NRL REPORT 3780

CONVERGING LENS DIELECTRIC ANTENNAS

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WASHINGTON, D.C.

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CONVERGING LENS DIELECTRIC ANTENNAS

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CONTENTS

ABSTRACT

In studying electromagnetic propagation through the exhaust flames of reaction engines, it has been found desirable to illuminate just a small part of the flame. This can be accomplished by using a converging lens antenna. The lens is made of polystyrene with double hyperboloidal surfaces and is fed with a cast aluminum horn. In evaluating S-, X-, and K-band antennas, it was found that a lens three wavelengths in diameter did not produce a focal image, whereas a nine-wavelength (or larger) lens did. The propagation measuring system uses two of these antennas, one for transmitting, the other for receiving. Such a system tends to eliminate refraction caused by the flame, reduces stray fields, allows the sampling of a smaller portion of the flame, and eliminates the possibility of a portion of the received power bypassing the flame and thereby obscuring the measurement.

PROBLEM STATUS

This report marks the completion of this phase of the problem. Work is continuing on other parts of the problem.

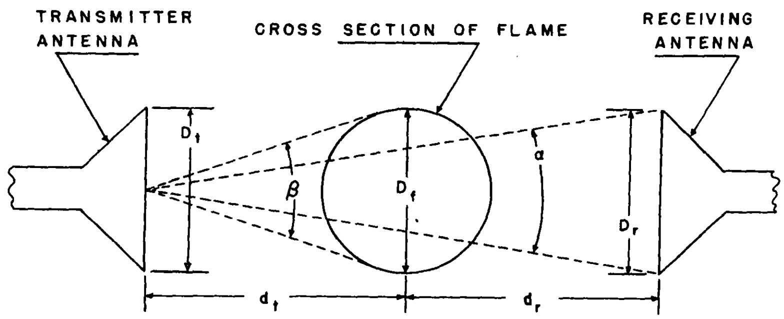
AUTHORIZATION

NRL Problem R11-013
NR 511-130

CONVERGING LENS DIELECTRIC ANTENNAS

THE NEED FOR A FOCUSING ANTENNA

The problem of determining the effect of reaction engine exhaust flames on electromagnetic waves involves the consideration of antennas to be used in taking measurements. In quantitative measurements it is desirable to have all the radiant energy which is intercepted by the receiving system pass through the flame (Figure 1). If $d_t \geq D_t^2/\lambda$, the transmitting antenna may be considered a point source and the only energy reaching the receiving antenna is that which is included in the angle, α, subtended by the receiving antenna aperture, D_r. Now, if the angle, β, subtended by D_f (diameter of the flame) is equal to or greater than α, all the receiving energy must pass through the flame. If β is less than α, part of the received energy does not pass through the flame, and the results of any measurements are extremely difficult to interpret because of diffraction effects. Stray reflections from the ground and other obstructions should be attenuated by the judicious use of absorbent materials.



$$d_t \geq \frac{D_t^2}{\lambda} \qquad \beta \geq \alpha$$

Figure 1 - Antenna arrangement

Basically, one or more of the following effects may occur to radiation in the presence of hot exhaust gases:

(a) Attenuation
(b) Reflection
(c) Refraction

Refraction may be eliminated by using a focused antenna system so that all the energy enters normal to the flame surface. This requires a cylindrical wave front; however, a spherical front should provide a good approximation. The focal point of such a focused antenna system is then at the center of the flame. An antenna with a point focus possesses the additional advantages of:

(a) Putting the available electromagnetic energy to the best use,

(b) Reducing stray fields and the accompanying reflections from the ground, nearby buildings, other equipment, etc.

(c) Concentrating the measurement on a smaller part, and hence more homogeneous sample of the flame,

(d) Plotting flame characteristics as a function of flame geometry,

(e) Producing the maximum field strength in the flame with a given transmitted power, and

(f) Permitting simultaneous measurements at different wavelengths through the same sample.

These advantages were deemed amply sufficient to warrant the use of a focused antenna for S-, X-, and K-band measurements.

DESIGN OF A FOCUSING ANTENNA

A preliminary attempt was made to produce a focusing antenna with a parabolic reflector in which the feed was purposely set beyond the focal point of the parabola. This system was attempted with a 12-inch-diameter dish operating at a wavelength of 10.7 cm. It did not perform satisfactorily for this problem because it produced an image 14 inches in diameter at the -10 db power points measured in a plane normal to the axis of the system. These measurements were made by exploring the field with a small probe. Theoretically, the reflector type should have an ellipsoidal shape to accomplish the task better, but since none was readily available, a lens type of antenna having additional advantages was tried.

