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ABSTRACT

This publication presents an antenna system that has been proposed as one of the candidates for the SCANSCAT (Scanned Scatterometer) radar application. It is the mechanically steered planar microstrip reflectarray. Due to its thin, lightweight structure, the antenna's mechanical rotation will impose minimum angular momentum for the spacecraft. Since no power-dividing circuitry is needed for its many radiating microstrip patches, this electrically large array antenna demonstrates excellent power efficiency. In addition, this fairly new antenna concept can provide many significant advantages over a conventional parabolic reflector.

The basic formulation for the radiation fields of the microstrip reflectarray is presented. This formulation is based on the array theory augmented by the Uniform Geometrical Theory of Diffraction (UTD). A computer code for analyzing the microstrip reflectarray's performances, such as far-field patterns, efficiency, etc., is also listed in this report. It is proposed here that a breadboard unit of this microstrip reflectarray should be constructed and tested in the future to validate the calculated performance. The antenna concept presented here can also be applied in many other types of radars where a large array antenna is needed.

Microstrip Reflectarray Antenna
for the
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I. Executive Summary

The mechanically steered flat microstrip reflectarray antenna has been proposed as one of the candidate antennas for the SCANSCAT (Scanned Scatterometer) radar application. Due to its thin, lightweight structure, the antenna's mechanical rotation will impose minimum angular momentum for the spacecraft. Since no power dividing circuitry is needed for its many radiating microstrip patches, this electrically large array antenna demonstrates excellent power efficiency. As will be described in this report, this fairly new antenna concept can provide many significant advantages over a conventional parabolic reflector.

The tasks that have been completed this year are the basic formulation of the antenna radiation fields and the generation of a computer code for analyzing the microstrip reflectarray's performances, such as far-field patterns, efficiency, etc. The formulation is based on the array theory augmented by the Uniform Geometrical Theory of Diffraction (UTD). It is proposed here that a breadboard unit of this microstrip reflectarray should be constructed and tested in the future to validate the calculated performance. This antenna concept can also be applied in many other types of radars where a large array antenna is needed.

II. Introduction

1. Antenna Requirements:

The Ku-band SCANSCAT antenna is required to generate two sets of pencil beams, as shown in Figure 1, to map the surface of the Earth for scatterometer application. One set should radiate at 36° from the nadir direction, while the other should be pointed at 49° from the nadir. Both sets of beams should be able to transmit and receive horizontally polarized electrical fields. Due to the azimuth scan speed of 16.4 rpm for the mechanical platform and relatively slower radar pulse return time, the transmit and receive beams at 36° elevation need to be separated in azimuth by 0.59°. Similarly, the transmit and receive beams at 49° elevation should be separated by 0.77° in azimuth. Consequently, a total of four beams are to be generated at the frequency of 13.995 GHz. Each beam needs to have a 3-dB beamwidth of not more than 0.7° with a peak gain of 47 dBi or more and sidelobe level not higher than -20dB.

2. Previously Proposed Concepts:

A previously proposed antenna system was a mechanically steered dual-reflector configuration as illustrated in Figure 2. This configuration, although simple in design and relatively low in cost, will require large physical volume, mass, and, worst of all, a momentum compensation system that will result in even larger mass. As a consequence, a task was recently engaged to study other antenna concepts that will lead to smaller antenna volume, mass, and spin momentum. Quite a few concepts[1] have been investigated, which include electronically scanned phased arrays, hybrid electronically/mechanically scanned arrays, and mechanically steered arrays. The phased array approach was ruled out due to its extremely high cost and complexity. The only technically viable phased array approach is the active array with distributed T/R modules. With approximately 33,000 radiating elements, T/R modules, and phase shifters required, the whole antenna system will cost about $20 million. In addition to the high cost, it will be difficult (if not impossible) for the phased array to generate horizontally polarized beams in all the azimuth directions required. Also, an impractically large amount of D.C. power (in the order of many Kilowatts) may be needed to bias and control the large number of T/R modules and phase shifters.

After a trade-off study, one antenna concept was selected for further investigation. This is the mechanically steered microstrip reflectarray, which consists of a single flat array disc (3.1-meter diameter) that is space-fed by a small low-gain antenna and mechanically spun in azimuth. This microstrip reflectarray offers much lower spin momentum, physical volume, and mass than the dual-reflector system. A detailed description of this antenna concept, as well as its advantages, are given in the following sections. Theoretical analysis of the antenna's performance was also carried out in this study effort. The basic array theory augmented by the Uniform Geometrical Theory of Diffraction[2,3] was utilized for the theoretical analysis. A user oriented computer code for analyzing the microstrip reflectarray has been successfully used to produce many valuable data.

