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**RADAR CROSS SECTION STUDIES**

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## **A. INTRODUCTION**

The ElectroScience Laboratory has been conducting a general study of evaluating scattered fields. The ultimate goal of this research has been to generate experimental techniques and computer codes of rather general capability that would enable the Aerospace Industry to evaluate the scattering properties of aerodynamic shapes. Another goal involves developing a sufficient understanding of scattering mechanisms so that modification of the vehicular structure could be introduced within constraints set by aerodynamicists. Last but not least, a major goal has been the development of indoor scattering measurement systems with special attention given to the compact range. There has been very substantial progress under Grant NSG 1613 in advancing the state-of-the-art of scattering measurements, control and analysis of the electromagnetic scattering from general targets.

## **B. PAST ACHIEVEMENTS**

### **1. Electromagnetic Scattering Analysis**

After a careful review of the analytic techniques available for handling the scattering from complex targets such as missiles and aircraft, it was very apparent that additional tools were needed. In order to confirm this evaluation, various targets were analyzed and measured to illustrate the magnitude of the problem. It appeared that presently available codes and solutions, although very inefficient in most cases, could be used for most basic shapes. However, as one attempted to shape the target, new mechanisms were needed to be added to

complete the solution but in many cases were not available. Thus, a major effort of this research was to solve these problems.

**a. UTD Extensions for Scattering**

The general concepts of the basic GTD and scattering analysis have been extended through the advent of the UTD and its extensions which are useful for solving a much broader class of problems. First, the equivalent current concept has been extended by introducing a creeping wave path from the shadow boundary to the diffracting edge. This has been used to obtain much better agreement with experimental data for low level scattering analysis of cones at non-normal incidence. This is quite important for low scattering missile shapes.

Next, the concept of corner diffraction was developed. This has been used to analytically obtain the scattering of certain shapes for which rather high experimental scattering values have been reported elsewhere. This is important in terms of scattering analysis of fins and wings and their control. This will be discussed in the control section later.

We have made a series of measurements for several generations of missile shapes provided by NASA and have obtained excellent agreement between theoretical and experimental results. Experimental patterns have been repeated after various features (such as fins and the RAM-JET engines) were added.

### **b. Flat Plate Scattering**

One of the dominant scatterers on missiles and aircraft takes the form of fins, wings, stabilizers, etc., that can be represented as flat plates. It has been shown by experiments that the scattering can be controlled by shaping such structures. Since there are examples in the literature of unexplained high scattering from such structures, it becomes important to study such structures quite carefully. A dissertation entitled "UTD Analysis of Electromagnetic Scattering by Flat Plate Structures" by F. Sikta [1] has been completed on this subject. It makes use of the corner diffraction coefficient, the equivalent currents and a novel edge wave analysis based on corner diffraction to treat a variety of plate structures. This includes the development of a solution which predicts the non-principal plane scattered field. This has not been considered by any realistic approach in the past. This analysis not only predicts scattering from such plates, but it should be useful to the designer in two ways: 1) in fixing the shape of the fin, and 2) in establishing the parameters and position of absorber required to reduce the scattered fields.

### **c. External Scattering from Jet Intakes**

The external scattering from the jet intake region for many missile geometries involves two major mechanisms; first, the direct scatter from the jet intake rim, and second, the multiple scatter from the surface (using geometrical optics) to the rim. The ogive shape has again been used as a base and a circular jet intake rim has been mounted on the

surface. Results show excellent agreement between measured and computed RCS for this case. This work is discussed in detail in a Ph.D. dissertation by Volakis [2]. It is observed that many of these tools are also useful for the analysis of the scattering from externally mounted stores.

#### d. Reflection from Edge Like Structures

A study of the reflection from 2-D geometries that resemble wing profiles was undertaken since agreement between theory and experiment revealed that the theory generally predicted a value in the side lobe region that was low compared to measurement. This study was designed to evaluate the scattering as a function of frequency from the low frequency region where the leading edge could be represented as a half plane to higher frequencies where the reflection from the leading edge could be predicted via geometrical optics. This transition region study failed to give the expected increase in the scattered field, because the missing term was associated with the edge waves discussed in a previous section. A dissertation by Dominek [3] has been completed giving this and other results to be discussed in the next few paragraphs.

This study used as canonical targets 1) circular cylinders, 2) parabolic cylinders and 3) elliptical cylinders. The data for the first and last target (1 and 3) was corrupted by the presence of a creeping wave which had to be separated from the specular scatter via transient or time domain techniques. The second case (2) provided an

exact solution for the specular scatter mechanism from the parabolic cylinder.

A model for the specular scatter was developed by Dominek that included not only the radius of curvature at the specular point but also the distance to the shadow boundary. This model provides a reasonable means of treating the transition region mentioned above.

This thorough study has shown that the scattering from the leading edge of the wing profile was definitely not the source of the discrepancy between theory and experiment for complex targets. This has since been clearly demonstrated to be due to edge waves.

## 2. RCS Computer Codes

We proposed at the onset of this effort to develop a general purpose RCS computer code; however, the low observable security guidelines did not permit us to do so. Thus, we had to abandon this area until recently. The security guidelines have been modified during 1985 which allows us to develop such codes but not operate them for classified targets.

### a. Aerodynamic/EM Interface

Careful examination of the various existing computer programs to represent body shape have been disappointing to a certain extent. The PANAIR program did not appear to be adequate, Rockwell's CDS system is company proprietary and at one time we were approached by a Northrop Engineer who had suggested their computer program for target shape may

be available; however, this did not occur. On the other hand, as stated earlier, NASA engineers had been examining our need and focusing their attention on the development of a suitable computer program to describe a general target shape. There were many discussions between NASA and OSU personnel to accurately pinpoint the needed parameters.

We have undertaken a joint effort with NASA (Langley, Virginia) to develop a general analysis for the scattering properties of complex aerodynamic shapes. Ray Barger [4] with the NASA aerodynamics group is basically putting the code together around their new aerodynamic geometry package. This geometry package is very significant in that it is designed to accommodate both the aerodynamic and electromagnetic features necessary for an accurate and efficient analysis. Our attention has been focused on the study of the limitation it may possess particularly in the region of forward scatter. This is essential when multiple scattering/diffraction occurs. This study has made use of an ogive although it is not restricted to this shape.

#### **b. Flat Plate Scattering Code**

In terms of shaping, it has been established that flat plate scattering is caused by various discontinuities such as an edge, corner, etc. If one curves the plate, some of the corners are now replaced by discontinuities in the radius of curvature. A study of these mechanisms is now complete. It makes use of the concepts of the UTD as applied to this new geometry. A dissertation on this topic by Chu [5] considers additional thin plate discontinuities and extends the analysis

to treat the diffraction from a smooth junction formed by two curved edges with different radii of curvature. A general computer program has been developed and delivered to NASA for such plates. Chu also considers the smooth junction formed by surfaces of different radii of curvature and has also developed diffraction coefficients for this type of discontinuity.

#### **c. Scattering Analysis and Codes**

The scattering analyses/codes have been extended in two general ways. First, the electromagnetic scattering techniques discussed by Volakis have been made much more general by using the geometry codes developed by Barger of NASA. In a Master's thesis, Campbell [6] has evaluated the scattered fields from obstacles placed on surfaces described by Barger's geometry code.

A new technique, designated as an envelope analysis, has been developed that should prove very useful to aerodynamicists in that it allows them to quickly estimate the scattered fields from a shape under consideration. A thesis by Pistorius [7] has been completed showing a number of examples, and this effort is continuing.

#### **d. Low Frequency Scattering Code**

A moment method code has been developed by Newman [8] and delivered to NASA which treats general shapes that are no larger than about ten square wavelengths. This code uses flat plate segments to simulate the structure. It is useful to treating objects whose overall length is not

more than a few wavelengths. For a missile, it could be useful up to about 100 MHz; whereas for a fighter aircraft, it could be used to about 20 MHz. It has been verified by measurements taken in our compact range.

### 3. Indoor Scattering Measurement Systems

It was very apparent at the onset of this grant that state-of-the-art measurements were needed in order to verify our theoretical solutions as well as identify new mechanisms. As a result, various indoor measurement facilities were evaluated to see their advantages and disadvantages. The compact range was most useful because it could handle large targets at high frequencies. Even though compact ranges were available in the early 1980's, they did not provide the performance needed for our sensitive measurements.