When grinding optical lenses it is most convenient to produce spherical surfaces although not optically most efficient. However, for radio wavelengths, it is entirely feasible to produce lenses with the optimum contour. It has been shown [1] that this contour should be hyperboloidal. With the proper constants inserted in the equation of the hyperbola, the final form for the surface[2] of the lens becomes:

$$X = \sqrt{\frac{Y^2}{n^2 - 1} + \left(\frac{f}{1 + n}\right)^2},$$

where f = focal length, and

n = index of refraction = (dielectric constant)$^{\frac{1}{2}}$

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[1] Southall, J. P. C., "Mirrors, Prisms and Lenses," page 619, 2nd ed., Macmillan Co., 1923

[2] The surface is actually the surface of revolution produced by revolving the hyperbola about its axis.

Other factors which must be considered in the design of a lens system are :

(a) The minimum diameter of the lens consistent with the wavelength, and

(b) The ratio of focal length to lens diameter.

Very little data was available for the proper choice of item (a); therefore it was decided to make the minimum diameter of the lens equal to 3 wavelengths in an attempt to restrict the weight and size of the antenna. This choice set the diameter of the S-band lens at 12 inches. Item (b) is mainly a consideration of the ability of the feeding source to illuminate the lens properly. If a horn feed is used, this factor can be as high as 3, producing a horn with a 40° total flare angle. Proper operation of a hyperboloidal lens depends on the feeding wave front being spherical and this has been shown to exist by Iams.[3] The center of curvature of the wavefront (corresponding to the object in optical systems) is in the horn throat approximately at the apex of the extensions of the inside edges of the horn surface.

DESCRIPTION OF ANTENNAS

Suitable horns were made of cast aluminum with walls 3/8 inch thick except for the K-band model which has 1/4-inch walls. This design produced a very sturdy horn which was not mechanically affected by the extremely high acoustic levels in the vicinity of reaction engines. The lenses were machined from polystyrene stock material and were bolted securely to a flange on the horn. This construction is clearly shown in Figures 2 and 3 which also illustrate how the waveguide flange was cast as an integral part on the back of the horn. In order to minimize the thickness of the lens which is quite large, the perimeter was made circular.

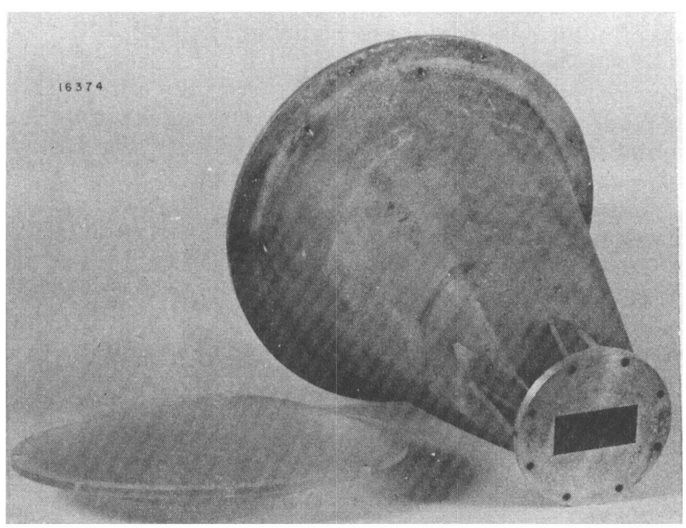

Figure 2 - Cast aluminum horn and converging lens

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[3] Iams, H., Proc. IRE 38, 543, May 1950