III. Description of the Microstrip Reflectarray

When many antenna elements with open or short circuited terminations are arranged in a planar aperture and are illuminated by a feed antenna as shown in Figure 3, these elements will re-radiate their illuminated energy into space. The total re-radiated energy will be non-coherent in phase, even when all the elements and their terminations are identical. This is because the fields that propagate to the elements from the feed have different path lengths, S_1, S_2, ...S_N, as shown in Figure 3(b), and thus form different phases. However, if each element's phase is adjusted to compensate for these different path lengths, the total re-radiated field can be made coherent and concentrated toward a specific direction. Many different types of radiators, such as horn, dipole, etc., can be used on the planar structure. If this planar structure is required to be thin, then a printed-circuit type of element needs to be employed. Several of these printed-circuit flat plate antennas have been attempted previously without much success. An early attempt[4] used the flat plate concept as a lens rather than as a reflector. Very low efficiency (25%) was reported. Recently, Malibu Research Center has demonstrated a flat plate reflector[5] without showing much data on efficiency. Both above attempts used either resonant slots or dipoles without any phase delaying transmission lines. Only the size of the slot or dipole is varied for phase trimming which is achieved by adding reactance into the element's radiation impedance. This is equivalent to saying that the phase of the dipole's surface current is different for different dipole lengths. With properly designed phase distribution, beam coherence can be achieved by these arrays. This, however, will result in reduced radiation efficiency. Since, for a particular frequency, there is only one optimum size of the resonant structure to transmit through or reflect energy, other sizes will result in low amplitude. Reference [4] printed that, "amplitude must be sacrificed at the expense of phase change". A more recent study[6] has used equal-size dipoles with periodic spacing so that all the dipoles have the same illumination phase as the feed. This is the so-called frequency grating and is very sensitive to frequency change. It is therefore used as a frequency scanned offset-fed flat reflector antenna. Aperture efficiency of 50% has been achieved by this antenna. Due to its required offset-fed configuration, this antenna cannot be effectively used in the SCANSCAT application.

The flat plate antenna proposed here uses the reflectarray[7] concept where a short transmission line is attached to each radiator for phase adjustment. The electrical lengths of these transmission lines are made different depending on their radiators' positions from the feed. All the radiators, however, are identical in size and are made of thin microstrip patches. This antenna, as shown in Figure 4, is called the microstrip reflectarray. It is composed of a thin (≤0.02 wavelength) slab of dielectric material having one side completely covered with a layer of thin metal (which serves as a ground plane) and the other side etched with many identical metallic microstrip patches. A feed antenna, located at an optimally designed distance from the flat plate, will effectively illuminate all the metallic patches. The size of each patch, which can be rectangular, square, or circular, is made to resonate at the same frequency as the feed antenna. A short transmission line is connected to each patch at one end with the other end of the line either open or short circuited. This transmission line can be either a microstrip line etched on the same side of the patches or a stripline sandwiched in an additional layered structure behind the ground plane. The advantage of the microstrip line is ease of fabrication with very little impact on antenna weight, while that of the stripline is minimum interference to the patch's radiation. When the radiation field of the feed antenna (in transmit mode) strikes each patch, the received resonant field of the patch will travel through its connected transmission line and be reflected by its open or short circuited termination and then re-radiate through the patch into space. Thus, all the microstrip patches behave as re-radiators, while the short transmission lines serve as phase delay lines. The lengths of these transmission lines are intentionally made different for differently located patches so that the path delay differences from the feed antenna can be compensated. With proper design and calibration of these line lengths, the re-radiated fields from all the patches can be made coherent and concentrated toward the broadside direction. Also by re-designing the line lengths, the main beam can be directed toward other directions. Since the required phase changes for all the elements are between 0° and 360°, the maximum length needed for the transmission line is only a half-wavelength. Consequently, the insertion loss associated with these short lines will be insignificantly small. However, this half-wavelength transmission line will work for a narrow bandwidth (≤1%) application. For a wider bandwidth, a frequency excursion error will occur, especially for the outer elements of the array (assuming the feed is located at the center axis of the array). In other words, the phase will accumulate more error for the outer elements. This accumulated phase error can be reduced by using longer transmission lines for the center elements and/or by using a larger f/D ratio (where f is the distance between the feed and the patches, and D is the diameter of the reflectarray).

