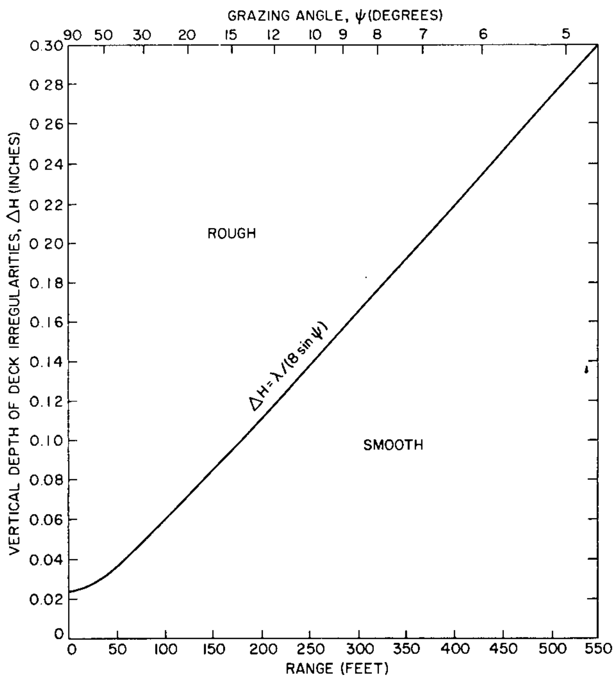


Fig. 5 - Maximum surface irregularities for a smooth surface (frequency, 60 GHz; transmitter height 30 feet; receiver height, 15 feet)

ANTENNA BEAM SHAPING

By shaping the transmitted beam so as to reduce the illumination of the deck, the reflected wave intensity and the depth of the nulls caused by interference between the direct and reflected waves would be reduced. A transmitting antenna pattern which is proportional to $\csc^2\theta$, where θ is the vertical angle, would provide uniform illumination over the deck (3) and would reduce the reflected wave relative to the omnidirectional case. Figure 7 shows a vertical pattern calculated from the equation

$$G_T(\mathrm{dB}) = 10 \log \left(\frac{2 + \csc\theta'}{30}\right)^2 , \quad (1)$$

where $\theta' = |\theta - 2| + 2$, which defines a beam pointed 2 degrees downward. (The depression of the beam is desirable to give a more uniform deck coverage.)

The receiving antenna must be able to receive a signal regardless of the position or orientation of the aircraft on the deck. Thus this antenna should be omnidirectional in azimuth and with a vertical beam large enough to pick up a signal from the transmitter without repointing as the aircraft is repositioned about the deck. The minimum range can be expressed by

