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A STUDY OF RADAR CROSS SECTION MEASUREMENT TECHNIQUES

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# A STUDY OF RADAR CROSS SECTION MEASUREMENT TECHNIQUES

by

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## ABSTRACT

A study of past, present, and proposed future technologies for the measurement of radar cross section was conducted. The purpose of the study was to determine which method(s) could most advantageously be implemented in the large microwave anechoic chamber facility which is operated at the antenna test range site by the Communication Systems Branch of the Information and Electronic Systems Laboratory at the Marshall Space Flight Center.

The progression toward performing radar cross section measurements of space vehicles with which the Orbital Maneuvering Vehicle will be called upon to rendezvous and dock is a natural outgrowth of previous work conducted in this laboratory in recent years of developing a high accuracy range- and velocity-sensing radar system. The radar system has been designed to support the rendezvous and docking of the Orbital Maneuvering Vehicle with various other space vehicles. The measurement of radar cross sections of space vehicles will be necessary in order to plan properly for Orbital Maneuvering Vehicle rendezvous and docking assignments.

The methods which were studied include: (a) standard far-field measurements, (b) reflector-type compact range measurements, (c) lens-type compact range measurements, (d) near field/far field transformations, and (e) computer predictive modeling. The feasibility of each approach is examined.

### ACKNOWLEDGEMENTS

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I wish to commend the careful, personal, and thorough direction of the summer program wrought by three coordinators, Dr. L.M. Freeman, Ms. Ernestine Cochran, and Dr. F.A. Speer. All three have added to the pleasure of this summer's program through their personable and efficient dispensing of information and their pleasant interactions with the faculty participants.

The most rewarding aspect of this summer's participation has been found in the numerous opportunities to experience the learning process through conversation and discussion with NASA personnel. My regard for their expertise and knowledge continues to grow, and I thank them all for willingly sharing their knowledge with me.

NOMENCLATURE

GHz	Gigahertz
MSFC	Marshall Space Flight Center
NBS	National Bureau of Standards
OMV	Orbital Maneuvering Vehicle
RCS	Radar Cross Section
R/D	Rendezvous and Docking

FIGURE

Figure 1.

Illustration of a Convex/Plane  
Convergent Lens.

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## INTRODUCTION

The Orbital Maneuvering Vehicle (OMV) is being developed by NASA to function as a fetch and retrieval vehicle. It will be sent out from its base (initially the shuttle, and eventually the permanent space station) to rendezvous and dock (R/D) with other space vehicles. The propulsion system of the OMV will be used to move the other vehicles to different orbits or to a base location for inspection, repair, or replenishment of consumables.

The OMV will be unmanned but will be flown by a man-in-the-loop pilot at a remote location. It will be equipped with a radar sensor to provide a capability for detecting the target vehicle at some large range and closing velocity data to support R/D maneuvers.

In order to plan effectively for such OMV-target vehicle encounters it is imperative that the mission planners have access to information regarding how large a radar reflection target the target vehicle will appear to the OMV radar sensor. Such information is the radar cross section (RCS) of the target vehicle, the value of which contributes toward determining the maximum range at which radar detection and tracking of the target vehicle can be expected of the OMV.

It is a valid and necessary undertaking to measure in advance the RCS of the space vehicles for which OMV R/D is anticipated. The desire to know the most plausible technique(s) for pursuing such measurements at the Marshall Space Flight Center (MSFC), the lead NASA center for OMV development, provided the genesis for this study.

MSFC enjoys the benefit, from the standpoint of performing RCS measurements, of having in place a large tapered-design microwave anechoic chamber, normally used for the measurement of antenna radiation patterns. The taper design is especially beneficial to RCS measurements because of the reduction of side wall scatter of stray radiation back into the detector antenna aperture (Ref. 1, p.391). The MSFC anechoic chamber measures about 40 meters in length (with somewhat more than 25 meters forming the taper) with a 9-meter by 9-meter transverse cross section at the large end. It would be possible for the anechoic chamber to be adapted to form a compact range for RCS measurement of large targets, measuring up to, perhaps, 6 meters in maximum transverse size.