Since the microstrip reflectarray does not require any power divider, its efficiency in a large array system is much higher than a conventional array having the same aperture size. One possible drawback of this reflectarray is that, in addition to the re-radiated fields from the patches, there will also be scattered field from the patches, reflected field from the ground plane (especially at off-resonant frequencies of the patch), and diffracted fields from edges of the flat plate. These backscattered fields may increase the sidelobe level and possibly distort the main beam shape. However, as long as the aperture directivity of the flat plate is sufficiently higher (25dB or more) than the feed directivity, the backscattered energy will be insignificantly small. In other words, as will be demonstrated in a later section, the microstrip reflectarray will be an efficient antenna system only if it has a large number of elements (thousands or more).

IV. Application to SCANSCAT

The proposed microstrip reflectarray for SCANSCAT is configured in Figure 5 where each patch has two orthogonally connected transmission lines with different lengths. Each one corresponds to a different elevation beam. Although not required, this orthogonal connection and the proper phase settings can separate the two different elevation beams 90° apart in azimuth. To meet the four-beam requirement of SCANSCAT, four feeds are needed as shown in Figure 5. Each two with the same polarization, due to their spatial separation, will generate the two separated transmit and receive beams. This is because each different feed location will form a different set of phases to illuminate the patches and, thus, generate a different beam position. Each two feeds that have different polarizations will generate two beams at different elevation and azimuth angles due to the two different settings of transmission line lengths on the microstrip patches. Because of the elegance of this design, all four beams will have horizontal polarization as required. These four beams are to be scanned in azimuth by spinning mechanically at the center of the circular flat plate. Due to the fact that the mass of the circular flat plate is more concentrated toward the center of rotation than the previously proposed dual-reflector design (Figure 2), the spin momentum will be much less. In addition, due to the microstrip design, the overall antenna volume and mass will also be much less than the dual-reflector system.

To meet the SCANSCAT's 47dBi of minimum gain requirement, approximately 65,800 microstrip patches are needed. This huge number of elements does not impact the efficiency of the antenna system since no power-dividing circuitry is needed for the reflectarray. The entire array has a diameter of 3.1 meters with a preliminarily designed feed location of 1.5 meters from the array. This 1.5 meters of feed separation (0.5 f/D ratio) is not necessarily an optimum number. If the feed gets too close to the array, the frequency excursion error will increase and therefore will narrow the operational bandwidth. If the feed is too far away from the array, the mechanical deployment and structure support problems may become severe. Certainly, the feed spillover efficiency and illumination efficiency are also determining factors in designing the feed location. This feed location optimization should be done together with a mechanical engineer.

V. Analysis of the Microstrip Reflectarray

Consider a planar array consisting of M x N microstrip patch elements that is non-uniformly illuminated by a low-gain feed at r_f as shown in Figure 6. Let the desired beam direction be specified by unit value U_o. Then the re-radiated field in the U direction will be of the form

$$E(\hat{u}) = \sum_{m=1}^{M} \sum_{n=1}^{N} F(\overline{r}_{mn} \cdot \overline{r}_f) \ A(\overline{r}_{mn} \cdot \hat{u}_o) \ A(\hat{u} \cdot \hat{u}_o) \cdot \tag{1}$$

$$\exp\{-jk[|\overline{r}_{mn} - \overline{r}_f| + \overline{r}_{mn} \cdot \hat{u}] + j\alpha_{mn}\} + E_r + E_d$$

where F is the feed pattern function, A is the pattern function of the microstrip patch on the flat plate, r_{mn} is the position vector of the mnth patch, and α_{mn} is the required transmission line phase delay of the mnth element for beam coherence. The condition that the beam will be coherent at desired direction U_o is

$$\alpha_{mn} - k[|\bar{r}_{mn} - \bar{r}_f| + \bar{r}_{mn} \cdot \hat{u}_o] = 2n\pi, \; n = 0, 1, 2.... \tag{2}$$

