

Applications of the Luneberg Lens

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ABSTRACT

A number of significant attempts at fabrication of the Luneberg lens have been made both at NRL and elsewhere. Some of these attempts have resulted in lenses of practical applicability, if suitable limitations are accepted. A brief resume of possible applications of the lens to problems in the field of microwave radar is given, and the state of the art regarding the fabrication of the lens is indicated.

PROBLEM STATUS

This is an interim report; work is continuing.

AUTHORIZATION

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APPLICATIONS OF THE LUNEBERG LENS

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UNCLASSIFIED

I. INTRODUCTION

The intent of this report is to describe briefly some possible applications of the Luneberg lens and to indicate the present state of the art in regard to the lens. It is felt that such a reporting is timely in view of the great interest being shown in Luneberg lenses.

R. K. Luneberg¹ developed the theory for this spherically symmetric lens in 1944 as an academic exercise in classical optics. In its simplest and best known form, the lens focusses an incident plane wave upon reception to a diametrically opposite point on its surface. See Fig.1. Workers in optics had no application for such a lens, nor could they construct one if they wished. Those working in the field of radar were quick to realize the potential usefulness of such a unique focussing device, but they, too, could not build one for lack of suitable materials and fabrication techniques.

The history of the Luneberg lens since its conception has been the history of its fabrication. Several laboratories have tried to construct a lens, but until recently results were largely impractical. Later in this report, a brief description is given of these efforts.

The Luneberg lens is composed of a dielectric material in which the dielectric constant varies continuously from a maximum of 2 at the center to unity at the surface. Referring to Fig.1, this variation in the dielectric constant ϵ is given by the formula, $\epsilon = 2 - r^2$, where r is the normalized radius. The sketch in Fig.1 may be interpreted as being in three or two dimensions. If in three dimensions, then the lens is a sphere, the source point S lies on the surface of the sphere, and rf energy emanating from S is collimated into a cylindrical shaft of energy in the direction diametrically opposite point S . If in two dimensions, then the lens is a thin circular disc, the source point S lies on the circumference of the circle, and the emergent rf energy lies in the plane of the lens. In the two-dimensional case, the lens proper is contained between metallic parallel plates. In both the three- and two-dimensional cases, characteristics of the radiation pattern are determined in the usual manner, i.e., by the extent of the lens aperture and the distribution of illumination over the aperture. Pattern characteristics of beam width, gain, and side lobe level have only recently been calculated for the perfect Luneberg² in three dimensions.

¹Luneberg, R.K., "Mathematical Theory of Optics," Brown University Graduate School, Providence, R.I., 1944.

²Braun, E.H., "Radiation Characteristics of the Spherical Luneberg Lens," IRE Transactions on Antennas and Propagation, Vol.AP-4,#2, April, 1955

The Luneberg's focussing properties are independent of frequency and polarization. Also, the lens is matched to space, so that there is no reflection at the surface where $\epsilon = 1$. Any practical limitation imposed by the radiation pattern or impedance is due to the manner in which the lens was built or to the materials used in its construction. For example, approximating the continuous variation of ϵ by a number of discrete steps establishes an upper limit of frequency beyond which the lens will not focus. As another example, the use of an artificial dielectric which is anisotropic restricts operation to a preferred polarization and can impose bandwidth limitations. As stated previously, the problem is how to build a practical Luneberg lens to meet the needs of a particular application. The more obvious of these applications are outlined in the following sections.

II. APPLICATIONS

There are numerous possible applications for this versatile lens. Those described below are stated in general terms without having in mind a particular system. References to work done at the Naval Research Laboratory are given where applicable for more detailed information.

A. 4π Solid Angle of Scan

The Luneberg is unique as a focussing device in that it can scan a beam throughout all space without any deterioration in the beam's characteristics. Referring again to Fig.1, as the point S is positioned on the surface of the sphere the transmitted beam is always diametrically opposite. Since the lens is spherically symmetric there is no preferred position of S.

A number of sources may be utilized, fed either sequentially or simultaneously. The feed motion problems inherent in obtaining large angles of scan by moving a single source may be circumvented by the use of such multiple sources. For example, the feed system may consist of a two-dimensional array of sources scanned over its extent by some rf switching scheme. This type of scanning has been accomplished in a practical design for a different type of lens.³ A one-dimensional array of sources, scanned over its length while being moved in some prescribed manner over the surface of the Luneberg, may also be used. Such a feed system has been demonstrated in the laboratory for use in a Cassegrain type of scanning antenna. A number of fixed sources, disposed in some manner over the surface, is another possibility. These sources need not be identical, but may differ in frequency and polarization. The sources may be energized simultaneously if desired. Applications of these feeding systems is limited only by one's imagination.

³Gabriel, W.F., Archer, D.H., Peeler, G.D.M., and Coleman, H.P., "A Volumetric Scanning GCA Antenna," NRL Report (In Process of Publication)

B. 360° of Scan with Stabilization

Scanning may be confined to a plane, say the horizontal plane, to obtain 360° of scan. For simplicity, one may visualize a single source S rotating in a circle about the spherical Luneberg. If the antenna assembly is mounted on an unstable base such as a ship, stabilization of the beam on the horizon may be desirable. This can be accomplished by moving the source S in a vertical direction to compensate for the ship's motion. Such a scheme is straightforward.