$$R_{min} = \frac{H_T - H_R}{\tan\left(T + \frac{B}{2}\right)} .$$

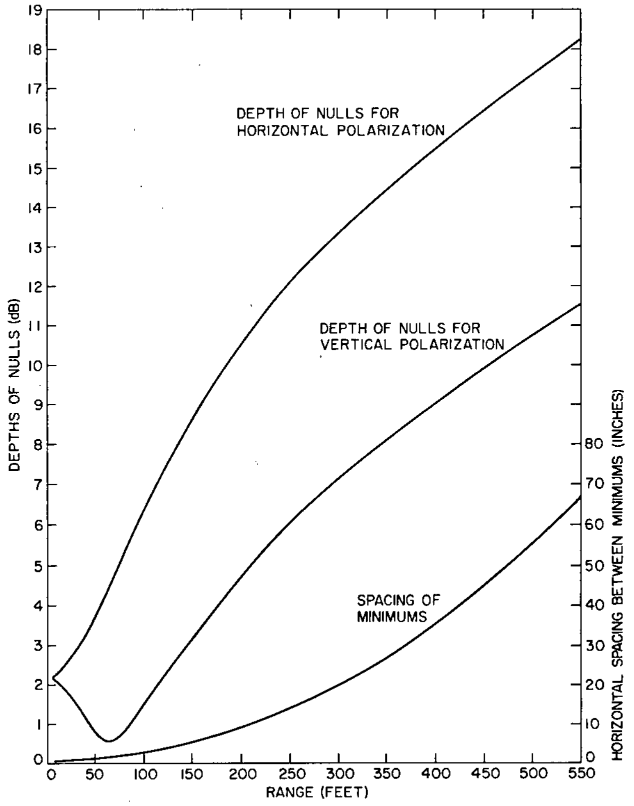


Fig. 6 - Maximum depths and spacing of minimums due to interference of a reflected wave from a smooth surface (frequency, 60 GHz; transmitter height, 30 feet, receiver height, 15 feet, dielectric constant, 2; conductivity, 3 mhos/meter; omnidirectional antennas)

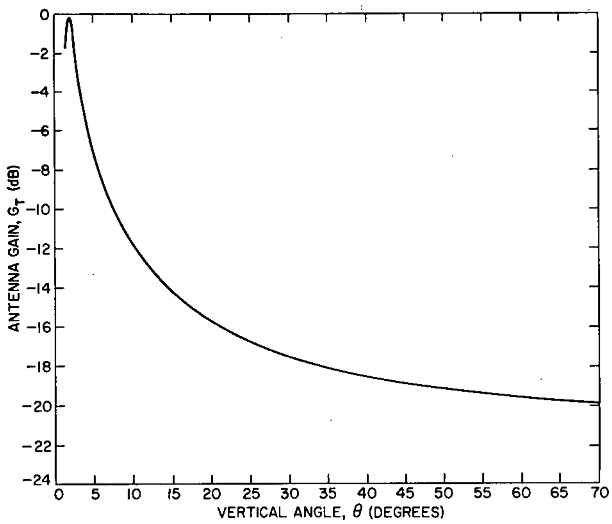


Fig. 7 - Vertical transmitting pattern calculated using Eq. (1)

For calculating the expected received signal a (sin x)/x receiving beam was used whose vertical pattern is defined by

$$G_R(\mathrm{dB}) = 10 \log \left[\frac{\sin 3(\theta - 20)}{3(\theta - 20)}\right]^2 . \tag{2}$$

This pattern has a vertical beamwidth of 53 degrees and is tilted 20 degrees upward. The pattern using this function is shown in Fig. 8.

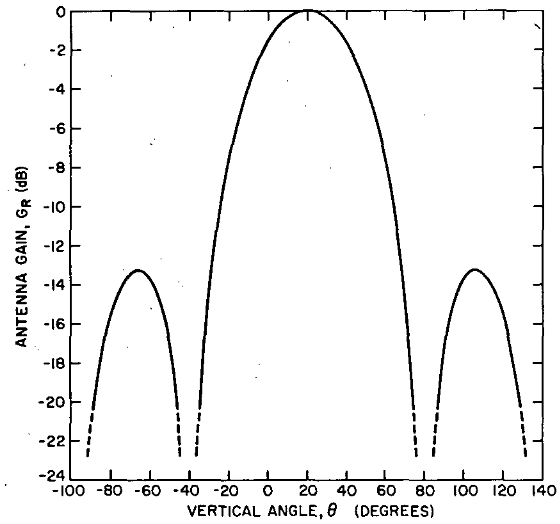


Fig. 8 - Vertical receiving pattern calculated using Eq. (2)

The general coverage that would be obtained with the above transmitting and receiving antennas, with no reflections present, is shown by the column entitled "Effective Loss" in Table 1. The effectiveness of the antenna patterns in reducing fluctuations in the received signal in the presence of interference is shown by the curves of Fig. 9, which were calculated using the antenna patterns of Figs. 7 and 8. The top curve in Fig. 9 shows that the $\csc^2 \theta$ transmitting antenna has its greatest effect at the longer ranges, and by comparison the curve next to the top curve shows that the $(\sin \theta)/\theta$ receiving antenna has its greatest effect at the shorter ranges. The combination of the $\csc^2 \theta$ transmitting antenna and the $(\sin \theta)/\theta$ receiving antenna reduce the multipath interference fluctuations to less than 6 dB over a range of 10 to 450 feet.