The feed function F is modeled by $\cos^q\theta$ function. For the pattern function A of the single square or rectangular microstrip patch on the flat plate, a simple closed form model using the dual-slot theory[3] is employed. This simple model, which is accurate enough for large array prediction, allows the computation time of many thousands of array elements to be significantly reduced. The radiation patterns of the θ and ϕ components from each slot of the dual-slot model, as illustrated in Figure 7, is given as follows:

$$E_\theta = -\frac{\sin(k\,a\cos\phi\sin\theta)}{k\,a\cos\phi\sin\theta} \cdot \frac{\cos(k\,b\sin\phi\sin\theta)}{(k\,b\sin\phi\sin\theta)^2 - (\pi/2)^2}\cos\theta \tag{3}$$

$$E_\phi = -\frac{\sin(k\,a\cos\phi\sin\theta)}{k\,a\cos\phi\sin\theta} \cdot \frac{\cos(k\,b\sin\phi\sin\theta)}{(k\,b\sin\phi\sin\theta)^2 - (\pi/2)^2}\sin\phi\cos\theta \tag{4}$$

where a is half the dielectric thickness (slot width) and b is half the patch width (slot length), and $K = 2\pi\sqrt{\epsilon_r}/\lambda_0$. The terms E_r and E_d in equation (1) are, respectively, the specular reflected field from the flat ground plane and the diffracted field from the edges of the ground plane. Both E_r and E_d are calculated via the technique of the Uniform Geometrical Theory of Diffraction[2,3]. Although E_r does not give an accurate solution for the scattered fields from the patches and the ground plane, it gives the worst solution (maximum backscattered field is reflection). This can be assumed because the patches are separated within a very small distance ($\leq$0.02 wavelength) from the ground plane, and the flat plate reflectarray can thus be treated RF wise as a perfect conducting plane. This is especially true at off-resonant frequencies. To accurately predict the backscattered fields from thousands of non-uniformly illuminated microstrip patches with unequal lengths of microstrip transmission lines will require the development of a complex analysis technique which is beyond the scope of the current allocated fund. The fields E_r and E_d, no matter how accurate their calculation, are insignificant to the main beam when the array aperture gain is about 30 dB higher than the gain of the feed antenna, which is indeed the case for SCANSCAT. Nevertheless, these two terms are included in the analysis so that the worst possible sidelobe level due to scattered fields can be predicted.

The efficiency of the microstrip reflectarray is primarily governed by the aperture illumination efficiency and feed spillover efficiency[8]. Aperture illumination efficiency is caused by unequal illumination of the array due to the feed pattern. The spillover efficiency is the ratio of the amount of feed energy that illuminates the entire array to the amount of energy that spills to the outside of the array. The calculation of these two efficiencies are very similar to that of a parabolic reflector. My colleague, Dr. Vahraz Jamnejad, with his many years of reflector experience, has assisted me in calculating these two efficiencies. With the q factor in the feed pattern $\cos^q\theta$ chosen to be 3 and the feed separation of 1.5 meters from the 3.1-meter diameter array, the efficiency of the overall microstrip reflectarray for the SCANSCAT is calculated as following:

Table 1. Estimated microstrip reflectarray efficiency for SCANSCAT

Type of Efficiency	Efficiency in Percent
spillover	91
illumination	83
patch loss	95
feed loss	95
termination loss	95
total	65

Because the proposed microstrip reflectarray for SCANSCAT is an electrically large array, the above estimated 65% antenna efficiency is considered quite good. In addition, the illumination and spillover efficiencies may be improved by optimally designing a special feed instead of using the $\cos^q\theta$ feed pattern.