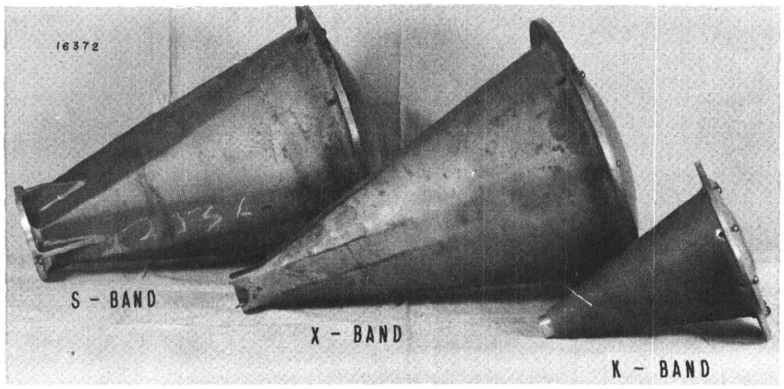

Figure 3 - Cast aluminum horns assembled with lenses

The S- and X-band antennas use the same lens. This is a 12-inch-diameter lens having object and image focal lengths of 18 inches; both sides of the lens are therefore identical. The K-band lens is 6 inches in diameter and has an object focal length of 9 inches and an image focal length of 18 inches to correspond with the other lenses. Both lenses in any one system are thus mounted approximately 36 inches apart.

ANTENNA PERFORMANCE

The S-band lens antenna was tested by probing the field. In the focal plane the field strength was reduced 3 db (in power from the maximum on axis value) along a 7-inch-diameter circle. The corresponding 10-db points were on a circle 14 inches in diameter.

Difficulty was experienced in performing similar tests on X- and K-band. This was attributed to the probe being so large that a true indication of the field was not obtained. As a result a series of additional tests was made as follows:

(a) A probe was moved parallel to but offset from the axis of the antenna. This resulted in a curve of field strength versus position which had a minimum when the probe was opposite the focal point.[4] This proved to be the most accurate method of finding the focal point.

(b) A pair of lens antennas, one transmitting and one receiving, was set up with a sheet of metal mounted normal to the axis of the lens system and midway between them. Varying sizes of holes were cut in the metal sheet so that their centers could be made to coincide with the axis of the lens system. It was assumed that the smallest hole which had little or no effect on the amount of energy received is an indication of the sharpness of focus obtained

(c) A straight section of waveguide was replaced by a pair of lens antennas properly spaced. Any decrease in energy was attributed to improper focusing of the antennas and consequent radiation of power in undesired directions. This evaluation was performed on K-band only with the result that no power was lost.

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[4] In the region very close to the lens an interference pattern is observed similar to that reported by C. L. Andrews in Phys. Rev. 71, 777, 1947

TABLE 1
Results of Antenna Tests

Test Designation	Antenna Under Test		
	S-Band	X-Band	K-Band
Image distance [1]	Indefinite	13 in.	14-7/16 in.
Aperture test [2]	6 in.	3 in.	2 in.
Waveguide substitution [3]	Not measured	Not measured	0 db
Field at half power point [4]	7 in.	Not measured	1-1/2 in.

1. Distance along the axis from the outside center of the lens to the point of sharpest image.
2. The diameter of aperture which causes no more than 3-db power loss when interposed between two lens antennas.
3. Loss in power transmitted when two lens antennas are substituted for a straight section of waveguide.
4. A plot was made of the field strength in a plane normal to the axis of th lens and containing the image. Figures given in above table are the diameter of the -3 db contour.

All of the above tests corroborate the fact that the lenses perform as predicted. The pertinent results of these tests are presented in Table 1. It is evident that the S-band lens has a rather poorly defined image which is undoubtedly due to its diameter being only 3 wavelengths. The X-band lens which is 9 wavelengths in diameter is much better in this respect and the K-band lens with a diameter of 14 wavelengths is still better. Even so, the S-band system has a sharp enough image so that only 3 db of power is lost when a sheet with a 6-inch hole is interposed between the antennas (test b above). Several slight discrepancies were found in the antennas; for instance, instead of being at 18 inches, the image was at 13 inches on the X-band model and 14-1/2 inches on K-band. This could be caused by the effective center of feed of the horn not being precisely in the throat. To test the validity of this assumption, a very small (7/8-inch x 9/16-inch) K-band horn was used to illuminate the lens. With the mouth of the horn placed at the design distance (9 inches) from the lens, the image was formed at 17-1/2 inches; in a perfect system the image would have been at 18 inches. (It was assumed that the center of feed of the small horn is at the mouth of the horn.)

In actual use the antennas were placed 36 inches apart as planned. Since the images are not very sharp, the loss in performance was negligible.

CONCLUSIONS

The hyperboloidal lens antenna has provided a practical solution in a system for measuring the electromagnetic propagation properties of flames. Lenses less than 3 wavelengths in diameter are ineffective, whereas lenses 9 wavelengths across are quite efficient.