The definition of RCS assumes that the target for which the RCS measurements are to be made is located in the far field (Fraunhofer region) of the illuminating radar source and, likewise, the reflected radar energy detector is located in the far field of the scattering target. For large targets (several meters in transverse dimension) and short radar wavelengths (the proposed OMV radar wavelength is of the

order of two centimeters) the far field distance between radar and target can be several kilometers. This derives from the generally accepted criterion for the far field threshold of  $2D^2/\lambda$ , where D is the transverse dimension of the scattering target and  $\lambda$  is the wavelength of the scattered radiation.

One is faced with the choice of either attempting to make RCS measurements on a far field range several kilometers long (in which case the radiated power requirements of the source radar would be very great, not to mention the difficulties associated with locating an appropriate site) or providing a compact range facility wherein Fraunhofer field conditions are produced artificially in short distances by use of reflector surfaces or lenses. Two other possibilities for determining RCS of complex targets might include (a) measuring scattered amplitude and phase in the near field (Fresnel region) of the scattering target and mathematically transforming those values to find the equivalent far field scattering pattern, and (b) by a purely theoretical approach, calculating with computer predictive modeling the expected RCS of the target. Such are the techniques explored in this paper.

## OBJECTIVES

The objectives which were established to guide this work were:

1. To perform as extensive a survey of relevant library sources as time would permit in order to establish the various alternative approaches to RCS measurement,

2. To examine the feasibility or plausibility of implementing each method at MSFC, taking into account the most advantageous utilization of current MSFC facilities, equipment, personnel, and expertise, and

3. To recommend a "best candidate" method or methods for the measurement of RCS of large radar targets at MSFC.

### RADAR CROSS SECTION - DEFINITION

The radar cross section (RCS),  $\sigma$ , of a target is a quantity, expressed in units of area, usually square meters, which denotes how effectively the target scatters incident radar energy away in a particular direction. From Skolnik (Ref. 2, p.40) and others it may be defined as that area intercepting energy in the incident target-illuminating beam which, if scattered isotropically, would produce a power density along a defined direction equal to that actually scattered by the target. In terms of the spherical coordinates,  $R$ ,  $\theta$ , and  $\phi$ , centered on the scattering target one can define a bistatic cross section,

$$\sigma(\theta, \phi, \theta_i, \phi_i) = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E^s(\theta, \phi)|^2}{|E^i(\theta_i, \phi_i)|^2}, \quad (1)$$

where  $E^i(\theta_i, \phi_i)$  is the amplitude of the incident electric field approaching along direction  $(\theta_i, \phi_i)$  and  $E^s(\theta, \phi)$  is the amplitude of the electric field scattered in the  $(\theta, \phi)$  direction (Ref. 3). It should be noted that the bistatic definition of RCS in equation (1) suggests a measurement along a direction different than that of the incident beam.

A more commonly considered definition of RCS assumes that the reflected radiation is detected along the reverse direction of the incident beam; i.e.,  $(\theta, \phi) = (\theta_i, \phi_i)$ . This more often used definition is termed (a) monostatic radar cross section, (b) backscatter radar cross section, or simply (c) radar cross section and may be written as

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E^s|^2}{|E^i|^2}. \quad (2)$$

In either definition of  $\sigma$  it is defined that the detection of the scattered echo is at such a large distance  $R$  as to insure that the scattered waves produce planar wave fronts. It is further implied that the target was positioned far enough away from the illuminating radar source so as to be in the far field and thus illuminated by planar incident wave fronts. This report assumes this latter definition of RCS (Equation 2).

A method for measuring  $\sigma$  is suggested by the standard radar equation,

$$\frac{P_r}{P_t} = \frac{G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \quad (3)$$



where  $P_r$  and  $P_t$  are received and transmitted power,  $G$  is the gain of the transmit/receive antenna,  $\lambda$  is the wavelength, and  $R$  is the antenna-target distance. Assuming  $P_t$ ,  $G$ ,  $\lambda$ , and  $R$  remained constant, one could say that  $\sigma$  is directly proportional to the received power,

$$\sigma = k P_r \quad (4)$$

where  $k$  is merely a proportionality constant. By using a standard target of accurately known radar cross section  $\sigma_0$  as a reference at the same point as the actual target one could say

$$\sigma_0 = k P_{r0} \quad (5)$$

where  $P_{r0}$  is the power received at the antenna from the reference target. Dividing equation (4) by equation (5) yields

$$\sigma = \left( \frac{P_r}{P_{r0}} \right) \sigma_0 \quad (6)$$

suggesting that a simple measurement of the ratio of the power scattered back into the antenna from the true target and from the reference target will determine  $\sigma$  in terms of the known  $\sigma_0$ . However, this overlooks an important point.