More than one source may be used. If all the sources scanned the horizon, a multi-beamed surface-search antenna system results. If the sources scanned at various vertical angles, a stacked-beam cosecant-squared antenna system capable also of height finding is possible. Various frequencies of operation and differing polarizations may be used.

If stabilization is not required, and a broad vertical beamwidth is acceptable, then for simplicity of structure, a two-dimensional Luneberg is preferable.

C. Sector Scan

Much of what was described in sections A and B could be repeated here for sector scanning if the sources were restricted to a limited region of the spherical surface. In those sections the symmetry of the Luneberg was exploited, so that it may appear at first thought that in sector scan this advantage is largely wasted. However, it is still possible to exploit the characteristic by means of reflecting plane mirrors.⁴

Consider now half a Luneberg lens as shown in Fig.2. A reflector is placed in contact with the plane surface of the lens. Rays emanating from a source S are reflected as shown, the angle of reflection being equal to the angle of incidence. Such rays are perfectly focussed, just as in the case of the full Luneberg, and appear to come from the virtual source S₁. Movement of the source S causes a corresponding movement of the beam in the opposite direction.

There is some deterioration of the radiated pattern. This is due to the fact that the effective aperture for the reflected beam is $l + \cos \beta$ and decreases as the angle β between the source and the axis of symmetry increases. In Fig.2 it is seen that some of the focussed radiation from the source S misses the reflector when β differs from zero. This radiation, termed the direct beam, has an aperture of $l - \cos \beta$. Fig.3 compares theoretical and measured pattern characteristics of a 36-inch diameter two-dimensional lens of the type diagrammed in Fig.2. The useful scan angle from such a lens may be increased somewhat by enlarging the reflector, although this expedient hardly seems worth while. Absorbent material may be used to absorb the non-reflected energy, consequently reducing side lobe levels.

⁴Peeler, G.D.M., Kelleher, K.S., and Coleman, H.P., "Virtual Source Luneberg Lenses," NRL Report #4194, 13 July 1953