A computer code based on the formulation in Equation (1) has been written with the FORTRAN language and user friendly inputs. For the SCANSCAT antenna, the patterns of the 36° and 49° scanned beams are calculated. For brevity's sake, only the 49° scanned beam patterns are presented here. Figure 8 gives the coordinate system of the reflectarray geometry. The radius of the reflectarray is 72 λ_o and the patch elements are spaced 0.5 λ_o apart, with λ_o being the free space wavelength. Each patch element is 0.32 λ_o x 0.32 λ_o square with a substrate thickness of 0.01 λ_o and a dielectric constant of 2.2. The feed has a symmetrical $\cos^q\theta$ power pattern with q = 3 and an illumination edge taper of -9dB. Figure 9 is the calculated far field pattern in the X-Z plane when all the phase delay transmission lines on the patches are set for a beam scan of 49° in the x-z plane. The feed is located at (XF, YF, ZF) = (0., 0., 0.) or (x, y, z) = (0., 0., 72 λ_o) with an f/D ratio of 0.5. Both the feed and the patches are polarized in the Y-direction so that, when the z-axis of the array is pointed at nadir and the beam is scanned in the x-z plane, a horizontally polarized beam is achieved. This pattern shows a 3-dB beamwidth of 0.75° and peak sidelobe level of -32dB. The beamwidth of 0.75° may be reduced down to the required 0.70° by a feed optimization program. It needs to illuminate the array more uniformly to increase the effective aperture and thus reduce the beamwidth. Figure 10 gives the ϕ-plane pattern (constant θ = 49° plane) with a 3-dB beamwidth of 0.64° and a peak sidelobe of -31dB. The calculated directivity of this 49° scanned beam is 50.3dBi which, after subtracting 65% of efficiency loss, indicates an antenna peak gain of 48.4dBi. This is about 1.4dB above the required minimum gain.

Figure 11 gives the ϕ-plane pattern when the feed is displaced 0.4 λ_o in the +y-direction (XF, YF, ZF = 0., 0.4 λ_o, 0.), while all other parameters of the array are kept the same as those for Figures 9 and 10. The beam shows a shift of 0.34° in the $-\phi$ direction. With a second identical feed located at YF = -0.4 λ_o, another beam with a 0.34° shift in the $+\phi$ direction can be formed. Separate transmit and receive beams can thus be achieved for the SCANSCAT. The shifted beam shown in Figure 11 has a coma lobe at -25dB level which is still acceptable to SCANSCAT. This coma lobe distortion is a consequence of phase errors that resulted from all the phase delay lines with settings designed for a focal feed rather than an off-focal feed.

To demonstrate the effect of backscattered field components -- E_r and E_d of Equation (1) -- Figure 12 presents the pattern for the same antenna (diameter = 144 λ_o) as in Figure 9 except with the horizontal axis expanded and with less sampling accuracy in the pattern. This pattern does not include the effect of E_r and E_d and shows no far-out sidelobes above -60dB (mainbeam peak is normalized at 0dB). With this same antenna design, Figure 13 shows the pattern that does have the terms E_r and E_d included. Many sidelobes are near the -40dB level which is much lower than the SCANSCAT requirement. Now, let us look at a smaller reflectarray with diameter of 10 λ_o, f/D ratio of 0.5, and feed pattern q factor of

3. The far field pattern of this antenna when scanned to 36° is shown in Figure 14 where E_r and E_d terms are not included. For the same antenna, the scan pattern with E_r and E_d included is given in Figure 15 where sidelobes of -17dB level are observed. Figures 12 through 15 have demonstrated that the microstrip reflectarray antenna will not have serious high sidelobe problems caused by the backscattered fields when the aperture directivity is significantly higher (such as 30dB) than the feed directivity. In other words, the microstrip reflectarray is a more effective antenna when it is electrically large. Figure 16 plots the calculated antenna gain (estimated loss included) versus the array aperture diameter. It shows that, at the SCANSCAT frequency, the antenna gain drops much faster with reduction in aperture size when the diameter is less than one meter.

VI. Advantages and Disadvantages of the Microstrip Reflectarray

The numerous advantages of the microstrip reflectarray, in addition to its excellent application to SCANSCAT, are separately discussed below:

1. The reflectarray, being in the form of a microstrip antenna, can be fabricated with a simple, low cost, and accurate etching process. Being flat, the microstrip reflectarray will be more cost effective than the parabolic reflector when manufactured. For example, the special molding process that is generally required for fabricating a paraboloid is not needed for a flat antenna.

2. Due to the fact that no power divider is needed, the insertion loss of thousands of microstrip patches in the reflectarray will be the same as the insertion loss of a single patch and thus achieve good efficiency. The efficiency is much better than that of a conventional array with the same aperture size and is estimated to be comparable to that of a parabolic reflector (55-75% efficient).

3. The main beam of the microstrip reflectarray can be fixed to point at large angles (up to 60°) from the broadside direction, while a parabolic reflector can only have limited scan (several beamwidths). Phase shifters can be placed in the phase delay transmission lines for electronic beam scanning.