The effect of using an imperfectly conducting surface ($\epsilon = 2$, $\sigma = 3$) is also shown in Fig. 9. For horizontal polarization the overall fluctuations are reduced by about 1 dB. For vertical polarization the reflection coefficient is less than for horizontal polarization (Figs. 1 and 2), and as a result the fluctuations are less by another 1 dB.

SPACE DIVERSITY

A space diversity system consisting of two antennas at the receiver could be used to eliminate or greatly reduce the multipath interference nulls. The antennas would be spaced vertically so that one antenna would be at a null of the vertical interference pattern when the other would be at a peak. This system would improve the received signal as the receiving antennas are moved about the deck but would require complicated receivers on each aircraft. Another method would be to place the two vertically spaced antennas at the transmitter. This method would require an ordinary receiver but a more

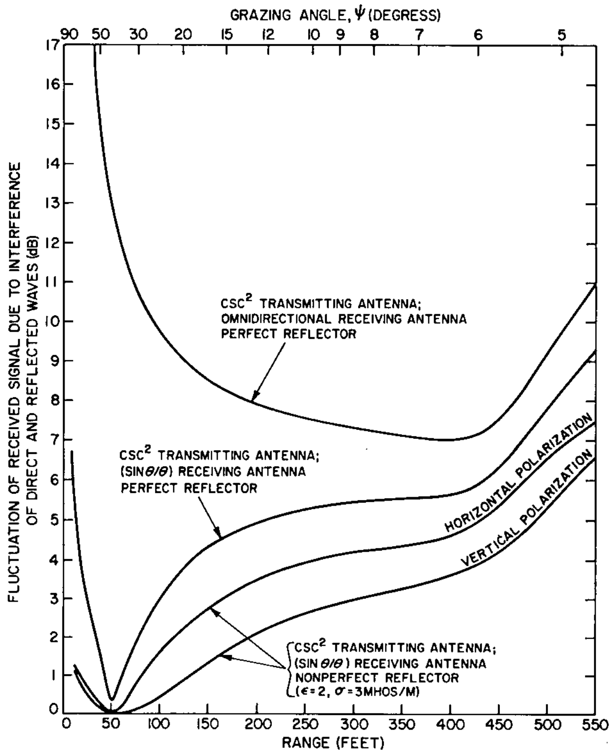


Fig. 9 - Additive effect of antenna patterns and reflection coefficient on the received signal, relative to the direct wave (transmitting antenna 30 feet high pointed 2 degrees downward with a gain given by Eq. (1) and receiving antenna 15 feet high pointed 20 degrees upward with a gain given by Eq. (2))

complex transmitter. If two antennas are fed from a common transmitter, additional sharp and deep nulls would be created by the interference of the waves from the two transmitting antennas. However, as will be shown later, a simple phase shifting technique can be used to eliminate this effect.

The best signal improvement due to space diversity is achieved when the transmitting antennas are separated by the distance between an adjacent maximum and minimum in the field interference pattern. This spacing was calculated, with the aid of a computer, by taking the electrical path differences for the various antenna heights and transmitter-to-receiver range shown in Fig. 10. It is seen that for a range greater than 100 feet the required vertical antenna spacing is relatively independent of the transmitter height. At a range of 300 feet, with the receiving antenna 15 feet above the deck, the spacing is 0.986 and 1.026 inch when the transmitting antenna height is at 10 and 50 feet respectively. For the linear portion of these curves this antenna spacing at the transmitter is approximated (2) by $\Delta H_T \approx 3R/FH_T$, where R is the transmitter-to-receiver distance in feet, H_R is the height of receiving antenna above the reflecting plane in feet, and F is the transmitter frequency in gigahertz.

Although the optimum spacing can be set for one range only, very good improvement would be realized when the antenna separation is within 50% of the optimum value (4).