Nevertheless, our analysis showed that the various features limiting the compact range could be improved. Thus, a major effort with NASA to develop such systems was initiated. This required us to develop new feeds, reflectors, measurement hardware and target mounts. This, in conjunction with the improved compact range reflector, will make the facilities at NASA and OSU the best scattering ranges in the world. In this regard, we visited the major facilities in Great Britain a few years ago in order to evaluate our system versus theirs, and we can report they had no comparable facilities.

a. Measurement Hardware

Originally, a standard CW nulling system was used for our measurements. This type of system is not very appropriate for compact range applications in that the horn-horn and horn-reflector-horn clutter terms are much larger than the target return. Two systems were proposed to solve this problem: 1) a pulsed/CW radar and 2) a linear FM system. It was decided that OSU would evaluate the pulsed/CW system and NASA the linear FM one. As a result of our effort, a 6-18 GHz pulsed radar was designed, constructed and evaluated. It very successfully eliminated the horn-horn and horn-reflector clutter terms. In addition, it uses off-the-shelf components and is capable of measuring an 8 foot target.

More recently, our effort has concentrated on the development of pulsed/CW radar systems for compact range applications. Our 2-18 GHz system has been designed, constructed, and tested and found to be very reliable, efficient, and accurate. A prototype Ka-band pulsed/CW radar using Ka-band components has been designed which is useful for frequencies between 30 and 35 GHz. After analyzing this system, it was found that it can be improved by using a minimum of Ka-band components. Using this approach the transmit pulse is generated using our 2-18 transmit box which is then sent to a frequency doubler to generate the Ka-band signal. The receive signal goes directly to a mixer which converts the Ka-band return to an IF frequency. The receive switches are then added to the IF receive system. Using this approach one could hopefully measure an 8 foot target with better than a 60 dB below a square meter background.

### **b. Target Mounts**

A complete low cross-section target pedestal was designed and built at OSU and delivered to NASA. In addition, a complete system controller was developed, delivered, and evaluated at NASA by OSU personnel. This complete system is a duplicate of the one presently operating at OSU.

In order to measure conical patterns, a new target mount extension has been designed which will be attached directly to the target. It will be able to hold several hundred pounds and handle a hundred foot-pounds of torque at various elevation angles (0°, 10°, 20°, 30°, and 40°). Using this mount, NASA will be able to obtain conical patterns about the rotated axis.

### **c. Compact Range Reflector Development**

Most of our effort has been devoted to the improvement of the compact range facilities at both NASA and OSU. The OSU designed edges have been installed on the NASA reflector, and field probing has indicated that these edges are performing as desired. A second set of curved surfaces constructed by NASA have also been placed on OSU's reflector. Even greater benefits are to be obtained in the future in that a blended surface has been designed that will make it practical to operate the compact range reflector at lower frequencies and for even larger targets.

These modified compact range reflector systems have attracted favorable nationwide attention from both government and industry. In particular, it has attracted the attention of several industrial

organizations who are installing such a system as well as the manufacturer of the original reflector. For example, Scientific-Atlanta has redesigned their reflector and contributed a larger version of said reflector to OSU.

In order to properly feed the new blended surface reflector, a subreflector system has been designed for compact range applications. In the process of designing this subreflector, it was found that one can correct the polarization problem associated with most off-set reflectors. This is done by tilting the subreflector axis relative to the main reflector axis. The tilt is rather small and in the off-set plane. This allows one to feed the main reflector properly to generate a uniform field in the target zone with excellent polarization purity.

The main reflector is still being designed in order to optimize its blended surface termination as well as the junction contour between the reflector and blended surface. It has been shown that this junction's diffracted field is dependent on the junction contour. Thus, an analysis to generate an optimum shape for this contour has been initiated as will be described later.

#### **d. Feed Designs**

The blended surface design for the compact range reflector allows one to measure much larger targets. However, one can't take advantage of this target size unless he is able to feed the reflector properly. Heedy [9] has designed an aperture-matched horn which is useful for this application; however, it is larger than desired and not as frequency

frequency agile as needed. As a result, other feed designs as well as subreflector approaches are being examined.

#### **e. Absorber Scattering Study**

A general study of absorber scattering has been initiated. This research effort involves both an analytic and measurement aspect in order to understand the scattering performance of commercially available pyramid and wedge absorbers. The analysis is based on a UTD corner diffraction solution which is modified to treat material structures. The major aspect of this analytic study is associated with the tip scattering. As this analysis was compared with measurements, it was ascertained that the absorber scatters incoherently; in which case, all the absorber contributes to the clutter throughout the room. Since the wall does not scatter coherently, one can't use a ray trace solution to design the anechoic chamber. Finally, the analysis and measurements by DeWitt [10] show that wedge material is clearly superior near grazing; whereas, the pyramidal material works better near broadside.

#### **4. Control of RCS**

The introduction of the traditional missile fins caused the scattered fields to increase substantially. Based on GTD scattering mechanisms and aerodynamic concepts supplied by C. Jackson of NASA, the fin shape was redesigned to lower its contribution to nearly that of the basic missile fuselage.

An oversized version was placed on the model, and the experiments verified our contention that a substantial reduction can be achieved by properly shaping the fins. This fin shape has been examined at NASA from an aerodynamic viewpoint and appears to have slightly better performance as compared with previous designs.

Based on experimental results, the major source of the scattered fields of the basic missile is from the rear of the fuselage. As a result, it was proposed that the rear be tilted to reduce this contribution which could also be used to good advantage from an aerodynamic viewpoint as well.

The jet intake is another major source of scattered fields. For the present model, it is shielded by the missile body from the radar over a wide range of aspects looking from below the missile. The success of this shielding has been demonstrated by experiment. It has been proposed that this region could be extended by tilting the normal to the inlet upward from the axis of symmetry.

##### 5. Waveform Processing Techniques

In the course of studying the reflection from the leading edge of a wing, the time domain techniques have been further developed by Dominek. These techniques generally required accumulation of data over a wide range of frequencies. This data is then transformed to the time domain, producing a series of scattered waveforms from each scattering mechanism. Unfortunately, when the portion of the spectrum of interest is that where the dimensions of the body are small in terms of

wavelength, these transient signals tend to overlap. Thus various types of windowing were introduced to obtain the desired separation. These techniques have proven useful in the evaluation and control of scattered fields.

This study has also produced some additional results for creeping waves. The importance of creeping waves arises in low level radar cross section (RCS) bodies since they can be scattered back by structures shadowed by the main body. A smooth, elongated missile-like body was made with several removable inlets to investigate, by measurement, the influence of a shadowed inlet in regions of low RCS. The measurements indicated a definite low level creeping wave interaction with the inlets. However, the level was near our lower measuring capability limit. This limit is being substantially reduced at the present time for future measurements. At the same time, a computer code was developed to calculate these creeping wave interactions based on GTD [11] and incorporating numerical techniques developed at NASA [4]. The accuracy of these calculations is dependent upon how well the GTD creeping wave formulation models surface diffraction mechanisms. It is well known that the formulation is very accurate for circular and spherical surfaces but very little study has been done on elongated surfaces. There has been an effort to compare the GTD creeping wave formulation to the true creeping wave values for spheroids and ellipsoids by extracting the creeping portion from the total scattered field of these two surfaces. There is as yet no valid asymptotic

solution for low frequencies in terms of the creeping wave format for elongated bodies; i.e., pariaxial diffraction occurs.

It is desired to remeasure the shadowed inlet RCS contribution in the improved anechoic chamber to have very reliable measurements and to finish the creeping wave comparison to establish the accuracy of the GTD formulation for elongated surfaces.

The time domain extraction technique discussed earlier is one of many possible techniques to obtain the frequency characteristics (RCS) of a particular scattering mechanism by a "filtering" process from the total scattered field of a body. Other filtering techniques are also possible such as one developed by Ksienski [12]. Ksienski's approach has been generalized and is actually similar to filtering techniques used in time series analysis and geophysical seismograph research. The literature has been reviewed in these other areas to find other applicable filter techniques that could prove useful in scattering problems.