The scattering of electromagnetic waves by a target can alter the polarization characteristics of the scattered waves. Thus  $\sigma$  becomes a function of the polarization of the incident and received waves. The scattered wave can be related to the incident wave by a four-element scattering matrix  $S$  given by (Ref. 1, p. 49)

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \quad (7)$$

so that

$$\begin{bmatrix} E_1^s \\ E_2^s \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} E_1^i \\ E_2^i \end{bmatrix} \quad (8)$$

where the subscripts 1 and 2 represent two orthogonal polarization directions,  $E_1^s$  and  $E_2^s$  are orthogonal components of the scattered wave amplitude and  $E_1^i$  and  $E_2^i$  are similar components of the incident wave amplitude.

The scattering matrix components can be related to RCS components,

$$S_{ij} = (4\pi R^2)^{-1/2} \sqrt{\sigma_{ij}} \quad (9)$$

leading to the definition of an RCS polarization matrix (Ref. 4, p. 30)

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} \quad (10)$$

If we consider horizontal and vertical polarization directions, the more complete picture of the meaning of radar cross section becomes

$$\sigma = \begin{bmatrix} \sigma_{HH} & \sigma_{VH} \\ \sigma_{HV} & \sigma_{VV} \end{bmatrix} \quad (11)$$

This matrix contains all the reflectivity information available from the target. The element  $\sigma_{VH}$ , for example, is the RCS measured when the incident waves are polarized along the vertical axis and the detected waves are horizontal polarization components. By the reciprocity theorem,  $\sigma_{VH} = \sigma_{HV}$  for a monostatic radar.

Each RCS matrix element consists of an amplitude and a phase. Coherent RCS measurements include amplitude and phase of the scattered waves. Traditional noncoherent RCS is defined by the measurement of amplitude only.

One last point needs to be made about RCS. It is very much dependent upon the viewing aspect of the target. In fact, for a complex target, as any space vehicle certainly will be, the RCS can fluctuate by several orders of magnitude (several tens of decibels), referenced to one square meter of cross section) in response to less than one degree change in aspect angle. In general, then,  $\sigma$  needs to be specified as  $\sigma_{ij}(\alpha, \beta)$  where  $i$  and  $j$  refer to the incident and received polarizations, and  $\alpha$  and  $\beta$  are two polar spherical angles (such as azimuth and elevation) which serve to specify the spatial orientation of the target relative to the direction of the incident beam. The complete radar signature of a target is the conglomerate of RCS information for all polarizations and all target aspect angles. Every different radar target has a unique radar signature, a fact which could conceivably enable an autonomous space vehicle to identify other space vehicles upon encounter. That topic, although an interesting one, goes beyond the scope of this study.

## COMPUTER PREDICTIVE MODELING

In principle, one should be able to predict the pattern of scattered radiation from a target if one knows the shape and electrical properties of the target and merely applies known principles of geometric and physical optics. In reality, the correct RCS can be calculated in detail only for a few target objects of simple shapes (sphere, cylinder, line, ellipsoid, for examples). Of the simple targets, the sphere is the only one for which, as a result of its spherical symmetry, the RCS is aspect independent.

The sphere, simple as it is, illustrates or hints at how complicated the prediction of RCS for a more complex target might become when one considers how the RCS of the sphere depends upon the dimensions of the sphere relative to the wavelength of the incident radar waves. For example, when the circumference of the sphere,  $C$ , is much smaller than the wavelength,  $\lambda$ , (the so-called Rayleigh scattering region) the sphere tends to ignore the incident radiation and the RCS can be quite small compared with the RCS found if  $C \gg \lambda$  (say  $C > 10\lambda$ , the so-called optical scattering region). For values of  $C$  roughly between one and ten wavelengths (the so-called resonance region) the RCS oscillates with a monotonically decreasing amplitude as it homes in on a constant optical RCS value equal to  $\sigma = \pi a^2$ , where  $a$  is the sphere radius. In other words, the optical RCS value is just the circular area of the sphere's projection on a plane normal to the incident beam.