4. Since the antenna is a flat structure, its mass is likely to be less than a curved parabolic reflector with equal aperture size. It can be more easily mounted onto the surface of a structure, such as a spacecraft's main body or a building, with less supporting structure volume and mass when compared to a parabolic reflector. As a possible application, this microstrip reflectarray can be made as the world's largest array antenna with relative ease in construction and low cost. This can be true because a flat reflectarray, where the RF loss is not a function of array size, can be constructed on flat land (aperture parallel to the land) with its feed mounted on top of a high tower. The size of the antenna is only limited by the tower height. A feed height of 1000 feet with an f/D ratio of 0.5 will result in an array with diameter of 2000 feet. This antenna size at 10 GHz can produce a pencil beam of 0.0035° in beamwidth and 95dBi of directivity.

One major disadvantage of the microstrip reflectarray is the narrow bandwidth of the microstrip patch. It is certainly no match to the wide band property of the parabolic reflector (theoretically infinite bandwidth). With conventional microstrip patch design, a maximum of 3% bandwidth can be achieved. With special design, such as a dual-stacked patch[9], the bandwidth can be increased close to 10%. The disadvantage of the narrow bandwidth of the microstrip reflectarray can be overcome somewhat by utilizing multiple-frequency operation. This is made possible for the flat reflectarray by using a multiple-layer design as shown in Figure 17 where the larger patches serve as ground planes for many of the smaller patches. A microstrip antenna having triple-frequency capability with a three-layer design has been successfully demonstrated[10]. Other multiple-frequency designs are also possible, such as multiple-ring patches and interlaced different-size patches, shown in Figure 18.

VII. Conclusion

The flat plate microstrip reflectarray antenna has been analyzed by the array theory augmented by the Geometrical Theory of Diffraction. Antenna performances, such as radiation pattern, directivity, efficiency, etc., have demonstrated that a SCANSCAT mechanically steered antenna is feasible. Its radiation efficiency is comparable to a parabolic reflector antenna, while having many mechanical advantages over a parabolic reflector. Due to its low RF loss characteristic, this antenna can be used in many large beam scanning radar applications.

VIII. References

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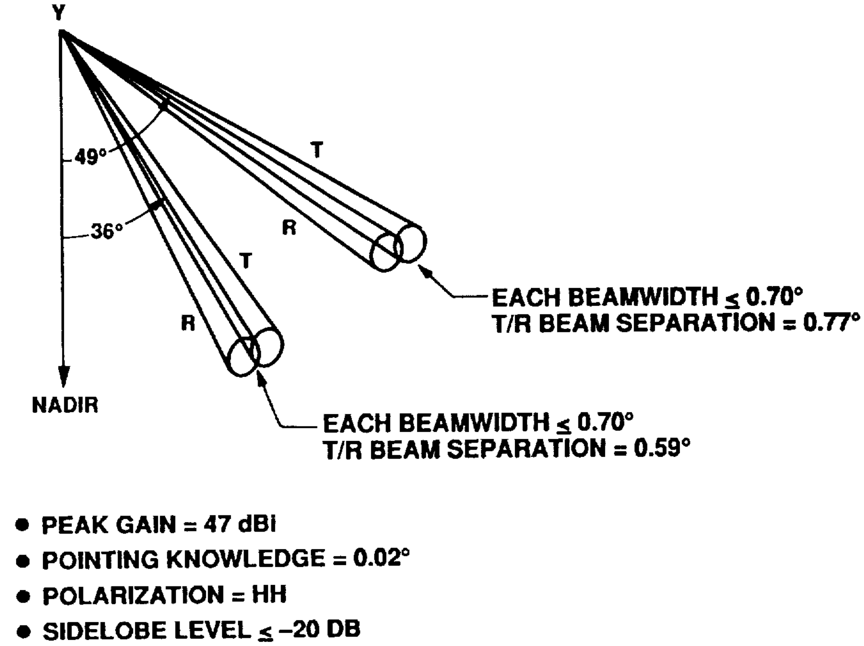


Figure 1. SCANSCAT antenna requirements.