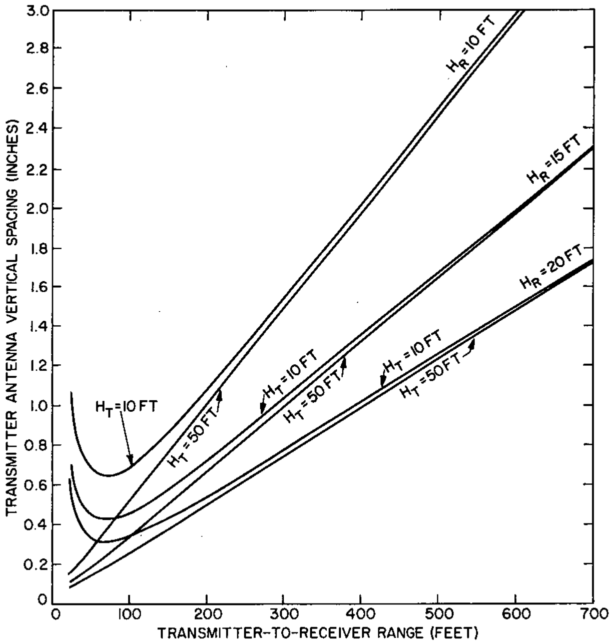


Fig. 10. - Transmitter diversity antenna spacing for a frequency of 60 GHz and several combinations of receiving antenna height (H_R) and transmitting antenna height (H_T)

Furthermore it can be shown that with a very large antenna spacing the improvement would approach the same value as the 50% case (2). For a representative installation that has been optimized at a range of 300 feet, very good improvement could be expected from ranges of 150 to 450 feet.

Thus, in setting up a dual-diversity system at the transmitter, the two transmitting antennas are vertically spaced so that the maximum of the multipath interference pattern from one transmitting source occurs at the receiver at the same position as the minimum of the pattern from the other source. These patterns calculated for a representative case are shown in Fig. 11 for ranges in the vicinity of 300 feet. The two upper curves show the pattern expected from a single antenna when at a height of either 30 feet or 30 feet 1 inch. A 1-inch spacing is used, which is chosen from Fig. 10, for optimum diversity. For the purpose of this calculation, only four signals were used: a direct and reflected wave from each antenna. From the two curves at the top of Fig. 11 this appears to provide the receiver with a reasonably steady signal, but as is shown by the lower curve the two resultants from the addition of the direct and reflected waves from the respective sources operating from a common transmitter will combine to produce a new interference pattern.

The causes of the various nulls can be readily seen by examining the relative phases between the four waves at the receiver as shown in Fig. 12 for transmitter-to-receiver ranges of 150 and 300 feet. At the 150-foot range the phase between the two direct waves is nearly 183 degrees and the phase between the two reflected waves is about 194 degrees, and when these four waves combine, almost complete cancellation results. The phase between the direct wave changes relatively slowly as the range is changed; it is necessary to go from a range of 150 feet to 300 feet for the phase to change from 183 degrees to 92 degrees. This phase change, however, will become more rapid at shorter ranges.