It might be inserted at this point that the fact that the RCS of the sphere (at least in the optical region) equals the projected area of the target along a plane normal to the incident beam can hardly be expected for any other targets. Some targets have RCS values a thousand or more times larger than its projection, or aperture, area, depending much more on the target shape than on the target size. As an example, a trihedral corner reflector formed by three square plates measuring ten centimeters on a side has a maximum RCS of over  $50 \text{ m}^2$  at a radar frequency of 35 gigahertz (wavelength = 8.57 mm). Thus, its RCS is roughly 2000 times its projected area.

The resonance region of RCS values for the sphere results from a "creeping wave" phenomenon at the resonance wavelengths ( $\lambda < C < 10\lambda$ ) (Ref. 4, p. 33). The wave is a surface wave induced by the incident beam. It travels around the back of the sphere and re-radiates toward the receiver, producing constructive and destructive interference with the specularly reflected wave, depending upon the sphere size. Similar "creeping wave" contributions are found in the scattered radiation from other complex targets when scattering centers on the complex target meet the "creeping wave" conditions. The "creeping wave" scattering event has been singled out merely to illustrate the level of details of target structure one must consider to represent fairly the nature of the scattered pattern of radiation from a complex target.

Pertaining to the microwave region of radar wavelengths where in almost all cases the dimensions of the scattering target are large in comparison to the wavelength, the Radar Cross Section Handbook, Vol.2 (Ref. 5) suggests seven different scattering mechanisms for complex targets, of which the creeping wave is one. Collectively the seven scattering mechanisms determine the radar signature of the target and, in addition, would need to be accounted for in any attempt at high fidelity predictive modeling. The seven scattering mechanisms are:

1. specular reflection,
2. scattering from surface discontinuities (edges, corners, etc.),
3. scattering from surface derivative discontinuities,
4. creeping waves,
5. traveling wave scattering,
6. scattering from concave regions (ducts, tri- or dihedrals, etc),
7. interaction scattering (e.g., multipath scatters from separate target scattering centers).

In most published accounts of RCS prediction of complex targets (see for example Ref. 6) the predicted result shows only gross agreement with measured patterns or else the "complex" target in the treatment is actually not very complex in reality (a "complex" target in some instances is defined as combinations of two, or perhaps three, different simple geometric shapes; e.g., a hemisphere fitted to the base of a cone or a cylinder plus a cone to represent a rocket, etc.).

Knott (Ref. 1, p. 5) points out that computer limitations restrict general solutions of the scatter problem to bodies not much larger in size than a few wavelengths ( $< 10$ ). This is far too small to be of much use in predicting scattering cross sections for large space targets. In the author's opinion, space vehicle radar targets are far too complex in their shapes to permit reasonable attempts at modeling accurate values of RCS, especially when one considers the numerous scattering mechanisms which contribute to various degrees.

#### TRANSFORMATION OF NEAR-FIELD MEASUREMENTS TO RCS

In the measurement of far-field antenna radiation patterns when the antenna aperture is very large relative to the wavelength some of the same considerations come into play as are evidenced in the measurement of RCS of very large targets. The problem arises because the  $2D^2/\lambda$  far

field threshold is so large as to render probing at such distances very difficult or impossible. In the case of antenna pattern measurements several groups report methods of probing the near field of the antenna and performing mathematical transformation of the near-field measured values to produce the far-field pattern. Ramat-Samil (Ref. 7) of the Jet Propulsion Laboratory reports a method for probing the near field (amplitude and phase measurements) in a plane-polar configuration and then transforming the data with a Jacobi-Bessel expansion algorithm to generate the far-field pattern. Joy (Ref. 8) at Georgia Institute of Technology reports a spherical surface near-field measurement approach which uses a spherical wave expansion algorithm to generate the far-field pattern. Antennas measuring up to 10 meters long by 4 meters high (including AWACS antennas) are tested in a planar near-field facility at the National Bureau of Standards (NBS) (Ref. 9) with the probed data being transformed to the far field by a plane wave scattering matrix theory (Ref. 10).