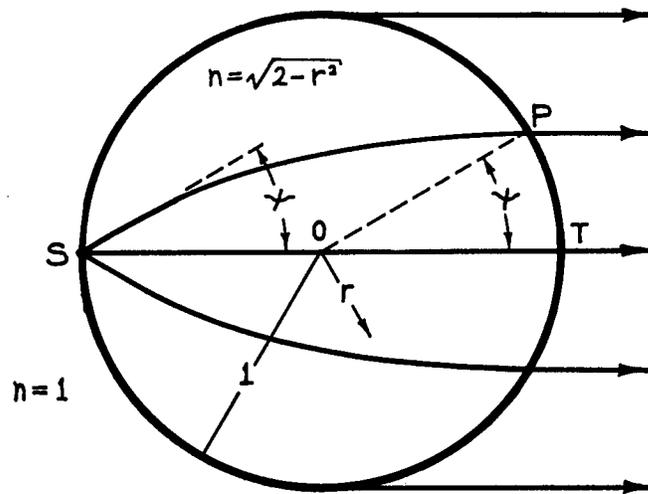


Fig. 1 - Rays in a Luneberg Lens

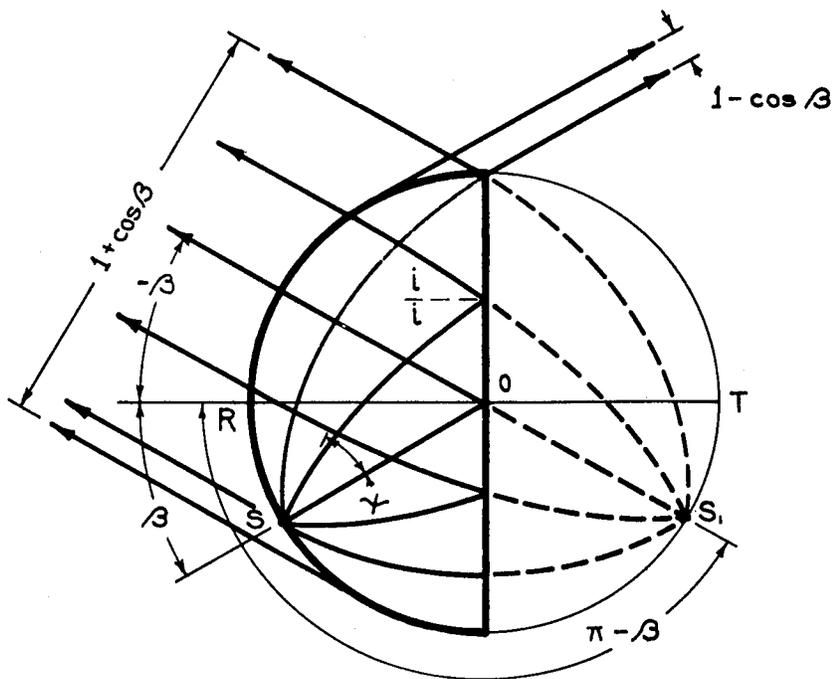


Fig. 2 - Rays in a One-Reflector Virtual Source Luneberg Lens

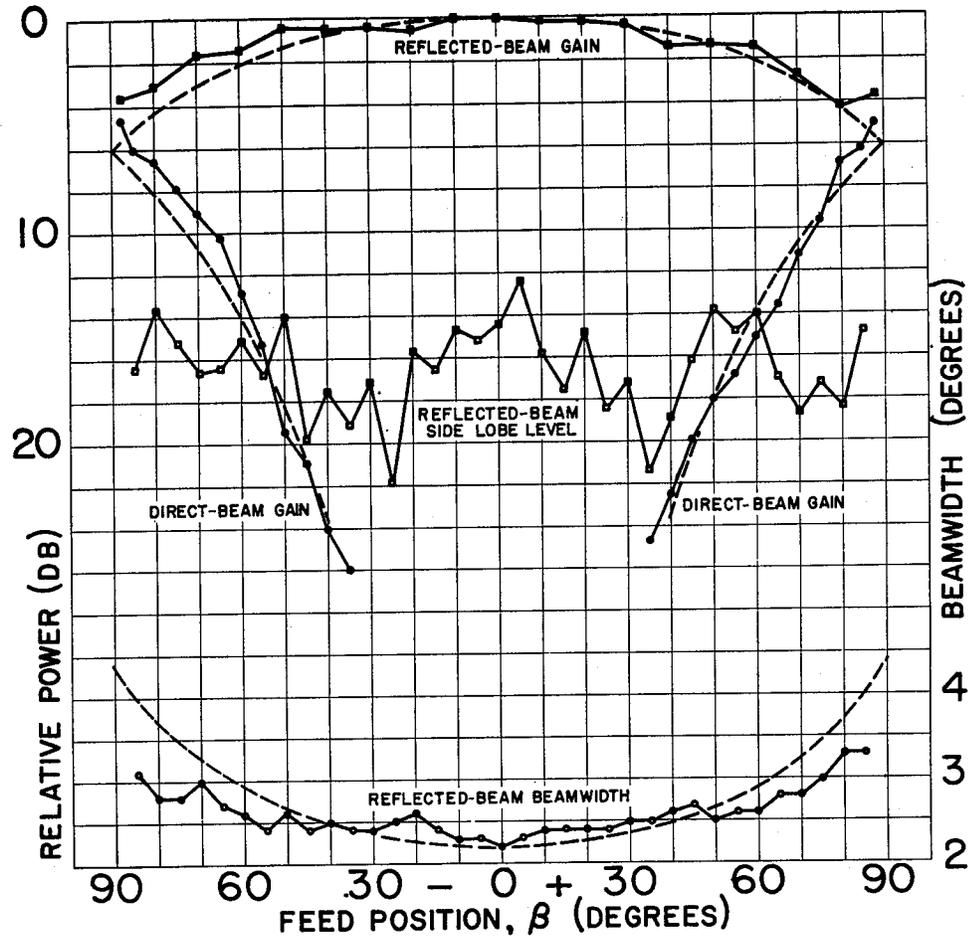


Fig. 3 - Theoretical and Experimental Data for a One-Reflector Virtual Source Lens

Scanning may be accomplished by moving the feed or the lens. In the case illustrated in Fig.2, it is natural to think of the feed moving. If, however, another half Luneberg were placed on the other side of the reflector, one might visualize the lens rotating. In this case the angular rate of scan is twice the angular rotation of the lens. Due to beam deterioration when the source approaches the reflector edge, the effective scan angle is somewhat less than 180 degrees. As in the case of the full Luneberg, multiple sources may be used to scan several sectors simultaneously, either in the same plane or in various planes.

The number of reflectors is not limited to one. It has been shown⁴ that for any odd number of reflectors the beam scans as described for a single reflector as the lens is rotated, while for any even number of reflectors the beam does not scan. In the latter case, the reflectors behave as corner reflectors. It should be noted that the use of reflectors may improve the mechanical properties of the lens system by providing support.

What has been stated above for the Luneberg with a reflector applies equally to two- or three-dimensional lenses. For the three-dimensional lens, stabilization may be accomplished as described in section B by movement of the source in the direction normal to the motion of scan.

Another application of the reflector is illustrated in Fig.4. The reflector is inclined at an angle α to the flat surface of a half Luneberg and the source S is on the axis of symmetry. If α is 5 degrees or less, then the beam is fairly well focussed in a direction making an angle of approximately 2α with the source. As the angle α becomes larger than 5 degrees, the beam displacement from the axis becomes more nearly equal to α and gain decreases. With α equal to 20 degrees the gain is down 3 db and the beam is displaced 23 degrees from the axis of the system. Pattern characteristics for a lens in which the reflecting surface only is moved are shown in Fig.5. This data, compared with that shown in Fig. 3, relates the performance of the two lenses. As the reflector is rotated about the axis of symmetry, a conical scan results. A spiral scan can be obtained by continuously varying the angle α from maximum to zero.