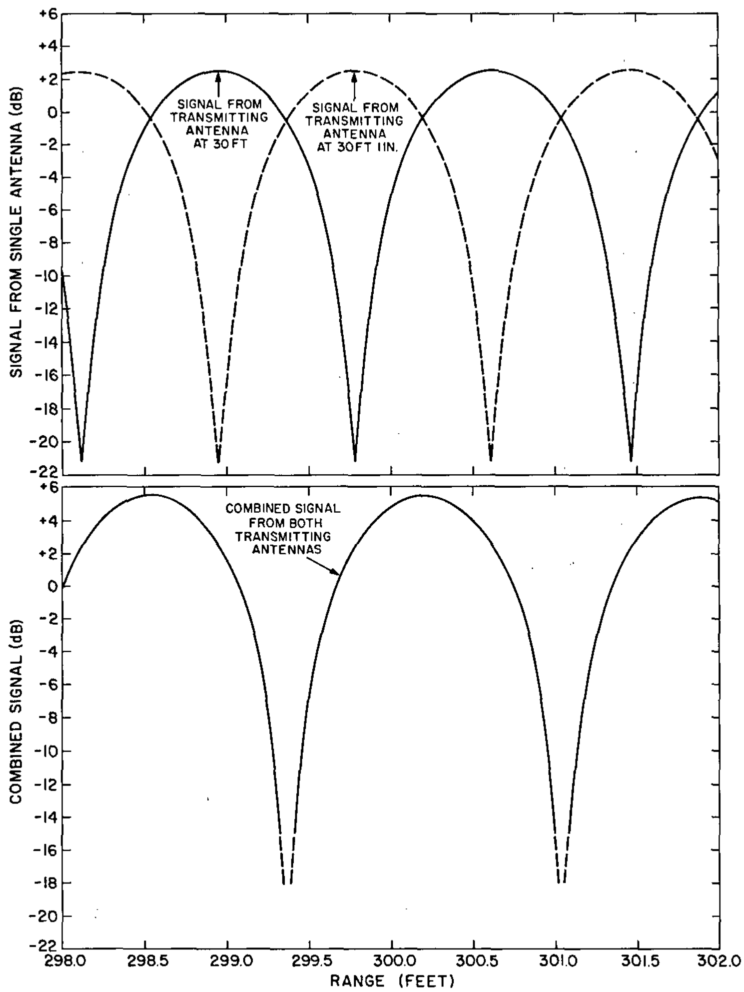
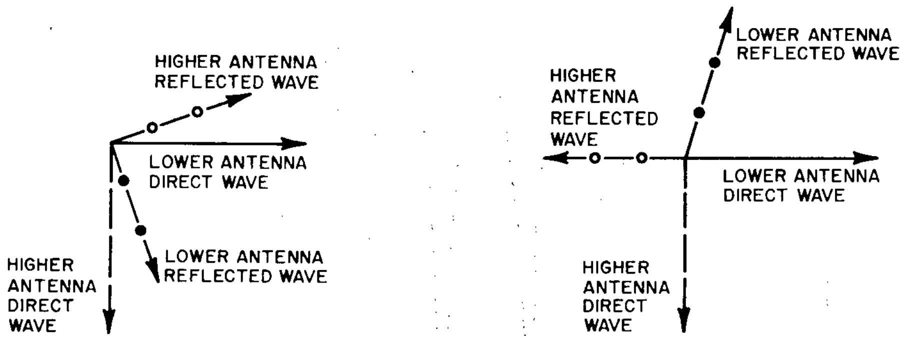


Fig. 11 - Combined signal from two transmitting antennas at the receiver, with reflections (frequency, 60 GHz; receiving antenna height, 15 feet)

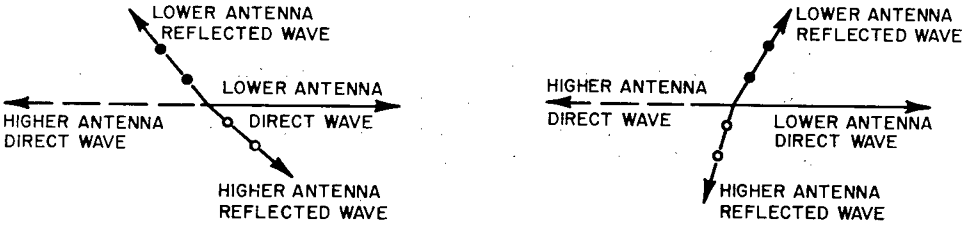
This is seen in Fig. 13, where the solid line shows the variation of the magnitude of the resultant from combining the two direct waves. At the minimums the phase between the two direct waves is 180 degrees and occurs at 150 and at 48 feet. Also in Fig. 13 is a similar curve, the dashed line, showing the resultant of the two reflected waves for a perfect reflector (reflection coefficient equals 1). The magnitude of this dashed line would be less for a nonperfect reflector.