A recent communication with NBS (Ref. 11) indicates evidence of a growing interest expressed to NBS for similar near-field/far-field transformation techniques to be applied toward determining RCS of large targets. Indications are that no group has reported success in any such venture. It may be that requirements of probe positioning accuracy and amplitude and phase measurement accuracy place such enormous constraints as to prohibit application of those methods to RCS determination of very large targets. The general axiom that probably applies here is that if this approach to RCS measurement presented only reasonably surmountable difficulties the chances are pretty good that some group would be reporting results based upon its implementation.

#### COMPACT TEST RANGES

To this point this report has not succeeded in proposing ways to measure RCS of large targets at microwave frequencies. There is a solution, though, through the utilization of a compact range. Compact test ranges for antenna pattern and RCS measurements establish far-field conditions (constant-amplitude, constant-phase, plane wave fronts) in a limited volume of space, known as the quiet zone or plane wave zone, in which the antenna under test or the RCS target is positioned. The quiet zone is produced by re-direction of the divergent beam from a radar source by means of reflector(s) or lens(es). The quiet zone has to be at least as large as the dimensions of the target to be measured. This also means that the aperture of the final lens or reflector has to be somewhat larger than the target's transverse dimension. Obviously then, to construct a compact range capable of measuring very large targets requires the use of very large reflectors or lenses.

For space satellites and vehicles the dimensions can be several meters, or even tens of meters, necessitating a large compact range if

full scale measurements are to be undertaken. A ploy often invoked to circumvent the requirements of such a large full-scale facility is to perform the RCS measurements on a scale model of the target. One can scale down the original dimensions of a large target to a fraction of that size if one simultaneously scales the wavelength accordingly. Such scaling reduces the size of the target being measured and likewise reduces the size of the quiet zone needed to accommodate the target.

As an example, one might wish to measure for a frequency of 12 GHz the RCS of a complex target measuring 10 meters in maximum dimension. A quiet zone of such dimension would be required for full-scale measurements. However, one could accomplish the same ends by making the measurements on a one-third scale model of the target in a compact range with a quiet zone only one-third as large, but at three times the original frequency, or 36 GHz.

In like manner, a one-eighth scale model of the ten-meter target would measure only 1.25 meters in maximum size and could be placed in a similar sized compact range with the measurements being made at a frequency of 96 GHz. Scaling is limited by the upper limit frequencies available with current state of the art. That is roughly 100 GHz at the present time.

#### REFLECTOR-TYPE COMPACT RANGES

Descriptions of many approaches to compact range design can be found in the literature (Ref. 1, Chap. 9; Refs. 12-16). The basic design uses as a reflector a section of a paraboloidal surface. This reflecting surface converts a divergent beam from a source at its focal point into a parallel beam which automatically meets the constant-phase far field requirements. Whether the constant-field amplitude requirements of the far field are met depends upon the reflector aperture illumination function of the source. Early design simply used a low-gain feed so that only a small fraction of the radiation emergent from the source was subtended and reflected by the reflector. This allowed a fairly uniform illumination of the reflector aperture and set the stage for a fairly uniform amplitude in the quiet zone. This method inherently caused low efficiency utilization of transmitted power, increased noise associated with the non-reflected energy which had to be absorbed in surrounding walls, and a natural tendency to introduce amplitude ripple in the quiet zone. The amplitude ripple results from diffraction effects arising from the strongly illuminated edges of the reflector.

Efforts to diminish the diffraction ripple in the quiet zone formed by a single reflector have included (a) serrating the edges of the reflector, (b) shaping the curvature at the edge of the reflector to minimize the abruptness of the discontinuity, and (c) tapering the

source illumination at the edges of the reflector to minimize the diffracted component in the quiet zone.