Another area where time series analysis and geophysical seismograph research can provide useful results is in high resolution time domain techniques. The time domain resolution capability of scattering centers is proportional to the frequency bandwidth. These other disciplines have generated techniques to "sharpen" the scattering center response that simulates the effect of having more bandwidth.

## **6. Material Study**

The use of materials has proven to be quite rewarding. Both anisotropic composite materials and absorbers have been used to eliminate the edge wave that is generated at a discontinuity such as corner, propagates along an edge and diffracts from a second discontinuity. This has proven to be a very significant scattering mechanism for both aircraft and missiles, particularly the supersonic vehicles with their sharp edges. This mechanism must be eliminated if the current analysis (and treatment) of leading and trailing edges is to be valid. A report has been written describing this result [13].

The rim for jet intakes has been shown to be a primary scattering source. Means of controlling this rim via the anisotropic material approach has been considered. A series of measurements have been made for open ended cylinders composed of such materials to obtain a basic data base. The results of these measurements have been interpreted. The use of these materials has proven to be a diagnostic tool in that diffraction/scattering from a given portion of a structure can be modified by its presence.

## **7. Design and Evaluation of Standard Targets**

A number of standard targets have been developed, constructed and tested by NASA and OSU. One, an "almond" shape, is a very low echo area object and has been used to study perturbations including small intakes. This same scatterer is of interest to DoD and industry as a test shape. The second test body called the "peanut," was used to study multiple

scattering. A third structure, the generic inlet has been compared very favorably with computations using a hybrid solution.

Canonical shaped bodies like the ogive and sphere-capped cylinder have been pursued as targets to evaluate a measurement facility. An effort is presently underway to efficiently generate the calculated scattered field from these bodies when they are electrically large to obtain an absolute reference of what a range should measure.

The "almond", has proven to be a very desirable support body in terms of its scattering characteristic. The almond allows a very large angular sector where the scattered field is very low. This feature allows the direct measurement of a subcomponent on the surface of the body without having the measurement corrupted by scattering arising from the support body. Effort is presently underway to rigidly support the almond on a low cross section column for measurements. Also, an effort is presently underway to evaluate other variations of the almond that provide a flat surface which would be very desirable for subcomponent mounting.

Another area of interest in terms of models has been the evaluation and testing of conductive paints. The present standard has been a silver based paint to provide the conductivity. It would be desirable to use a lower cost paint such as a copper based paint. A unique approach to test the various paints has emerged and is presently underway. It involves using the results of the inlet studies to predict the return for a perfectly conducting inlet which will be

compared to inlets that will have their interiors coated with the various conductive paints.

#### 8. Aircraft Blockage of Ground-Satellite Link

The potential for an aircraft to fly directly through a ground station-to-satellite link becomes more significant if the link is located closer to an airport, obviously. Because this situation is much more likely near airports, it is appropriate to examine the effects of such an encounter.

There were two aspects to this study: 1) an aperture blockage theoretical solution developed by Rudduck and Lee [14] was used to calculate the effect of a large aircraft (C5) for various satellite ground station antenna diameters, and 2) the compact range facility at OSU was used to measure the blockage of various targets, including a 737 aircraft, and to validate the theoretical solution of item 1).

The measurements verified the theoretical analysis in that the blockage results from the obstruction of the line-of-sight signal. In all cases if a large aircraft flew directly through a ground station-satellite link, there can be a drop in the system gain. What effect this has on the system is dependent on the system under consideration. However, as shown in Ref. [15], if the aircraft is in the near field of the ground station, the gain loss is substantial, and one would assume that the link would be lost during the time period that the aircraft blocks the line-of-sight signal.

## 9. Inlet Internal Scattering Analysis

A hybrid technique was used to analyze the general rectangular inlet structure. The agreement of this solution's results with experimental ones was excellent. In addition, it was studied further to determine how much of the complexity of the internal fields needs to be retained in order to obtain good results. It was surprising to learn that only three waveguide modes dictated by the angle of incidence were required to generate accurate results even when the rectangular cross section is relatively large in terms of the wavelength. Furthermore, this hybrid technique, which involves a combination of high frequency (HF), modal and multiple scattering methods, has been developed to deal with a variety of inlet shapes which can be approximated by joining together piecewise linearly tapered and/or circularly bent sections of waveguides for which the modes can be determined. This hybrid technique basically involves expressing the modes in terms of an equivalent set of modal rays and then finding the elements of the junction scattering matrices in a relatively simple manner, via HF techniques, to characterize the junction discontinuities. The interactions between junctions (discontinuities) is accounted for by the self consistent multiple scattering method to arrive at the total field scattered by the inlet model. This work is summarized in Ref. [16].

A second much simpler ray optics model was also studied by Burkholder [17]. It was found that good results are obtainable even from this simple geometry. This is especially true for internal structures that are very large electrically.

In both cases, the analytic results were compared with measured results obtained using the compact range system. The inlet models were supplied by NASA.

## 10. Antenna Studies

### a. Array Scan Impedance

The study of scattering by antenna arrays is continuing. The general property of the array that needs to be evaluated and controlled is the array scan impedance. It is very important that this scan impedance be made as independent of scan angle as possible. To this end our original studies involved techniques for controlling the impedance of an array of "V" dipoles over a conducting plane. A reasonably constant scan impedance has been obtained for such an array. However, when the feed lines were inserted, these desirable results were seriously perturbed.

### b. Microstrip Scattering

In this section the current and future work on the method of moments (MM) analysis of the radiation and scattering from microstrip antennas and arrays is described. A microstrip antenna is a metal patch printed on an electrically thin grounded dielectric substrate. The main purpose of our effort is to develop an accurate and computationally efficient model for the radar cross section (RCS) of a rectangular microstrip antenna over a very broad frequency range. The RCS of the

microstrip antenna is an important problem since its scattering can be dominant when mounted on a low RCS structure.

Our past work [18-23] (and that of others) on microstrip antennas has mostly dealt with the radiation problem. In this case, we were interested in the transmitting properties over a frequency range within a few percent of first resonance. We are now interested in the scattering properties over a frequency range of several octaves. A result of this is that the current distribution on the microstrip patch is very complicated, as compared to the relatively simple current distribution on a transmitting microstrip near the first resonance. Thus, we must use many terms,  $N$ , in our MM expansion of the microstrip current. This presents a problem, since the CPU normally increases as  $N^2$  in a MM solution.

We have done two main things to obtain an efficient MM solution with reasonable CPU times. First, we have formulated the solution so that the reasonable CPU time is proportional to  $N$  rather than  $N^2$ . This minimizes the CPU time to compute the RCS at a single frequency; however, a second problem remains. The microstrip antenna is a highly resonant device. A plot of RCS versus frequency would consist of a series of large, but narrow peaks. In order not to miss one of these peaks, we must take small steps in frequency. Consider the computation of the RCS of a microstrip antenna from 1 to 10 GHz. If we take frequency steps of say 10 MHz, then this would result in 1000 evaluations of the MM computations, and the total CPU time would be prohibitive. To alleviate this problem we have developed a technique of

interpolating the MM impedance matrix. In the above example, we might compute the MM impedance matrix every 500 MHz, resulting in a factor of 50 decrease in CPU time. The impedance matrix at an intermediate frequency works because the elements in the impedance matrix are a much more slowly varying function of frequency than the scattered field.

At present, we have developed a computer code capable of computing the RCS of a rectangular microstrip patch over a broad frequency range. We are in the process of obtaining measurements to verify the accuracy of the code.

The present code does not consider the microstrip feed. For the antenna problem, one can use an extremely simple model for the feed, which assumes an extremely thin substrate. However, for the RCS problem we can not assume a thin substrate, since the frequency of the incident wave might be much greater than the frequency of the first resonance of the patch. Thus, our efforts have been directed toward developing a suitable model for a microstrip feed. This model will enforce continuity of current at the feed line to microstrip patch junction, and not be dependent on a thin substrate approximation. Basically, this will be done by taking our past work on wire to plate junctions [24-27] and modifying it for the microstrip antenna.