D. Passive Reflector

The Luneberg lens may be used as a passive reflector in a manner analogous to a corner reflector. A reflecting spherical cap is placed in contact with the lens as illustrated in Fig.6. Incident energy is focussed at a point S determined by the angle of arrival. The rays are reflected at S, the angle of reflection being equal to the angle of incidence, and emerge in the same direction from whence they came. Perfect focussing is thus obtained for all angles of arrival within the extent of the reflecting spherical cap. It is readily seen that for optimum performance, the cap should be somewhat less than a hemisphere to prevent undue shadowing while allowing maximum angle of coverage.⁵ The Luneberg

⁵Gorr, B., and Holt, F.S., "Modification of the Luneberg lens to Perform as High-Gain Wide Angle Reflector," AFCCRC Internal Memorandum, 15 Feb 1956

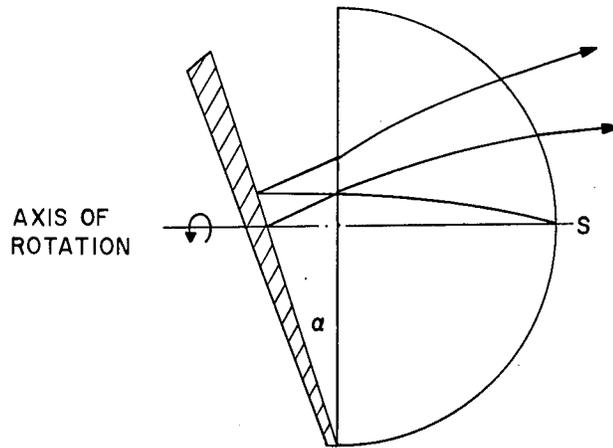


Fig. 4 - A Modification of the One-Reflector Virtual Source Lens

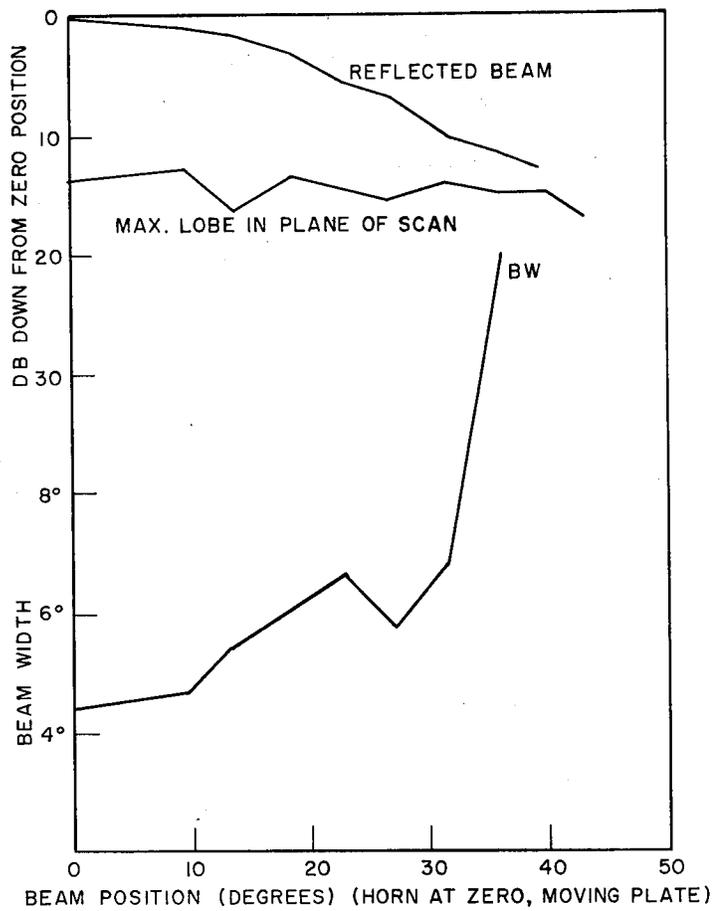


Fig. 5 - Pattern Characteristics of the Modified Virtual Source Lens

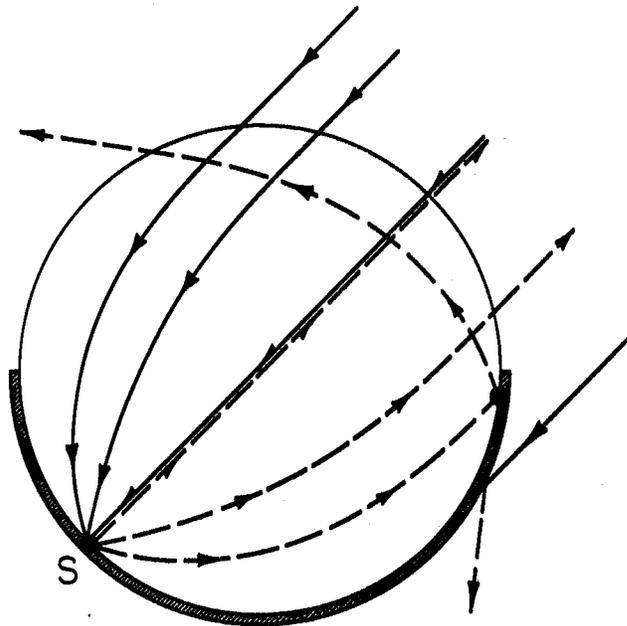


Fig. 6 - The Luneberg Lens as a Passive Reflector

performs better electrically than the corner reflector since it is effective over a much greater solid angle and it focusses perfectly, thus maximizing antenna gain. For limited angles of incidence the virtual source type of lens might also be used as a passive reflector.