In recent years different groups have developed compact ranges which use two reflectors (a subreflector for shaping the illumination pattern presented to a larger primary reflector). The Harris Corporation (Ref. 16) plans to use a Cassegrain configuration with a shaped 8-foot subreflector to reflect energy from a high-gain feed horn on to a 20-foot primary reflector, capable of operation in the 2-18 GHz frequency range. This system produces a 10-foot spherical quiet zone characterized by less than  $\pm 0.25$  dB amplitude ripple, 0.2 dB amplitude taper in the quiet zone, and  $\pm 2$  degrees of phase ripple. They claim 98% of the radiated energy is focused into the quiet zone. The 98 percent radiation efficiency reduces significantly the amount of spillover energy that must be absorbed in the anechoic chamber walls, reduces the transmit power requirements, and relaxes the dynamic range requirements of the detector system.

Although the Harris system is "planned", they actually have operational a much smaller prototype system with a 46-inch diameter main reflector which produces a quiet zone of approximately 75% of that diameter. It operates from 16-46 GHz and has an amplitude ripple of  $\pm 0.5$  dB and a phase ripple of  $\pm 4$  degrees. The amplitude taper in the quiet zone is less than 0.1 dB.

Vokurka (Ref. 15) reports on a dual reflector compact range. The reflectors are cylindrical parabolics mounted on perpendicular axes. The main reflector measures 2.1 meters by 1.9 meters and operates at frequencies of 12-38 GHz. It produces a 1.2 meter quiet zone with 0.25 dB amplitude taper, 0.4 dB (peak-to-peak) amplitude ripple, and a  $\pm 2$  dB phase ripple. The main advantages of this new design are improved compactness and lower costs. A larger system of this dual cylindrical parabolic design capable of producing a 7-meter by 5-meter quiet zone is planned for the European Space Technology Center at Noordwijk, The Netherlands.

Clearly, reflector-type compact ranges large enough to accommodate the size of targets for which RCS measurements are anticipated in this study are now, or soon will be, available. An overriding drawback to them, however, will be cost. It would be extremely desirable to find an economical route for adapting the available microwave anechoic chamber at MSFC to function as a compact range for RCS measurements. That possibility will be explored in the next section.

#### LENS-TYPE COMPACT RANGES

A far-field radiation pattern can be effected by using the focusing properties of a microwave lens instead of a reflector(s). The

properties of microwave lenses have been explored thoroughly in a series of reports from Brown and Jones (Ref. 17) and in work done by Kock (Ref. 18). Chapter nine of Milligan's book on modern antenna design (Ref. 19) has very useful information on the use of the lens in antenna design. Microwave lenses can be divided into two major categories based upon whether they are constructed of materials for which the index of refraction is greater than unity (dielectric, or delay lenses) or less than unity (channel or waveguide lenses).

Dielectric lenses can be further categorized as true dielectric or artificial dielectric devices. An artificial dielectric lens has an advantage of much less weight, although much more volume, than a lens with similar focusing properties made of a true dielectric material (e.g., polystyrene, lucite, polypropylene, methyl methacrylate, etc.). An artificial dielectric is formed by impregnating a regular 3-dimensional array of small conducting beads or disks in a low-density foam to simulate the lattice structure of a crystalline material. The effective index of refraction can be established by the array density of the conductors.

Dielectric lenses accomplish their microwave focusing by delaying propagating wavefronts incident from a source point by an amount proportional to the thickness of dielectric material through which the refracted beam travels. Waveguide lenses provide focusing, or wavefront shaping, because electromagnetic waves channeled through a hollow metallic waveguide have a phase velocity in excess of the unchanneled free-space speed of light. As a result, a waveguide lens capable of converting a divergent beam into a parallel beam has a general concave shape whereas a similarly capable dielectric (delay) lens has the classic convex shape.

The topic of microwave lenses is explored in this report because it has been noted that a large microwave lens ("large" meaning up to eight meters in height or diameter) positioned in the MSFC anechoic chamber at a point where the taper begins, approximately 25 meters from a radar feed/receiver antenna at the tapered end, conceivably could allow a large plane wave quiet zone (perhaps as large as 6 x 6 x 10 meters) in the large end of the chamber. Such a system would provide a focal length/diameter (f/D) ratio of approximately three. Calculations have shown that a dielectric lens made of polystyrene (index of refraction  $\sim 1.6$  at a broad range of frequencies including the microwave region of interest) of front side-convex, back side-planar shape would be only 52 centimeters thicker at its center than at its edges.