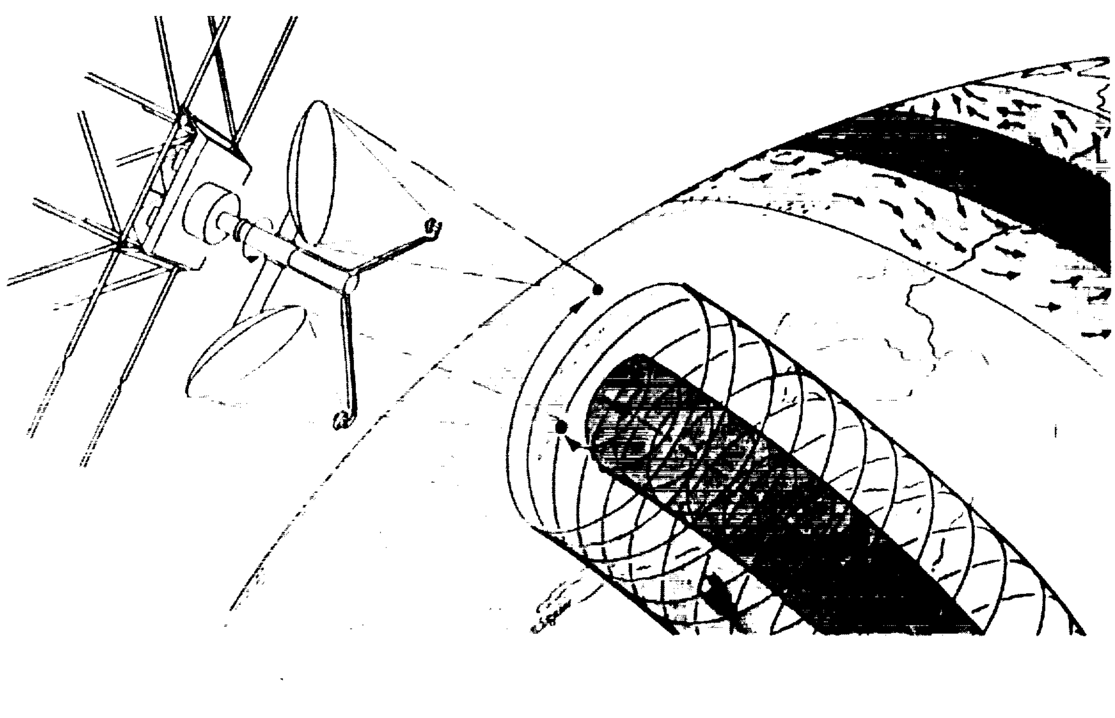


Figure 2. Mechanically steered dual-reflector configuration.

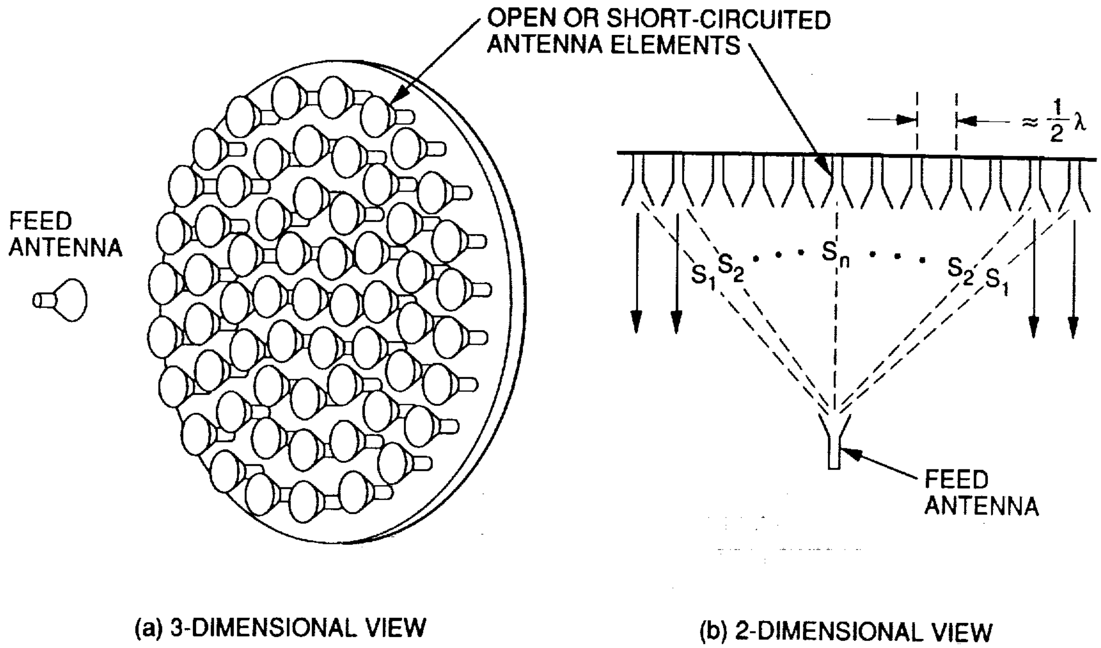


Figure 3. Planar array reflector antenna.