## C. PRESENT PROGRAM ACHIEVEMENTS

### 1. Indoor Scattering Measurement System

#### a. Compact Range Reflector Development

This section represents a major portion of our effort based on the interest directed by NASA (Langley). The compact range has become a very hot topic because it can provide very accurate results if it is designed properly. Thus, it has been our objective to examine the errors associated with the reflector system and correct them whenever possible. In terms of the reflector, the edge diffractions are the major source of ripple errors. So a major effort has been directed toward the reduction of these errors.

In order to accomplish this task, we have already developed a numerical technique to compute the diffraction from blended surfaces. The technique is based on the corrected PO solution [28]. Using this novel approach the total scattered fields in the near zone of the reflector are computed. One can then subtract the specular reflection term from the total scattered fields to obtain the diffracted fields. Using this numerical technique a computer code to analyze semi-circular compact range reflector has been developed by Gupta and Burnside [29] and delivered to NASA (Langley). The code can be used to compute the total near field of the reflector or its individual components (specular reflection, aperture blockage scattered fields and feed spillover) at a given distance from the center of the paraboloid. The code computes the fields along a radial, horizontal, vertical or axial cut at that

distance. Thus, it is very effective in computing the size of the "sweet spot" for such reflectors.

The computer code, as mentioned above, can treat only semi-circular reflectors. The technique, however, is applicable to arbitrary edge paraboloid reflector. For arbitrary edge reflector, the technique becomes numerically inefficient in that computation time to carry out the PO integration way become a limiting factor. Other methods to compute diffracted fields from the blended surfaces therefore need to be developed.

This code allows us to evaluate the presently-available Scientific-Atlanta reflectors and has shown that improvements are needed. Specifically, the edge contour of the parabola must be changed as shown by Pistorius [30], and the aperture blockage by the feed antenna reduced, the taper must be improved and the cross-polarization errors removed. As shown by analysis [30], these errors can all be reduced by using a dual chamber concept which utilizes a Gregorian subreflector located in a second small anechoic room. A small opening is then cut between the two chambers, so that the subreflector fields can fully illuminate the main reflector. This system is presently being constructed at NASA (Langley) and will be tested at OSU this coming summer.

#### **b. Measurement Hardware**

A new very wide frequency band pulsed/IF radar system was designed, constructed and tested during this research period. It is distinct from

our previous system because the receive line switches have been moved from the RF side of the receive mixer to the IF side. This allows us to reduce the amount of RF hardware and still maintain excellent performance. Our sensitivity has improved by about 10 dB; in addition, our 5ns wide receive pulse has allowed us to remove more room clutter which makes the system more stable. With our present room arrangement, our background after computer subtraction is about 70 dB below a square meter. With processing this can be improved by at least another 20 dB.

Using this new IF receive line, the Ka-band system has been greatly reduced in complexity and cost. In addition, its performance has improved in terms of clutter and background levels achievable.

#### **c. Target Mounts**

The studies of absorber scattering have been useful in target mount designs. A target mount extension (designed at ESL) for the ogival pedestal, which directly attaches to the target, required treatment to reduce the mount scattering. A shroud was built to fulfill the need. The shroud consisted of commercially available layered absorber panel that was properly cut to form a wedge transition between the mount and free space.

Another mounting scheme has also been finalized. This entails the positioning and mounting of targets that require rigid metal mounts for stability. The mount concept is universal in the sense that the same hardware can be used for a variety of targets without having to have a unique mount for each target.

As shown by Lai [31], the metal ogive pedestal has too large a backscatter at lower frequencies. In addition, its bistatic scattering is not insignificant especially for scattering centers located off of the pedestal. To reduce the RCS of the pedestal, a treatment study will be initiated. On the other hand to reduce the bistatic scattering, one must consider other mounting techniques.

#### **d. Absorber Scattering Study**

Based on the analysis of DeWitt [10], the absorber scattering properties are dictated by the homogeneity of the material. Attempts were made to get better material from absorber manufactures, but they don't seem to have the quality control necessary to improve the situation. They claim that their thin flat material is as homogeneous as they can possibly achieve with their present manufacturing techniques.

With this input, an absorber study was initiated to examine this flat material. It does appear to be more homogeneous, but flat material has too large a reflection coefficient. Thus, various layered wedge absorber designs have been examined using this material. A 10 dB improvement has been achieved using this approach, but more refinement is needed.

#### **e. OSU/ESL Compact Range Improvements**

The anechoic chamber for the compact range has been drastically improved. The improvements entailed the refinishing of the reflector

surface to provide a smooth rolled edge transition, a complete new absorber treatment of the walls, floors and ceiling, a raised floor to accommodate the ogival pedestal base and the installation of an overhead, remote controlled bridge crane to facilitate target mounting. An oral paper will be submitted for presentation at the 1987 Antennas Measurements Techniques Association Symposium in Seattle, Washington concerning these improvements.

**f. Recent Indoor Scattering Measurement Publications**

1. W.D. Burnside, A.K. Dominek, M.C. Gilreath and R. Barger, "Blended Surface Concept for a Compact Range Reflector", Low Observables Symposium Digest, June, 1986.

The compact range has been used for many years to measure directive antenna patterns. More recently, however, there has been increasing interest to use the compact range for scattering measurements. In order to provide the proper field illumination for such measurements, the traditional designs must be improved in terms of the stray signals coming from the reflector termination. One attempt to improve the field quality in the measurement zone was to use a rolled edge structure added to the basic parabolic reflector. This improved system performance but required excessively large structures to meet the system requirements. Thus, a novel blended surface was developed which satisfies the measurement requirement without adding large structures. This new design can provide ripple levels no larger than 1/10th of a dB across the target zone as will be shown in the oral presentation.

2. W.D. Burnside and L. Peters, Jr., "Target Illumination Requirements for Low RCS Target Measurements", Low Observables Symposium Digest, June, 1986.

There has been renewed interesting RCS measurements recently especially for the evaluation of low backscatter targets. In order to accurately measure such targets, one needs to evaluate the system performance for such applications. One such performance check is the field quality measured within the target test volume. The question is then asked, "What is a satisfactory amplitude and phase requirement?" The normal 1 dB amplitude specification is not satisfactory because it doesn't indicate whether the error is due to a field taper or ripple. Taper indicates a uniform phase but variable amplitude; while, ripple indicates the presence of a stray signal. This paper indicates why one should require less than a 1/10th dB ripple error for low RCS target measurements; whereas, a dB taper is satisfactory.

3. W.D. Burnside, "Monostatic and Bistatic Scattering by Metal Ogival Target Support", Low Observables Symposium Digest, June 1986.

A major problem associated with quality scattering measurements is the scattering characteristics of the support structure used to hold as well as rotate the target under test. Ideally, one needs to hold hundreds to thousands of pounds without disturbing the measurement of the target. It is obvious that one cannot achieve such an ideal goal; nevertheless, the need exists, and better solutions result from knowledge of the present approaches. The major support mount used today appears to be a metal conical ogive tilted at an angle with respect to the incident plane wave. The backscattered field from such a structure is rather small considering its size; however, its bistatic scattering is quite large. This bistatic scattering implies that the target/mount interaction terms can be rather large to the extent that the measured result is corrupted by this error. These observations will be presented in terms of both theoretical and experimental results.

4. B.T. DeWitt and W.D. Burnside, "Electromagnetic Scattering by Pyramidal and Wedge Absorber," Low Observables Symposium Digest, June 1986.

The design of a modern anechoic chamber is very much dependent on the scattering of the absorber used to line the walls. Many chamber designs are based on specular scattering models for the absorber which do not appear to be valid based on our measurements. It appears that the pyramidal absorber scatters more as a random rough surface which leads one to a completely different chamber design and arrangement of absorber. This is especially true for radar cross section (RCS) measurements in that pyramidal absorber can backscatter a very large signal near grazing incidence. The wedge material is far superior for grazing incidence, which implies that it can be very useful for RCS chamber designs.