There are many applications for the Luneberg as a passive reflector, such as a radar target or a radar marker for navigation. These applications do not in general impose as many or as severe requirements on the Luneberg as do applications involving the transmission of high rf energy levels. For this reason the first Luneberg lens to be commercially produced is the passive-reflector type. Spheres up to 36 inches in diameter are advertised as shelf items. The spherical cap is utilized to hold the lens in position, providing a neat solution to the support problem.

Attempts have been made to simplify the Luneberg to the utmost as a passive reflector. It has been shown, for example, that a constant dielectric sphere with $\epsilon = 4$ has fair focussing properties. Some thought has been given to optimizing the performance of a sphere utilizing only two different dielectric materials. Also, a combined lens-corner reflector has exhibited a wider angle of performance than just a corner reflector. No doubt other improvements will emerge as the scope of applications widens.

III. PRACTICAL CONSIDERATIONS

As stated before, use of this very versatile lens is delayed because of fabrication difficulties. In order for one to understand this situation, it is helpful to be familiar with the specifications imposed on a Luneberg.

A. Dielectric Constant

The dielectric constant ϵ of the lens varies continuously as $\epsilon = 2 - r^2$, from a value of 2 at the center to unity at the surface. This is the only variation for a sphere with the source on its surface. If the shape of the lens is altered,⁶ or if the source is positioned elsewhere than on the surface,¹ a different law of variation of ϵ results. All such laws known to the authors demand an ϵ greater than 2.

Fabrication of materials having the required value and distribution of ϵ within a sphere had proved to be an insurmountable obstacle until quite recently. To date, no way has been found to make a successful Luneberg with a continuous variation of dielectric constant. Success has been achieved by approximating the required variation of ϵ by discrete steps, that is, by building up the sphere with a number of concentric shells of a given ϵ . The first such practical lens⁷ was made of a mixture of shredded polystyrene and expandable polystyrene beads. This lens, although built and tested over a year ago, has not yet been used in an antenna system, owing largely to its high cost and weight.

⁶Eaton, J.E., "An Extension of the Luneberg-type Lenses," NRL Report #4110, 16 Feb 1953

⁷Peeler, G.D.M., Coleman, H.P., Electronics Div., NRL, and Volk, M.C., Guming, W.R., Emerson & Guming, Inc., "Microwave Stepped-Index Luneberg Lenses," NRL Report #4843, 26 Oct 1956

There is a fundamental limitation imposed on the lens by the present state of the art in controlling the value of the dielectric constant of any one shell. At the present time, no manufacturer has demonstrated his ability to reproduce shells which are isotropic and homogeneous to within a tolerance better than $\pm .02$ in dielectric constant. Since $1 \leq \epsilon \leq 2$, the number of shells is limited to 25 at the most. This in turn limits the size of the lens, for the thickness of the shells cannot be too gross as compared to the wavelength of the rf energy used. There is no known relation which can be applied to determine how many shells are needed for a lens of a given size, or how large a lens can be built for use at a given frequency. This problem is being worked on⁸ and preliminary results, although tremendously complicated, indicate that it may be possible to compute a relationship between number of shells, lens size, and rf wavelength.

Investigators experimenting with Lunebergs have learned to make rough estimates of the number of shells required. For example, from previous work done at this laboratory on two-dimensional lenses, it was felt that ten (10) steps were adequate for the 18-inch diameter spherical Luneberg⁷ for use at X-band. Measurements showed that the lens performed as predicted at a wavelength of 3.2 cm. The side lobes were down by about 18 db as compared to a level of 20 db predicted by Braun's work. The aperture efficiency was 63 percent which compares quite favorably with 65 percent for a paraboloid operating under the same conditions. At 1.8 cm the side lobes rose to an average of 15 db and when the lens was operated at 0.8 cm no position of the feed could be found where the lens would focus. No attempt was made to obtain a general relationship between the number of steps and the shortest wavelength at which the lens would focus, since this would be costly, time-consuming, and open to suspicion due to the uncertainties in lens construction.

B. Dielectric Loss

Because the Luneberg is a very thick lens, it is necessary that the lens material have a very low dielectric loss characteristic. Just how low this loss should be depends on the diameter of the lens in terms of wavelength. An exact solution for the actual dielectric losses as a function of the lens radius would be difficult to obtain. However, the field density over any cut through the lens is inversely proportional to the square of the lens radius and the volume of dielectric material is directly proportional to the cube of the radius. A fair approximation to the dielectric losses is that they are directly proportional to the lens radius. It is obvious then that the lens material must be nearly lossless, with $\tan \delta < .001$ preferably. This requirement puts a severe limitation on the types of material that can be considered.

⁸Braun, E.H., NRL Report In Process of Writing

Also, the loss factor imposes a limit on the size of the lens. There is no point in contemplating microwave lens with an aperture diameter much more than 50 wavelengths, for with presently available materials most of the transmitted and received energy would be expended in the lens. For that matter, a large lens poses a heat transfer problem, as the dielectric material is an excellent heat insulator.

C. Weight

Another important consideration is the weight of the lens. If polystyrene is used as mentioned in section A, then weight rapidly becomes prohibitive. Polystyrene has a specific gravity close to unity, so that a spherical Luneberg made of polystyrene has a specific gravity of about one-third. The 18-inch diameter lens referred to previously⁷ weighs about 35 lbs. Support for the full sphere is a problem; the use of metallic plane mirrors for sector scan and spherical caps for the passive reflector are solutions for those two cases. It appears likely that a lens with a diameter greater than 3 feet and made of materials now available would crush part of its fragile outer shells if placed on a flat surface.