Different combinations of lens surface shapes can be used to form a convergent dielectric lens. For a given lens aperture and focal length the convex/plane shape has the least volume, mass, and thickness. It is an example of a "single-surface" lens in that all the bending of the incident wave propagation direction occurs at the front (convex) surface when rays are incident upon the lens from a focal-point mounted wave source. Let us now look at the required surface curvature for such a lens (see Fig. 1).



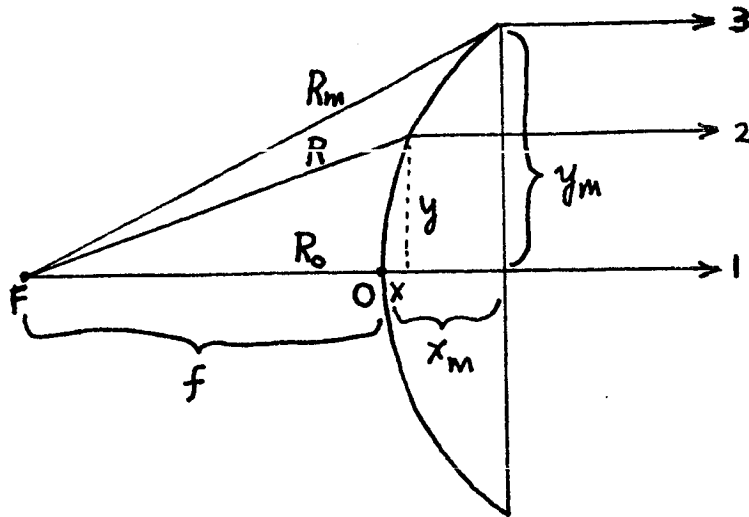


Figure 1. Illustration of a convex/plane convergent lens of focal length  $f$  and radius  $y_m$ . The thickness of the lens is  $x_m$ . An arbitrary ray follows a path in air of length  $R$  from the focal point  $F$  to a point on the front surface at coordinates  $(x, y)$  where it is refracted to follow a path parallel to the axis. The index of refraction of the lens material is  $n$ .

In the figure we define  $f$  as the focal length, the distance from the focal point  $F$  to the point  $O$  on the front surface where the line from the focal point through the central axis of the lens contacts the surface. The lens converts incident spherical wave fronts into transmitted plane wave fronts. This condition is met when the electrical (or optical) path length from the focal point (source) through the lens is the same for all incident rays. If we let  $n$  denote the index of refraction of the lens material, this requires for rays 1 and 2:

$$f + nx_m = R + n(x_m - x) , \quad (12)$$

which becomes

$$f + nx = R \quad (13)$$

where

$$R = [(f + x)^2 + y^2]^{1/2} \quad . \quad (14)$$

Substituting (14) into (13) to eliminate R yields the equation of the convex surface:

$$2fx(n - 1) + x^2(n^2 - 1) - y^2 = 0 \quad . \quad (15)$$

Equation (15) defines a hyperboloidal front surface and will permit the calculation of lens thickness,  $x_m$ , assuming the lens narrows to a thin edge of zero thickness (an unrealistic expectation). If we let  $n = 1.6$ , radius,  $y_m = 4.0$  meters, and  $f = 25.0$  meters, we find  $x_m = 0.52$  meters. In practice, to provide a sounder weight-bearing base to the lens, a constant thickness increment  $\Delta x$  could be added over the entire back surface plane without altering its focusing properties.

The thin edge lens has a volume of about  $13 \text{ m}^3$  which leads to a mass of about 14,000 Kg (15 tons) for polystyrene. Since the center of gravity of the thin-edge lens is approximately 17 cm from the plane surface an additional slab thickness of about 30 cm (minimum) would need to be added to provide rotational stability to the upright-mounted lens. To provide a sufficiently wide base would require at least a 50-cm thickness increment added to the back surface. Unfortunately, this leads to a projected lens mass of about 41,000 Kg (45 tons).