5. W.D. Burnside, R.C. Rudduck, I.J. Gupta and J. Clerici, "Electromagnetic Performance Study of Scientific-Atlanta's New Compact Range," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

In this paper a theoretical study is reported of the electromagnetic performance of the new Scientific-Atlanta compact range reflector system. The reflector consists of a 15-foot semi-circular parabolic reflector with a 5-foot blended rolled edge added to the circular section and skirt mounted on the base. The performance of this system is examined in terms of its probed near field data at the center (36-feet) and back end (50-feet) of the target zone. The calculated results are for the three-dimensional reflector and include the skirt and blended rolled edge diffracted field as well as the aperture blockage scattering caused by the feed and associated feed/mount structure. The potential target zone size based on these parameters is presented as a function of frequency and desired ripple level requirement.

6. C.W.I. Pistorius and W.D. Burnside, "A Concave Edged Reflector with Blended Rolled Surface Terminations for Compact Range Applications," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

A compact range is a facility used for the measurement of antenna and target scattering parameters. It offers many advantages over other types of ranges, and consequently a lot of effort is being directed towards the improvement of compact range performance. This discussion focuses on the reduction of diffracted fields from the termination of the parabolic main reflector.

7. W.D. Burnside, P. Bohley and D. Jones, "A Broadband, Inexpensive, Ka-band Pulsed Radar System," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

There has been much interest recently in Ka-band scattering measurements. Although Ka-band components are steadily improving, one is presently limited to narrow bandwidths (2 GHz) for higher power (more than 100 milliwatts) applications. If the whole waveguide bandwidth were useable, one could scan the target in frequency, transform to the time domain and simulate a very narrow pulse illuminating the target. With such a system, one could identify scattering centers separated by just an inch or so.

8. A. Lai and W.D. Burnside, "Monostatic and Bistatic Scattering by Metal Ogival Target Support," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

The ogival target-support pedestal is claimed to have a low radar cross section (RCS); yet, it can handle very large and heavy structures. This paper attempts to find out whether this claim is true through analysis as well as measurements. The pedestal backscatter is just one aspect of this study. Another more serious issue is associated

with the bistatic scattering by the pedestal which influences the target illumination.

The pedestal is formed by fitting two conical pieces of metal together to make an ogive which is smaller at the top than the bottom. The whole pedestal is tilted forward to reduce the amount of scattering to the radar. The backscattered field from the support as well as the bistatic scattering around it are analyzed and verified by experimental results.

9. C.W.I. Pistorius, "New Main Reflector, Subreflector and Dual Chamber Concepts for Compact Range Applications," Ph.D. dissertation, The Ohio State University, December 1986.

This study proposes several design improvements that can be made to the antenna system of a compact range to enhance the system performance; viz.,

1. Shaping the edge contour of the parabolic main reflector.
2. Adding blended rolled surfaces to the edges of the parabolic main reflector.
3. A dual chamber configuration in which the main reflector and target zone are contained in one chamber and the feed assembly together with a Gregorian subreflector in the other. This study is mainly concerned with the absorber fence separating the two chambers.

The first two suggested improvements are aimed at reducing the diffracted fields from the main reflector. These diffracted fields interfere with the plane wave and degrade system performance in that they create a ripple in the reflected plane wave. A dual chamber configuration has several advantages. The use of a tilted Gregorian subreflector reduces the amplitude taper in the reflected field considerably, and virtually eliminates the cross-polarization errors. Since the main reflector and target zone are isolated from the feed assembly and subreflector by the absorber fence, minimal scattering from the subreflector or spillover from the feed illuminate the main reflector or target zone. The suggested design improvements will thus enable one to design a compact range with very small amplitude taper, ripple and cross-polarization errors in the illumination of the target zone.

10. I.J. Gupta and W.D. Burnside, "User Manual for Semi-Circular Compact Range Reflector Code," Technical Report 716148-18, generated under Contract NSG 1613 for NASA/Langley Research Center, January 1987.

A computer code has been developed at The Ohio State University ElectroScience Laboratory to analyze a semi-circular paraboloidal reflector with or without a rolled edge at the top and a skirt at the bottom. The code can be used to compute the total near field of the reflector or its individual components at a given distance from the center of the paraboloid.

The code computes the fields along a radial, horizontal, vertical or axial cut at that distance. Thus, it is very effective in computing the size of the "sweet spot" for a semi-circular compact range reflector. This report describes the operation of the code. Various input and output statements are explained. Some results obtained using the computer code are presented to illustrate the code's capability as well as being samples of input/output sets.

11. W.D. Burnside, M.C. Gilreath, B.M. Kent and G.L. Clerici, "Curved Edge Modification of Compact Range Reflector," IEEE/AP-S Transactions, Vol. AP-35, No. 2, February 1987.

For many years, the compact range has successfully been used to design and evaluate many electromagnetic radiation and scattering systems. However, it has had limited use for large structures because of the large discrepancy between the reflector and target zone sizes. The limitation results from the large edge diffracted signal which emanates from the termination of the reflector. Previous attempts to solve this problem have involved using serrated edges to diffuse the diffracted field. While this reduces the edge diffracted field in the target zone, it is not eliminated. In addition, one has introduced many new corners which also diffract into the target zone. A curved edge modification is presented which reduces the edge diffraction by an order of magnitude or more and in the process does not create new mechanisms which perturb the plane wave in the target zone. Using this curved modification, one is able to design a compact

range reflector whose target zone cross section approaches the size of the reflector parabolic surface. This makes the compact range ideal for scale model measurements since larger targets (antennas) can be measured. It also makes it more practical to consider systems which can measure full scale vehicles.

12. D.N. Jones, "A Very Wide Frequency Band Pulsed/IF Radar System," Master's Thesis, The Ohio State University, March 1987.

A pulsed/IF radar for compact range radar cross section measurements has been developed which converts RF returns to a fixed IF, so that amplification and gating may be performed at one frequency. This permits the use of components which have optimal performance at this frequency which results in a corresponding improvement in performance. Sensitivity and dynamic range are calculated for this system and compared with our old radar, and the effect of pulse width on clutter level is also studied. Sensitivity and accuracy tests are included to verify the performance of the radar.

13. C.W.I. Pistorius and W.D. Burnside, "The Design of Blended Rolled Edges for Compact Range Main Reflectors," Fifth International IEE Conference on Antennas and Propagation, University of York, UK, March 30-April 2, 1987.

A compact range is a facility used for the measurement of antenna radiation and target scattering patterns. Normally, a compact range employs a parabolic main reflector to convert the spherical wave originating from a point source at the focus to a reflected plane wave for illumination of the target zone. However, the reflected field exists as a plane wave only over the surface of the parabola, and stops abruptly at the surface termination. Consequently, there are diffracted fields emanating from the terminating edges to make the total field smooth and continuous. These diffracted fields degrade the uniformity of the plane wave by interfering constructively and destructively with it, thereby causing unwanted amplitude and phase ripples. The elimination of the edge diffracted fields is thus a major consideration in the design of compact range main reflectors. In fact the usable area of

the target zone, relative to the size of the parabolic main reflector, is largely determined by the edge treatment of the main reflector.

## 2. Aircraft Blockage of Ground-Satellite Link Publications

W.D. Burnside, R.C. Rudduck, A.K. Dominek and T.H. Lee, "Simulation of an Aircraft Flying Through a Ground Station to Satellite Link," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

The potential for an aircraft to fly directly through a ground station-to-satellite link becomes more significant if the link is located closer to an airport, obviously. Because this situation is much more likely near airports, it is appropriate to examine the effects of such an encounter.

There are two aspects to the work reported here: (1) an aperture blockage theoretical solution developed by Rudduck and Lee was used to calculate the effect of a large aircraft (C5) for various satellite ground station antenna diameters, and (2) the compact range facility at The Ohio State University was used to measure various targets, including a 737 aircraft, and to validate the theoretical solution in item (1).

## 3. Material Study

A report has been issued summarizing the use of composite materials. A second report is in preparation that initiates an analytic study for the scattering from composite materials. Our work with W.T. Hodges in this area has proven to be very rewarding in that we have gained a much better physical insight into the structural features of composites. Work has been focussed on structures that are self supporting and will achieve the desired electromagnetics performance.

A study has also been initiated on the use of resistive sheets (R-cards) for RCS control. Actually the composite material might be regarded as an anisotropic R-card.

Often the concept of using highly directive (narrow beam) scatterers is invoked in RCS studies. A report which focuses attention on the requirements that must be met so that this is a valid technique has been written.