D. Other Desirable Features

The outer shell of the Luneberg must of necessity be tenuous, since ϵ approaches unity on the surface. In addition to the strength problem mentioned above, there is also a problem of porosity. It is important that no water find its way into the lens from the surrounding atmospheric conditions, for then the dielectric loss increases prohibitively. Thus it is desirable that the lens material be unicellular to prevent water absorption. Added protection can be obtained by placing a very thin and tough waterproof bag, a sort of tight-fitting radome, over the lens.

The bag-like radome just mentioned can provide other types of protection. It is important, for example, that the lens possess good resistance to weathering. Without some kind of radome, the fragile outer shell would weather poorly. Also, the lens must possess chemical stability, that is, its desirable characteristics should not deteriorate with time. For example, radiation from the sun, especially ultraviolet, affects some plastics. The subject radome could be made to exclude ultraviolet.

The lens material must possess mechanical stability. It must not crack or craze with time or under the influence of changing temperatures. Coldflow or creep of the material must be avoided.

The material must be homogeneous and isotropic, for otherwise the performance characteristics of the lens would be a function of position.

IV. FABRICATION TECHNIQUES

To appraise the Luneberg problem as a whole and to predict what its future may be, it is felt that a knowledge of what has been done in the past is essential. The following comments are brief, but, it is hoped, informative.

A. Early Attempts

1. Shortly after World War II, the Antenna Laboratory of the newly-formed Air Force laboratory in Cambridge, Mass. (now named Air Force Cambridge Research Center (AFCRC) and located at Hanscom Field, Bedford, Mass.) became interested in techniques for fabricating Lunebergs.

Early in 1947 a contract was let by AFCRC with Case Institute of Technology to investigate geodesic surfaces for focussing electromagnetic waves. In this case, the variation in ϵ is simulated by increased path length for the rf energy traveling in the TEM mode between parallel plates. The result of this study was the "tin hat," a dome-like parallel-plate region as illustrated in Fig.7. The first model was of plaster of paris, 36 inches in diameter, built in 1948. Energy leaving the feed at various angles traverses geodesics, paths of least distance, to the semicircular line aperture. This design had mechanical drawbacks, but behaved well electrically.⁹ Since then various other laboratories have improved the mechanical design by using aluminum spinings, until now the "tin hat" appears practical for a two-dimensional lens.

By 1950 AFCRC designed and built another type of two-dimensional Luneberg. The lens was made of solid dielectric and so shaped that when placed between circular parallel plates as shown in Fig.8, the resulting air-dielectric combination gave the desired value of ϵ at any one point. This design, although it neglected the trapping effect of the solid dielectric, gave encouraging results. Results were not published, nor was the design improved.

In 1951 AFCRC built a two-dimensional parallel-plate Luneberg with a continuously varying ϵ obtained by compressing a properly shaped mound of foamed polystyrene. This technique was then extended to produce a three-dimensional Luneberg by using a number of compressed dielectric layers of the correct size and with the proper variation of dielectric constant. This technique was not too promising, largely because the foamed material did not crush uniformly. Test results¹⁰ were reported relatively recently, together with more recent results.

⁹Fine, E.C., "The Metal-Plate Analogue of a Luneberg Lens," NRL Report "Proceedings of the Third Symposium on Scanning Antennas," p.30, 1950

¹⁰Corkum, R.W., Gutman, A.S., Hiatt, R.E., "The Luneberg Lens of Continuously Varying Dielectric Constant," AFCRC-TR-54-103, Oct 1954