The phase between the direct and the reflected waves from each antenna changes very rapidly. In the 300-foot-range region the phase changes approximately 180 degrees for every 10-inch change in range. Since the resultant of the two direct waves changes much more slowly in phase and amplitude, the resultant of the two reflected waves will spin about it (compare Figs. 12a with 12b and Figs. 12c with 12d). The adding and subtracting of these two resultants create the fast fluctuations in the combined signal shown in Fig. 14 for ranges near 148 feet. A general view of the rather complicated interference pattern is shown in Fig. 15 for ranges of from 50 to 400 feet. Here envelopes of the maximums and the minimums of the signal fluctuations are shown. The maximums are spaced every 10 inches for ranges around 300 feet and 2-1/2 inches at 100 feet.



(a) Range R = 300.2 ft and reflection coefficient magnitude for horizontal polarization ρ_H = 0.71

(b) R = 301 ft (300.2 ft + 10 in.) and ρ_H = 0.71



(c) R = 150 ft and ρ_H = 0.51

(d) R = 150.8 ft (150 ft + 10 in.) and ρ_H = 0.51

Fig. 12 - Magnitude and phase of direct and reflected signals at a receiving antenna 15 feet high from two transmitting antennas 30 feet and 30 feet 1 in. high (omnidirectional antennas, frequency of 60 GHz, and a perfect reflector)

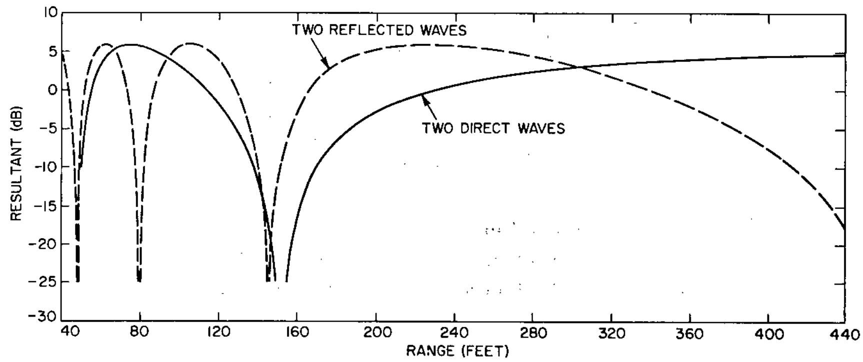


Fig. 13 - The resultant of two direct waves and the resultant of two reflected waves for a perfect reflector with the antenna heights as stated in Fig. 12 and a frequency of 60 GHz

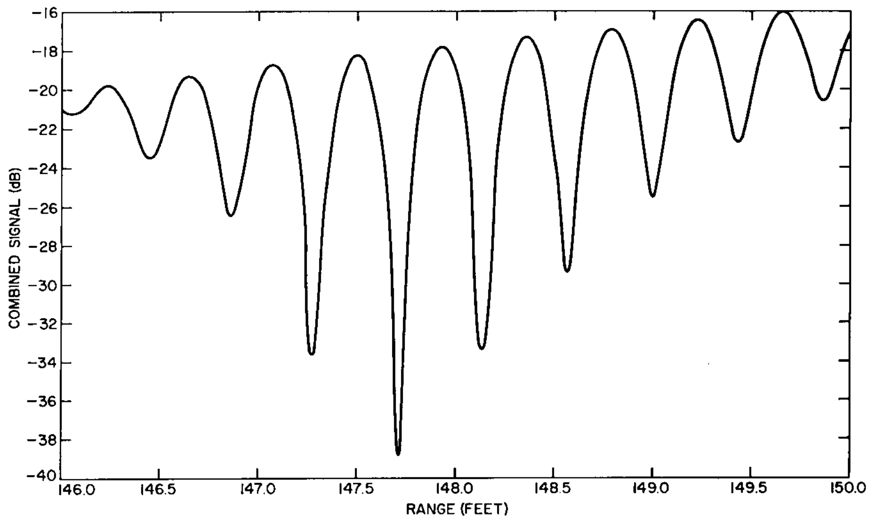


Fig. 14 - Fluctuation of the combined signal using the direct and reflected waves from two transmitting antennas for the antenna heights of Fig. 12, horizontal polarization, a smooth reflective surface, and a frequency of 60 GHz