**a. Publications**

1. L. Peters, Jr., A.K. Dominek, R. Swann, W.T. Hodges and S. Wozniak, "Edge Wave Control Using Absorber on Composite Material," Report 716148-15, generated under Contract NSG 1613, July 1986.

"Classified Report"

2. E.H. Newman, R.J. Marhefka and L. Peters, Jr., "Scattering from Nearly Flat Surfaces or Nearly Straight Edges," Report 716148-17, generated under Contract NSG 1613, October 1986.

"Classified Report"

3. A.K. Dominek and L. Peters, Jr., "Use of Resistive Cards for RCS Control," to be written.

**4. Waveform Processing Techniques**

The general direction of this area of research is to improve the resolution and quality of data obtained using various processing

techniques. These studies have been directly applied to a number of real world situations and have shown some successes. This whole effort will continue in an attempt to develop new and more powerful tools to extract more information from measured data.

As a result of our studies, a new cross-range measurement algorithm has been developed for specific application to the compact range. Using this approach, the target is examined at a few look angles in one plane by simply moving the feed antenna. Since each feed position can be calibrated, the down range image plots from each look angle can be combined to create a cross-range scattering center location. More will be presented on this topic in the future.

#### a. Publications

1. A.K. Dominek, W.D. Burnside and L. Peters, Jr., "Mechanism Extraction," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

The total scattered field from a complex, electrically large target is comprised of several scattering mechanisms. Each individual scattering center has its unique scattering character as a function of target orientation and frequency. Hence it is desirable to isolate a scattering mechanism to acquire its dependencies. The extraction of a particular mechanism from other mechanisms can be done by knowing its spatial location. The spatial information is contained in the phase associated with each scattering mechanism. Thus, a 'filter' can be constructed to numerically extract the scattering properties of a particular scattering center by recognizing its spatial location. This can be done as a function of angle and frequency from calculations or measurements. The filter can be realized either as a data smoothing process using special mean square error methods or as a gating procedure in a transformed space of the variable of interest to

isolate a mechanism. Examples will be shown to demonstrate the properties as well as accuracies of both techniques.

#### 5. Design and Evaluation of Standard Targets

The evaluation of the almond test body has progressed to the point of routine use for subcomponent measurements. The almond version most commonly used is the 'flat' one which on side has a planar surface to facilitate subcomponent mounting. A flush, removable ogival plate which covers a cavity region has been incorporated on this flat portion.

The calculation of the scattering from an almond body is presently underway using a "March-in-Time" approach of Bennett's [32]. This calculation is being performed on a Cray computer located at Carnegie-Mellon University. Such calculations are useful for performance checks on measured results from anechoic chambers.

The evaluation and testing of conductive paints has been performed using rectangular inlets. This novel approach uses the properties of the cavity to ascertain the performance of conductive coatings. This information is valuable due to the cost saving of not using a silver based paint, especially for large models. An oral paper will be submitted for presentation at the 1987 Antennas Measurement Techniques Association Symposium in Seattle, Washington on this topic.

### a. Publications

1. A.K. Dominek, H.T. Shamansky, R. Wood and R. Barger, "A Useful Test Body," Antenna Measurement Techniques Association Symposium, Ottawa, Canada, September 23-25, 1986.

The advent of improved compact ranges has promoted the development of a test body, named the almond, to facilitate the measurement of scattered fields from surface mounted structures. A test body should at least have the following three features: (1) provide a very small return itself over a large angular sector, (2) provide an uncorrupted and uniform field in the vicinity of the mounted structure and (3) have the capability to be connected to a low cross-section mount. The almond satisfies the first two requirements by shaping a smooth surface which is continuous in curvature except at its tip. The name almond is derived from its surface similarity to the almond nut. The surface shaping provides an angular sector where there is no specular component. Hence, only low level tip and creeping wave scattering mechanisms are present resulting in a large angular quiet zone. The third requirement is accomplished by properly mounting the almond to a low cross-section ogival pedestal. The mount entails a metal column between the almond and the pedestal covered with shaped absorbing foam. These contoured pieces hide the column and form a blended transition from the almond to the pedestal and yet allow an unobstructed rotation of the almond. Backscatter pattern and swept frequency measurements performed in our compact range illustrate the scattering performance of the almond as a test body. The almond body alone has a backscatter level of  $-44$  dB/m<sup>2</sup> in its quiet zone. Comparisons of measured hemisphere backscattered returns on the almond are made with those calculated of a hemisphere over an infinite ground plane for both principal polarizations for a verification performance test.

## 6. Electromagnetic Scattering Analysis

### a. Physical Optics Correction

The physical optics (PO) solution has been known for many years to be an approximate solution. In fact, the physical theory of diffraction

(PTD) is an addition to PO which makes it more correct in terms of scattering from edge structures. The PTD has become accepted as a major analysis tool for scattering calculations in that it can be easily implemented. Nevertheless, both PO and PTD are still approximate results and as such have potential errors. One error is associated with the current abruptly stopping at the shadow boundary on a curved surface. This error has been examined and found to be quite serious for low observable targets. Thus, a general approach to solve such problems has been developed and published.

#### **b. Low Frequency Scattering Code**

Over the last few years the Electromagnetic Surface Patch (ESP) code has been delivered to and used by many engineers in industry, government and universities. These users had suggestions which were incorporated into the code. This year the number of changes became large enough that we felt that a revised version of the code and user's manual was warranted. The revised code (ESP Version III) and user's manual are now ready for distribution.

#### **c. Bistatic Scattering from a Cone Frustum**

Bistatic scattering has become of interest recently in that the scattering level is difficult to control for all bistatic angles. With this in mind, a research effort has been completed to study the bistatic scattering from conical shapes, the cone frustum being the target of interest here.

#### d. Inlet Scattering

An efficient hybrid procedure was developed, as mentioned in the previous annual report, for analyzing the electromagnetic scattering by a class of inlet shapes that can be modeled by joining together piecewise, linearly tapered, and/or circularly bent sections of waveguides for which the modes can be found analytically. This hybrid procedure begins by breaking up the modal fields in terms of an equivalent set of modal rays, and then using these modal rays in conjunction with asymptotic high frequency techniques (such as the geometrical and physical theories of diffraction) to find the elements of the generalized junction scattering matrices in a relatively simple form. These scattering matrices fully characterize the reflection and transmission properties of the junctions between different waveguide sections. The interaction between different waveguide sections (discontinuities) is readily accounted for by the self consistent multiple scattering method. When applying this approach to a general rectangular inlet cavity, it was also mentioned previous, that, a further simplification was achieved because only a set of three consecutive waveguide modes dictated by the angle of incidence were needed to get accurate estimates of the RCS for sufficiently large waveguides. During the present period, that selective modal scheme has been studied for other inlet waveguide shapes such as strongly linearly tapered as well as circular inlets. While it is found that more selective modes are required for the latter configurations than for the rectangular case analyzed previously, it is true that the selective

modes still form a far smaller set than the large number of all the propagating modes within the inlet waveguide. The work on the hybrid approach for analyzing the junction scattering matrices and the evaluation of the RCS of some inlets, as well as the selective modal scheme are described in a report and a few papers which are listed later in the section on recent publications.

Before proceeding to analyze the RCS of more inlet shapes, it appears appropriate at this time to consider alternative efficient approaches for analyzing inlets with smooth transitions and tapers which could also account for inlet wall treatments. Such a study of this complex problem is under way. The hybrid modal ray approach discussed earlier will become more difficult and cumbersome for arbitrarily shaped inlets and for treated inlet walls, as the modes are very difficult to find for the latter case. Nevertheless, the studies performed thus far on a class of perfectly-conducting inlet models (for which the interior modes can be found easily) provide a useful estimate of the upper bound for the inlet RCS values; the treated inlets would of course yield mostly lower RCS values.

#### **e. Publications**

1. I.J. Gupta and W.D. Burnside, "A Physical Optics Correction for Backscattering from Curved Surfaces," in IEEE Trans. on Antennas and Propagation, May 1987.