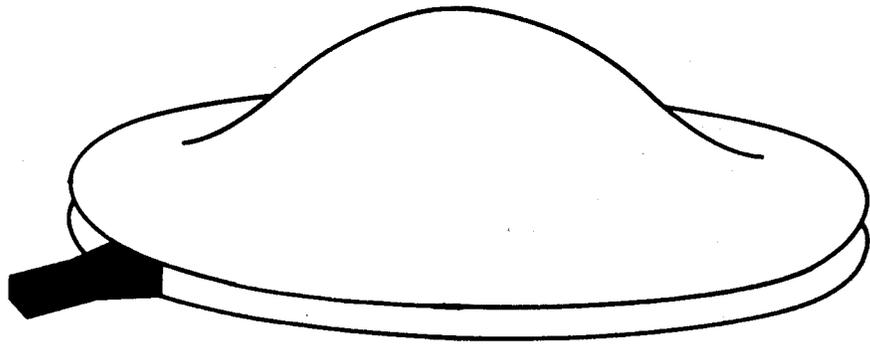


Fig. 7 - The "Tin-Hat" Analogue of the Luneberg Lens

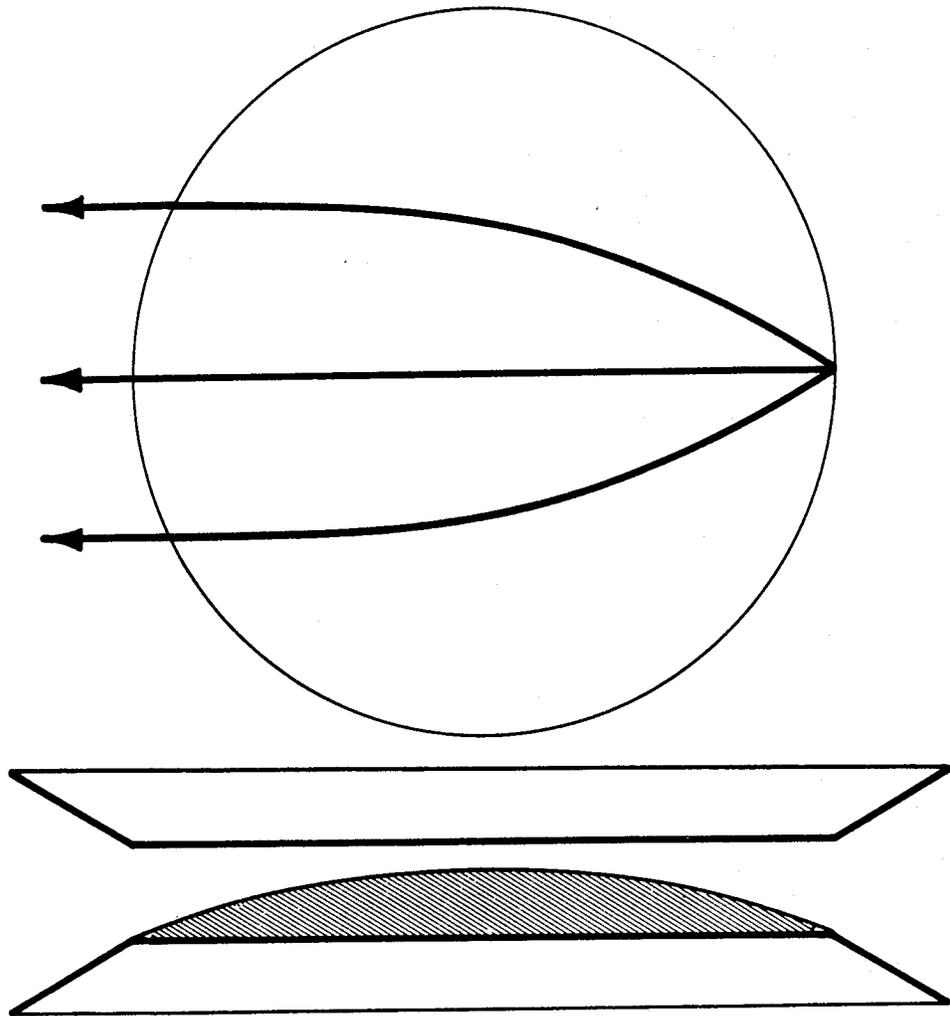


Fig. 8 - Parallel Plates Partially Filled with Dielectric Material as a Luneberg Lens

2. To the best of the authors' knowledge, the first three-dimensional Luneberg was built at Hughes Aircraft Company, Culver City, California, about 1950. It consisted of a number of concentric hemispherical shells of appropriate ϵ . The shells were turned on a lathe from blocks of compressed polystyrene foam. No report of results was made available, and it is presumed that the lens was unsuccessful for the reason stated above.

3. The first three-dimensional lens¹¹ to have some measure of success was conceived and built at the Airborne Instruments Laboratory, Inc., Mineola, Long Island. This 12-inch diameter lens consisted of several thousand glass pyrex balls so dispersed throughout a supporting foamed polystyrene material to produce approximately the desired variation in ϵ . A novel feed system was utilized, with scanning through 360° accomplished by rf switching.

4. Early efforts at the Naval Research Laboratory were directed toward the construction of two-dimensional Lunebergs. In the first type of lens constructed, variation of ϵ was obtained by using the waveguide effect on the rf energy. As sketched in Fig.9, the E-vector of the rf energy is parallel to the plates, so that the velocity of propagating is a function of plate separation and the material between the plates. Energy leaving the feed follows paths of least time, so that this lens is similar in that respect to the geodesic analogue of the tin hat mentioned earlier. This lens performed as predicted and was reported¹² in the literature.

An attempt was also made to develop a material covering the required range in ϵ and to approximate the lens by hand-forming a small number of concentric annular rings. At that time the only technique which appeared to promise adequate density control involved the use of foamed rubber and rubber plastic materials. The supplier of this material, however, was unable to avoid the use of carbon black in the rubber compounding and the effort failed due to excessive losses in the higher dielectric constant materials. No report was made of these lenses.

5. Several laboratories tried by chemical means to foam dielectrics to produce the prescribed variation in ϵ . All these attempts at "foaming in place" failed. Both loaded and unloaded dielectrics were used, but the results were uniformly bad. This technique is attractive and has been tried again quite recently, but the required variation in ϵ has not been adequately approximated.

¹¹Jasik, H., "Spherical Luneberg Lenses," NRL Report #4000, p.89, 1952

¹²Peeler, G.D.M., Archer, D.H., "A Two-Dimensional Luneberg Lens," NRL Report #4115, 2 March 1953. Also, IRE Transactions, Antennas & Propagation, Vol.AP-2, #3, July 1954 (Same authors and title).