The mass of a dielectric lens can be reduced drastically through a process of "zoning" (Ref. 19, p.278). Zoning is the systematic cutting away of lens material, usually from the plane back side, to stepped depths equal to integer numbers of wavelengths. The integer wavelengths of lens thickness cut away permits transmitted rays to pass through with the same phase as they would have had without the zoning. Zoning changes the character of the lens in two detrimental ways; (a) it introduces a diffraction ripple component in the transmitted beam caused by the zoning edge discontinuities, and (b) it causes the lens to take on a very narrow frequency band response (set by the zoning thickness increments). The solid lens enjoys a very broad band applicability and does not suffer the limitations of the zoned lens.

By comparison, a waveguide-type lens is useful over only a narrow frequency band for which it is designed. Only the solid lens has broad band frequency response, allowing its use over an octave band, or more. As has been demonstrated earlier, a solid lens of typical plastic materials of the size needed for a large compact range application would be a very heavy lens. That fact leads to a natural conclusion: if a lens-type compact range were desired and if it were to be useful over a suitably broad band of testing frequencies, the lens probably should be designed of a lower density foam-type artificial dielectric material, something akin to the lenses designed by Koch (Ref. 18).

Two lens-type compact ranges have been reported in the literature. Mentzner (Ref. 20) pioneered with a not-too-compact design having a f/D ratio of 9. The large focal length was employed to decrease the amplitude taper across the lens aperture. Oliver and Saleeb (Ref. 21) introduced a novel feature by introducing a controlled amount of loss into the lens which effectively compensated for the transverse amplitude taper across the lens aperture. Their lens was only 0.44 meter in diameter, however. It was made of very low density (and low index of refraction, 1.03) polyurethane foam and had a thickness (0.5 meter) greater than its diameter.

There are other problems to be overcome in design of lens-type compact ranges. One is the loss of wave energy from front surface reflections. Another is the problem of energy reflected back into the feed horn from both the back surface reflections and the front surface (at least from near the central axis). The latter problem can be taken care of by two methods: (a) by tilting the lens a small angle, or (b) by constructing the lens in two halves with a one-half wavelength stagger in the position of one half relative to the other. The first problem will tend to lower the radiation efficiency of the lens-type compact range. It can be ameliorated by using lenses of low index of refraction.

#### CONCLUSIONS AND RECOMMENDATIONS

This report has examined five possible approaches to RCS measurement of large complex (space vehicle and satellite-type) targets at radar frequencies of 10 GHz and above. A brief review of the five with any salient recommendations follows:

1. Actual far-field measurements ( $R > 2D^2/\lambda$ ) are untenable because the far field range distances for targets meters in size at wavelengths of millimeters (or a few centimeters) is of the order of several kilometers. This would call for large power transmission capability and a very large measurement facility.

2. Computer predictive modeling seems to be limited to complex targets of small dimension (only one to ten wavelengths, depending upon the level of symmetry inherent in the target shape). That is simply one or two orders of magnitude too small to be applicable to the size targets under consideration.

3. Probing of the amplitude and phase of the reflected waves in the near field environment of a large target in an anechoic chamber followed by a mathematical transformation to generate the RCS of the target would seem to have promise, although it seems to be a very delicate and demanding operation. A plus for MSFC is the availability of a CRAY supercomputer to handle rigorous mathematical computations. At

this writing, however, the author has found no reports in the public domain literature to indicate that any groups are actually using such an approach for RCS measurements although many are using it to measure antenna radiation patterns of large antennas. It is recommended that the feasibility of this approach be examined more thoroughly.

4. An obvious route that could be taken is that of purchasing a commercially available reflector-type compact range RCS measurement facility to be installed in the MSFC anechoic chamber. This would entail a large capital expenditure. We are not aware of any such ranges presently available which would be able to accommodate full-scale models of targets of interest, but scaling model measurements could certainly be employed. This would be a recommended path to follow if economic constraints did not weigh adversely.

5. Finally, the adaptation of the microwave anechoic chamber into a lens-type compact range facility has an intrinsic appeal to this investigator in spite of the associated problems which have been addressed in this report. Admittedly the lens would have to be very large, and all the difficulties of producing a constant-phase, constant-amplitude plane wave quiet zone would have to be addressed. It seems that they are all soluble problems. It is recommended that further consideration be given to the fabrication of an artificial dielectric (metal delay foam-type) lens of the type used by Koch (Ref. 18) at the Bell Laboratories in such an application.

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