The conventional physical optics (PO) approximation used to calculate the scattered fields from a conducting body leads to incorrect scattered fields even in the specular reflection region. This is true even when all

other subdominant terms are assumed to be absent. The inaccuracy stems from the fact that the surface currents used in the PO approximation suddenly truncate at the shadow boundary of curved surfaces resulting in an erroneous contribution. Expressions for these shadow boundary (end point) contributions are presented in this paper. It is shown that if these end point contributions are subtracted from the conventional PO results, one obtains a better representation of the true scattered field. For illustration, backscattered fields from various conducting bodies are computed using the corrected PO solution and are compared with the exact scattered fields.

2. I.J. Gupta, C.W.I. Pistorius and W.D. Burnside, "An Efficient Method to Compute the End Point Contributions in PO Solution," submitted for publication in IEEE Trans. on Antennas and Propagation.

A method is given to compute the end point contributions in the physical optics solution for electromagnetic scattering from conducting bodies. the method is applicable to general 3-dimensional structures. The only information required to use the method is the radius of curvature of the body at the shadow boundary. Thus, the method is very efficient for numerical computations. As an illustration, the method is applied to several bodies of revolution to compute the end point contributions for backscattering in the case of axial incidence. It is shown that the end point contributions obtained using the method are asymptotic in a high frequency sense.

3. E.H. Newman and R.L. Dilsavor, "A User's Manual for the Electromagnetic Surface Patch Code: ESP Version III," Report 716148-19, prepared under Grant NSG 1613 between the National Aeronautics and Space Administration, Langley Research Center and The Ohio State University Research Foundation, May 1987.

This report serves as a user's manual for Version III of the 'Electromagnetic Surface Patch Code" or ESP code. ESP is a user-oriented code, based upon the method of moments (MM) for treating geometries consisting of an interconnection of thin wires and perfectly conducting polygonal plates. Wire/plate junctions must be about  $0.1\lambda$  or more from any plate edge. Several plates may intersect along a common edge. Excitation may be by either a delta-gap voltage generator or by a plane wave. The thin wires may have finite conductivity and also may contain lumped loads. The code computes most of the usual quantities of interest such as current distribution, input impedance, radiation efficiency, mutual coupling, far zone gain patterns (both polarizations and radar-cross-section (both/cross polarizations)).

4. Waturu Ebihara and R.J. Marhefka, "Bistatic Scattering from a Cone Frustum," Report 716148-16, prepared under Grant NSG 1613 between the National Aeronautics and Space Administration and The Ohio State University Research Foundation, August 1986.

The bistatic scattering from a perfectly conducting cone frustum is investigated using the Geometrical Theory of Diffraction (GTD). The first-order GTD edge-diffraction solution has been extended by correcting for its failure in the specular region off the curved surface and in the rim-caustic regions of the endcaps. The corrections are accomplished by the use of transition functions which are developed and introduced into the diffraction coefficients. Theoretical results are verified in the principal plane by comparison with the moment method solution and experimental measurements. The resulting solution for the scattered fields is accurate, easy to apply, and fast to compute.

5. "Electromagnetic Scattering from a Class of Open-Ended Waveguide Discontinuities," A. Altintas, P.H. Pathak and W.D. Burnside, Technical Report 716148-9, prepared by the Ohio State University ElectroScience Laboratory on Grant NSG 1613, for NASA/Langley Research Center, Hampton, Virginia 23665, March 1986. (This report has been prepared from the dissertation by A. Altintas which was submitted to OSU in partial fulfillment for the Ph.D. degree, 1986.)

A relatively simple high frequency analysis of electromagnetic scattering from a class of open-ended waveguide discontinuities has been developed. The waveguides are composed of perfectly-conducting sections in which the electromagnetic field can be written as a sum of waveguide modes. Junctions are formed at the open-end and also within interior regions where different sections are joined. The interior modal field is expressed in terms of an equivalent set of "modal rays." The reflection and transmission properties of each junction are described in terms of a scattering matrix which is determined by combining the modal ray picture with high frequency techniques such as the geometrical theory of diffraction (GTD), the equivalent current method (ECM), and modifications of the physical theory of diffraction (PTD). A new set of equivalent currents are employed in this ECM analysis which leads to a simple treatment of many types of junction discontinuities. Also, a new procedure is presented to improve the efficiency of the aperture integration at the open end which is required in the PTD procedure for finding the fields radiated from (or coupled into) the open end. Once the scattering matrices are determined via the aforementioned high frequency techniques, they are then combined using a self-consistent multiple scattering method to obtain the total scattered fields. The accuracy of the present approach has been verified by comparison with other available solutions and measurements wherever possible.

6. "A Selective Modal Scheme for the Analysis of EM Coupling into Or Radiation from Large Open-Ended Waveguides," A. Altintas, P.H. Pathak, and M.C. Liang, paper accepted for publication in the IEEE Transactions on Antennas and Propagation.

The problem of electromagnetic coupling into or radiation from open-ended waveguides is addressed here. Of particular interest is the high frequency range where a large number of propagating waveguide modes can be excited and conventional procedure requiring a summation over a large number of propagating modes can become cumbersome and inefficient. A selective modal scheme is proposed based on the observation that the modes which contribute most significantly to the fields coupled into the waveguide are those whose modal ray directions are most nearly parallel to the incident wave direction. This concept is illustrated by calculating the EM radiation and backscattering from open-ended parallel-plate, rectangular, circular and sectoral waveguide geometries. The calculations employ the usual geometrical optics, aperture field and Ufimtsev edge current techniques. Also included are some measured results which further verify the accuracy of the above computations.

7. "An Efficient High Frequency Analysis of Modal Reflection and Transmission Coefficients for a Class of Waveguide Discontinuities," by P.H. Pathak and A. Altintas, paper submitted to J. Radio Science.

A relatively simple and efficient high frequency analysis of electromagnetic modal reflection and transmission coefficients for waveguide discontinuities which are formed by joining different waveguide sections is presented. The analysis extends the concept of equivalent edge currents and utilizes it in conjunction with the reciprocity theorem to describe interior (waveguide) scattering effects. It is noted that the previous use of equivalent edge currents was mostly restricted to exterior scattering by edged bodies, and its application to deal with interior scattering was limited to those guide

geometries for which image theory could be used effectively to account for the interior wall effects. The present extension allows one to treat more generally two and three-dimensional geometries. In particular, expressions for two-dimensional reflection and transmission coefficients are developed and numerical results are shown for a flanged, semi-infinite parallel-plate waveguide, and for the junction between two linearly tapered waveguides. One sample result is also shown for the reflection coefficient of a three-dimensional open-ended circular waveguide. Detailed expressions for three-dimensional waveguide discontinuities are being reported separately.

## 7. Antenna Studies

When one examines the scattering from a microstrip antenna, the biggest concern is the frequency bandwidth over which the radar signal can scan the antenna. Most of the analyses associated with microstrip antennas has been for the radiation band of frequencies. This allowed researchers to develop solutions which were appropriate for that special case but not for others. As a result, considerable effort was spent developing an efficient, and thus practical, moment method solution for the microstrip antenna. This approach is valid for a wide range of frequencies and yet very efficient.

At present, a computer code capable of computing the RCS of a rectangular microstrip patch over a broad frequency range has been developed. The accuracy of the code has been verified by comparison with measured RCS results versus frequency.

The next step in this development is to treat the microstrip feed lines. These lines would represent possible lines to feed the microstrip in the normal antenna mode or may be used to control its scattering.

### **a. Publications**

1. E.H. Newman and F. Forrai, "Scattering from a Microstrip Patch,"  
IEEE Trans. Antennas and Propagation, Vol. AP-35, March 1987.

The purpose of this paper is to present a solution to the problem of plane wave scattering by a rectangular microstrip patch on a grounded dielectric substrate. The solution begins by formulating an electric field integral equation for the surface current density on the microstrip patch. The integral equation is solved using the method of moments. Computed data for the patch RCS is found to be in close agreement with measurements over a broad frequency range. The microstrip RCS versus frequency is shown to consist a number of large peaks.

### **8. Miscellaneous Measurements**

#### **a. Rough Surface**

A variety of measurements have been performed during this past year. One centers around the scattering from rough surfaces near grazing. Measurements of a plate with periodic sinusoidal variations were obtained and compared with simple theory. The peak to peak surface variations were .01 and .03 inches. The resonant behaviour of the scattered fields were readily apparent and agreed with the calculations for incident angles less than  $30^\circ$  from grazing.