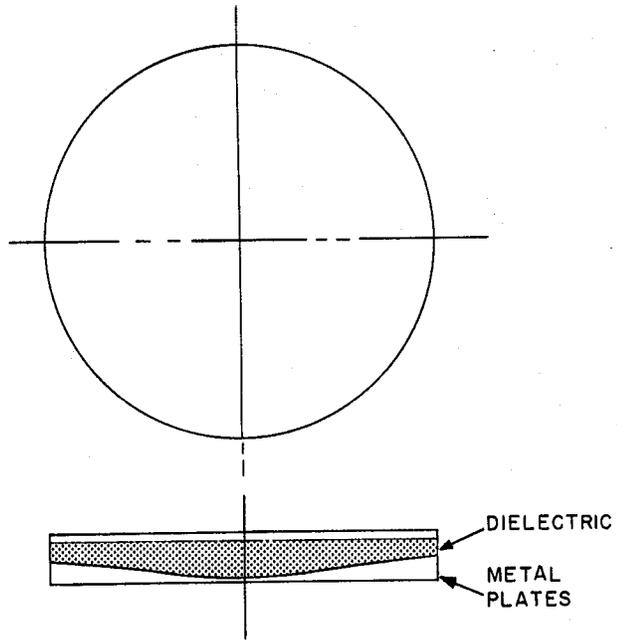


Fig. 9 - TE₁₀ Mode Luneberg, Comprised of Dielectric-Filled Almost-Parallel Plates

B. Current Attempts

1. Several laboratories, including the Naval Research Laboratory, have fabricated material for a Luneberg lens by creating voids in a sheet of solid dielectric material. Although two-dimensional lenses have been fabricated this way, the technique does not seem a practical one to extend to the construction of three-dimensional lenses.

2. The various potential uses of the Luneberg lens have become so well known by now that several commercial companies are trying to develop new plastics for possible applications. Briefly, these approaches are as follows:

a. Expandable Polystyrene Beads. By mixing partially expanded beads with a higher dielectric constant material in proper proportions a dry mixture capable of moulding is obtained. This technique was used successfully in fabricating the 18-inch sphere for this laboratory.⁷

b. Dielectric Loading. This technique is similar to that above, except a binder is used to hold the two different dielectrics together. Lenses fabricated in this manner have not been entirely satisfactory. The radiation pattern of such a lens varied with scan angle, thus indicating inhomogeneities in the lens.

c. Metallic Loading. The idea here is to add metallic dust to increase the dielectric constant of a very lightweight material without increasing the loss or permeability. Ordinary fabrication techniques introduce anisotropy, so that special techniques have been devised to add the metallic dust without introducing preferred orientations of the particles. Experimental lenses fabricated with such material have shown high losses and poor radiation patterns.

3. The most significant and promising technique now being explored is the use of artificial dielectrics. An artificial dielectric is a configuration of metallic objects, small compared to the wavelength of the operating rf energy but large compared to the molecules of a natural dielectric. These metal objects when placed in an electromagnetic field become polarized, i.e., have poles induced on their surfaces, and thus create an electromagnetic field of their own which did not exist previously. This newly created field reacts with the rf field which produced it, producing an effect much like that of a dielectric material.

For certain simple object shapes such as spheres or cylinders, this "artificial" dielectric effect is calculable. A theoretical and experimental investigation of this effect produced by thin

pins were made at this laboratory. Using the results, a two-dimensional Luneberg was designed and built.¹³ Test results showed the lens to have radiation pattern, antenna gain, and impedance characteristics as expected from lens theory.

An extension of the above to three-dimensions was cut short by the demands of the military draft and departure of personnel to commercial laboratories.

4. Recent work with dielectric materials to modify their properties by high intensity radiation shows some promise of developing suitable lens materials. The Chemistry Division at this laboratory has, for example, solidified some of the silicones with radiation from a cobalt 60 source.

V. CONCLUSIONS

At the present time small two-dimensional microwave Luneberg lenses can be built using (1) variable dielectric material between parallel plates, (2) constant dielectric material between properly shaped plates, (3) the geodesic analogue of the "tin hat", or (4) artificial dielectrics between parallel plates. Small three-dimensional microwave lenses can be built using expandable polystyrene beads. It may be possible to use techniques other than the above, but feasibility has not been demonstrated. The word small, used to describe lens size above, is meant to be about 5 feet maximum at the present state of the art, lens size decreasing with rf wavelength due to excessive loss in the dielectric.

There are applications also for a large two- or three-dimensional Luneberg at UHF. Lens size would be in some cases in excess of one hundred feet. It is obvious that the mechanical problem is one of great complexity. In looking over all possible approaches to this problem, one is led to conclude that the most promising and perhaps only approach is through the use of artificial dielectrics. Since the wavelength to be used is about a meter, the metallic objects may be several inches in extent. Fabrication techniques for the obstacles and construction techniques for the lens need to be surveyed anew.

Applications of the Luneberg lens have been few, despite the unique advantages offered. This slow progress is due entirely to a lack of suitable materials and practical design techniques. The future of the Luneberg lens is, however, promising and progress is accelerating due to the increasing number and diversity of efforts being put to bear on the problem.

¹³Peeler, G.D.M., Reuss, M.L., "A Two-Dimensional Pin Luneberg," NRL Report In Process of Writing