RECOMMENDATIONS

It is recommended that other groups making measurements of electromagnetic propagation through the exhaust flames of rocket engines consider the use of similar lens antennas. In addition to the previously mentioned advantages, this would also allow greater accuracy in comparing the results of various workers in the field.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the contributions of Dr. J. I. Bohnert and K. S. Kelleher of this Laboratory to the theoretical analysis of the problem. D. H. Russell made many of the measurements during the course of this study.

* * *

APPENDIX
Additional Refinements

Since this report was written additional evaluation work was accomplished which is of sufficient importance for an addition to this report. As mentioned on page 5, the focal image did not appear at the expected distance from the lens. Working on the assumption that the center of feed of the horn is not precisely known, it was possible to compute its location using the results of the experimental determination of the image plane position. This calculation made for the K-band horn shows that the effective center of feed of the horn is 10.25 inches from the lens, instead of 9 inches as was originally assumed. With this information, a new lens was made using the 10.25-inch figure with the result that the focal image appeared at the proper distance from the lens; namely 18 inches.

In evaluating this new lens, a probe was moved parallel to the axis of the lens as described on page 4, measurement (a). It was observed that the position of the minimum was a function of the displacement of the probe from the len's principal axis. This is illustrated in Figure 4 where the observed data of several paths are plotted. These plots have been smoothed for clarity; actually there appeared up to ± 1-1/2 db variations with half-wavelength periodicity. The minimum points are connected by the dotted curve, and it is seen that this approaches the true image as the distance off the principal axis increases. It is believed that spherical aberration prevents all these minimum points from appearing opposite the image point.

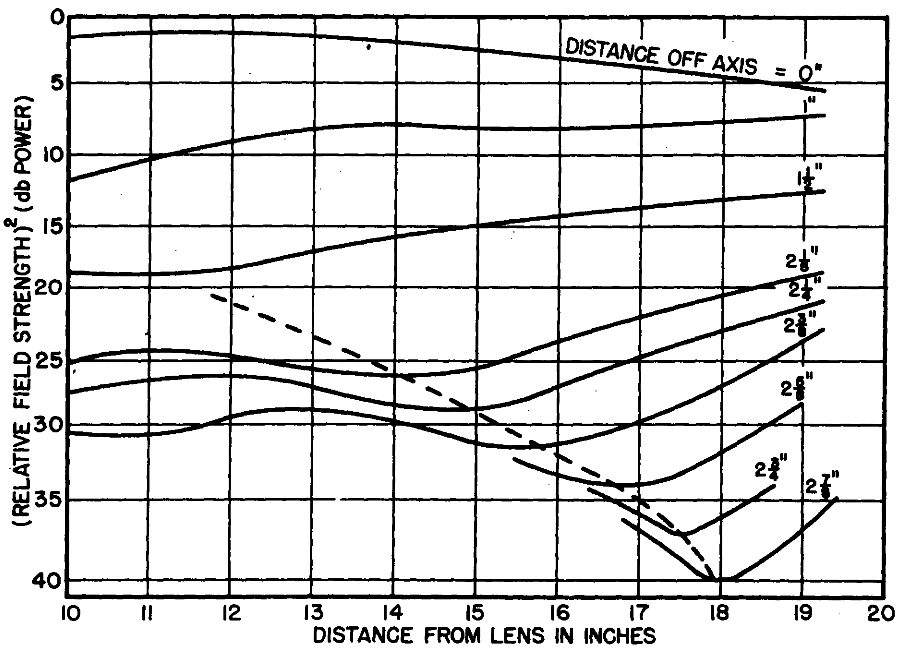

Figure 4

One additional effect of interest will also be mentioned. Consider a plane sheet of dielectric, such as polystyrene 1/4 inch thick, as interposed between two lens antennas in a transmitting-receiving system. As the sheet is moved toward either one of the antennas, it will be observed that the receiver output, when plotted against position of the sheet, appears to be a sine wave of approximately 3-db power peak-to-peak amplitude and half-wavelength periodicity. The same effect has been noted in the design and evaluation of radomes.[5] Should the same effect be present in the propagation measurements through hot gases, the same error would be involved. Further study along these lines is contemplated.

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[5] Redheffer, R. M., "Microwave Antennas and Dielectric Surfaces," J. App. Phys., Vol. 20, p. 397, April 1949

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