#### **b. Resistive Cards**

Another series of measurements involve effectiveness of resistive cards on thick edges. Resistive cards are very useful for scattering reduction from thin edges but when the edge becomes thicker, the scattering phenomenon changes. The scattering reduction from an

elliptic edge was measured over a broad band of frequencies at several look angles for single and multiple resistive card configurations.

#### c. Contour Rim Inlets

The scattering reduction possible on shaping the rim of inlets was experimentally studied. Four different rim contours were tested: a straight circular rim, an outwardly expanding rim, an inwardly contracting rim and a rim contour that oscillated about a plane. It was found that no significant difference was observed among a series of pattern and swept frequency measurements. Conceptually, an oscillating rim would reduce the axial backscattered field if enough phase difference could be achieved.

#### d. Images

A new scheme to generate two-dimensional images of scattering centers has been developed. This technique entails the processing of downrange, bandlimited impulse responses from two look angles which are symmetrically offset a slight distance from the downrange symmetry axis of the compact range reflector. The returns from the two look angles are paired together and the downrange location of the scattering centers is the average downrange distance of each pair. The crossrange displacement of the scattering center is obtained from the relative downrange offset between the average downrange location and the individual returns. To determine whether the scattering center is located to the left or right of the downrange symmetry axis, the

measurement which precedes the average downrange location is used. This algorithm is well suited for reflection and diffraction mechanisms.

## REFERENCES

- [1] F.A. Sikta, "UTD Analysis of Electromagnetic Scattering by Flat Plate Structures," Report 711930-2, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Grant NSG 1613 for National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, December 1981.
- [2] J.L. Volakis, "Electromagnetic Scattering from Inlets and Plates Mounted on Arbitrary Smooth Surfaces," Report 711930-5, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Grant NSG 1613 for National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, August 1982.
- [3] A.K. Dominek, "A Uniform Electromagnetic Reflection Ansatz for Surfaces with Small Radii of Curvature," Ph.D. dissertation, The Ohio State University, Department of Electrical Engineering, 1984.
- [4] R.L. Barger, "A Procedure for Designing Forebodies with Constraints on Cross-Section Shape and Axial Area Distribution," NASA Technical Paper 1881, Langley Research Center, 1981.
- [5] T.T. Chu, "First Order Uniform Theory of Diffraction (UTD) Analysis of the Scattering by Smooth Surfaces," Final Report 711930-6, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Grant NSG 1613 for National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, April 1983.
- [6] R.H. Campbell, "Electromagnetic Backscatter from a Flat Plate in the Vicinity of a General Curved Surface," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1984.
- [7] C.W.I. Pistorius, "An Envelope Description of the Backscattered Power Patterns of Conducting Bodies," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1984.
- [8] E.H. Newman, P. Alexandropoulos and E.K. Walton, "Polygonal Plate Modeling of Realistic Structures," IEEE Transactions on Antennas and Propagation, Vol. AP-32, No. 7, July 1984.

- [9] D.J. Heedy, "An E-Plane Analysis of Aperture-Matched Horn Antennas Using the Moment Method and the Uniform Geometrical Theory of Diffraction," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1984.
- [10] B.T. DeWitt, "Analysis and Measurement of Electromagnetic Scattering by Pyramidal and Wedge Absorbers," Ph.D. dissertation, The Ohio State University, Department of Electrical Engineering, 1986.
- [11] P.H. Pathak, W.D. Burnside and R.J. Marhefka, "A Uniform GTD Analysis of the Diffraction of Electromagnetic Waves by a Smooth Convex Surface," IEEE Transactions on Antennas and Propagation, Vol. AP-28, pp. 631-642, September 1980.
- [12] A.A. Ksienski, "A Method of Resolving Data into Two Maximally Smooth Components," Proceedings of IEEE, Vol. 73, No. 1, January 1985.
- [13] L. Peters, Jr., R.T. Swann and W.T. Hodges, "An Experimental Investigation of Electromagnetic Scattering Properties of Flat Composite Structures," Technical Report 716148-2, prepared under Grant NSG 1613 for National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, October 1984. (This is a classified project.)
- [14] R.C. Rudduck and T.H. Lee, "Reflector Antenna Code" under development for National Aeronautics and Space Administration, Langley Research Center.
- [15] R.C. Rudduck, W.D. Burnside, A.K. Dominek and T.H. Lee, "Simulation of an Aircraft Flying Through a Ground Station to Satellite Link," Technical Report 716148-7, generated under Grant NSG 1613, for National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, February 1986.
- [16] Ayhan Altintas, "Electromagnetic Scattering from a Class of Open-Ended Waveguide Discontinuities," Ph.D. dissertation, The Ohio State University, Department of Electrical Engineering, 1986.
- [17] R.J. Burkholder, "High Frequency Backscatter Analysis of Electrically Large Inlets," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1985.
- [18] E.H. Newman, "Strip Antennas in a Dielectric Slab," IEEE Transactions on Antennas and Propagation, Vol. AP-26, pp. 647-653, September 1978.

- [19] E.H. Newman and P. Tulyathan, "Analysis of Microstrip Antennas Using Moment Methods," IEEE Transactions on Antennas and Propagation, Vol. AP-29, pp. 47-54, January 1981.
- [20] E.H. Newman, J.H. Richmond and B.W. Kwan, "Mutual Impedance Computation Between Microstrip Antennas," IEEE Trans. Microwave Theory and Tech., Vol. MTT-31, pp. 941-945, November 1983.
- [21] E.H. Newman and J.E. Tehan, "Analysis of a Microstrip Array and its Feed Network," IEEE Transactions on Antennas and Propagation, Vol. AP-33, pp. 397-403, April 1985.
- [22] B.W. Kwan, E.H. Newman and R.G. Kouyoumjian, "Mutual Coupling Between Microstrip Modes on a Dielectric Coated Cylinder," IEEE Transactions on Antennas and Propagation, in preparation.
- [23] B.W. Kwan, R.G. Kouyoumjian and E.H. Newman, "An Asymptotic Evaluation of the Mutual Impedance Between 2-D Strips on a Dielectric Coated Circular Cylinder," IEEE Transaction on Antennas and Propagation, in preparation.
- [24] E.H. Newman and D.M. Pozar, "Electromagnetic Modeling of Composite Wire and Surface Geometries," IEEE Transactions on Antennas and Propagation, Vol. AP-26, pp. 784-789, November 1978.
- [25] E.H. Newman and D.M. Pozar, "Considerations for Efficient Wire/Surface Modeling," IEEE Transactions on Antennas and Propagation, Vol. AP-28, pp. 121-125, January 1980.
- [26] D.M. Pozar and E.H. Newman, "Analysis of a Monopole Mounted at or Near the Edge of a Wedge," IEEE Transactions on Antennas and Propagation, Vol. AP-29, pp. 488-495, May 1981.
- [27] D.M. Pozar and E.H. Newman, "Analysis of a Monopole Mounted Near an Edge or a Vertex," IEEE Transactions on Antennas and Propagation, Vol. AP-30, pp. 401-408, May 1982.
- [28] I.J. Gupta and W.D. Burnside, "A Physical Optics Correction for Backscattering from Curved Surfaces," IEEE Transactions on Antennas and Propagation, May 1987.
- [29] I.J. Gupta and W.D. Burnside, "User Manual for Semi-Circular Compact Range Reflector Code," Technical Report 716148-18, generated under Contract NSG 1613 for National Aeronautics and Space Administration, Lewis Research Center, January 1987.
- [30] C.W.I. Pistorius, "New Main Reflector, Subreflector and Dual Chamber Concepts for Compact Range applications," Ph.D. dissertation, The Ohio State University, Department of Electrical Engineering, 1986.

- [31] A. Lai, "A GTD Analysis of Ogive Pedestal," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1986.
- [32] C.L. Bennett and R. Hieronymus, "Space-Time Integral Equation Approach to Solution of Plane Symmetric Scattering Problems," Report SCRC-CR-75-9, Sperry Research Center, May 1975.