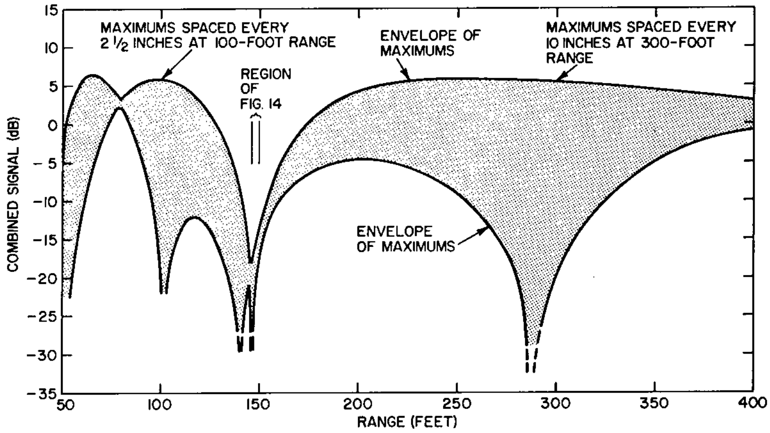


Fig. 15 - An expansion of Fig. 14 showing the envelope of maximums and minimums of the combined signal using the direct and reflected waves from two transmitting antennas

At about 150 feet a deep reduction in signal is observed both in the maximums and in the minimums which is due to the two direct waves and also the two reflected waves being nearly 180 degrees out of phase, as in Fig. 12c. At about 300 feet the resultant of the direct waves is approximately equal to the resultant of the reflected waves (Fig. 13). This produces very deep nulls and high maximums as the two resultants combine and cancel each other, as shown in Fig. 15.

In the representative case discussed, a 1-inch vertical separation of two transmitting antennas would provide very good diversity improvement. The overall physical size of the antenna, whose measured pattern is shown in Fig. 7, would be approximately 1 inch horizontally and 12 inches vertically. (The aperture is 0.3 x 8.5 inches.) To physically displace two of these antennas vertically by only 1 inch would require a horizontal displacement, D_H in addition to the vertical displacement D_V (Fig. 16). A two-element antenna array is thus formed with the elements positioned at the antenna centers along the line AA which is at an angle α with the horizontal such that $\tan \alpha = D_V/D_H$ and the element spacing D_E along the line AA is $D_E = D_V/\sin \alpha$.

This array with elements spaced by several wavelengths has a vertical pattern with many lobes, as shown in Fig. 17, with the envelope of the maximum being the element pattern. The first and second nulls correspond to the minimums at 150 and 50 feet in Fig. 15.

In this arrangement effective space diversity will be realized when the plane of the reflecting surface (as from various aircraft) is not parallel to the line AA, Fig. 16, but little improvement will be evident when a reflecting surface is nearly parallel to this line. In an actual installation there will be many reflected waves from surfaces at numerous angles, and improved reception would be expected when using this transmitting antenna system (provided phase modulation as discussed in the next section is used to eliminate the effect of the nulls in the array pattern).

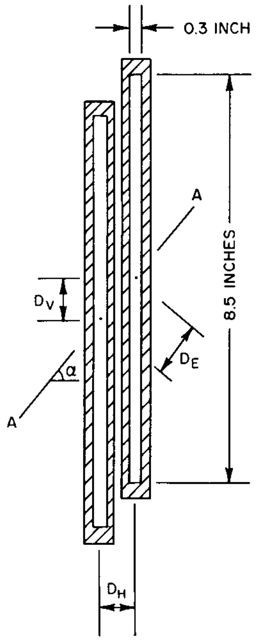


Fig. 16 - Transmitting antenna array

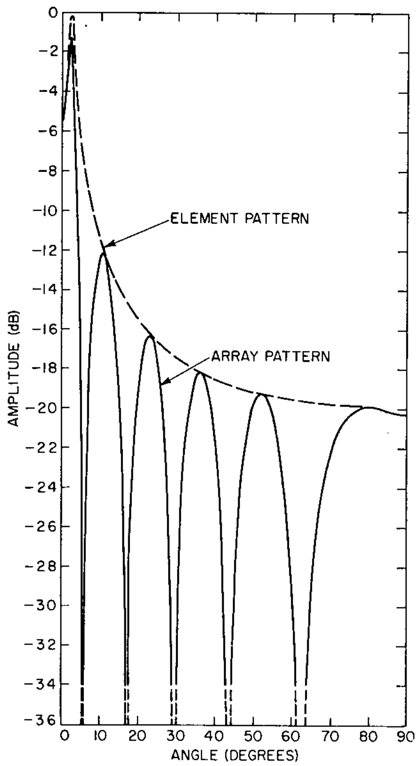


Fig. 17 - Pattern of a two-element array, such as shown in Fig. 16, for an element spacing D_E of 1 inch, an element pattern as given by Eq. (1), and a frequency of 60 GHz

PHASE MODULATION

Referring to Fig. 15, the nulls near 150 feet, where the two direct waves nearly cancel each other, can be eliminated by phase modulating one antenna, which is equivalent to electronically scanning the lobe pattern up and down. When the phase of the wave from one of the antennas is changed by 180 degrees, the relative phase between the two direct waves and that of the two reflected waves will be changed by the same amount. This will cause the null at 48 feet (Fig. 13) to shift to 75 feet and the one at 152 feet to shift to a very large range outside that being considered. Likewise the nulls caused by the two reflected waves (Fig. 13), which can be reduced by beam shaping, at 47, 80, and 146 feet will be moved to 62, 105, and 225 feet respectively. Continuously modulating the phase of the wave from one antenna between 0 and 180 degrees, at a rate that would not distort the data being transmitted, would average the received signal and eliminate the effect of these deep nulls on the received signal.

Another method for eliminating the interference between the direct signals would be to transmit two nonsynchronous signals from the respective antennas. This would be the case if two independent transmitters were used.

FREQUENCY DIVERSITY

The use of a frequency diversity system is another method which would improve the received signal when interference due to specular reflections are present. The optimum frequency separation is given (2) by $\Delta F \approx R/4H_T H_R$, where R is the transmitter-receiver distance in feet, H_T and H_R are the respective transmitter and receiver antenna heights in feet, and ΔF is the frequency separation for best diversity improvement in gigahertz. As in the space diversity case, very good improvement can be obtained even with a deviation in R of ±50% from the optimum value. For a representative installation with $R = 500$ feet, $H_T = 30$ feet, and $H_R = 15$ feet, the required frequency difference would be $\Delta F \approx 280$ MHz. The method would require either a frequency swept transmitter or two discrete transmitter signals. The receiver bandwidth would of course be greater than in the equivalent space diversity case.

CONCLUSION

Reflections in the flight deck environment could introduce substantial signal variations over the carrier deck. However, by shaping the antenna patterns of both the transmitting and receiving antennas, an appreciable improvement would be achieved. This improvement would most likely be sufficient for ordinary purposes, from both the signal security viewpoint and the equipment feasibility viewpoint.

Nevertheless, if necessary, the remaining multipath interference could be eliminated by using diversity techniques. A very promising approach is to use one transmitter with two spaced antennas, with appropriate phase shifting. Because of the deterioration in performance that would occur if the phase shifter were to fail, a fail-safe arrangement should be used to turn off one antenna in the event of phase shifter failure.

If the space diversity system were to use two independent transmitters, one for each antenna, then a coherent interference pattern would not exist. The equipment redundancy of this approach would also have some advantage from the overall reliability viewpoint. Although some degradation in performance would occur if one transmitter failed, it would not be a total failure.

Hence, the potential multipath interference problem is one that can be reduced to easily managed proportions.

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Secure communication						
Flight decks						
Inertial navigation						
Data transmission						
Millimeter waves						
Multipath transmission						
Wave propagation						
Multipath interference effects						
Antenna beam shaping						

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Security Classification