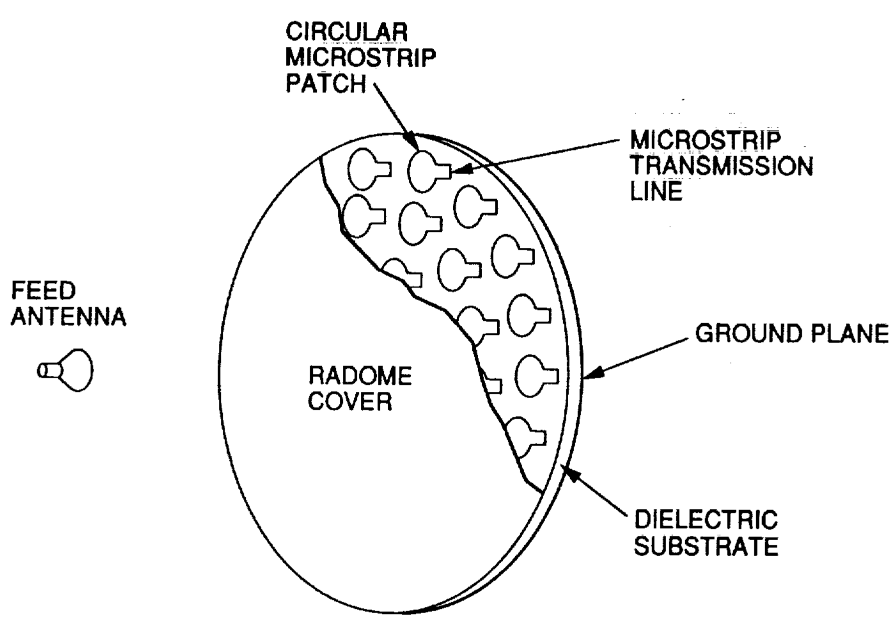
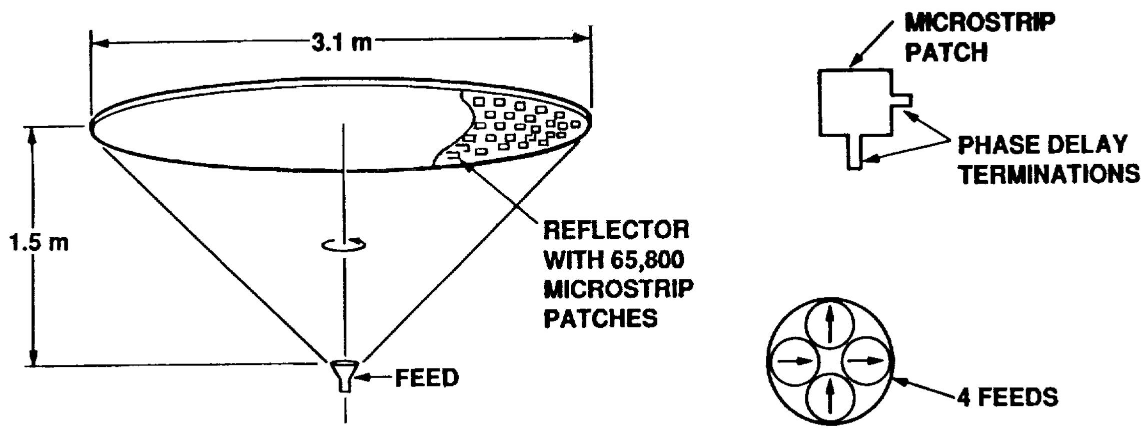


Figure 4. Flat plate microstrip reflectarray.



- TWO BEAMS IN DIFFERENT ELEVATIONS ARE SEPARATED 90° IN AZIMUTH WITH BOTH HAVING HH POLARIZATION
- 65,800 MICROSTRIP PATCHES CAN BE FABRICATED WITH SIMPLE CIRCUIT ETCHING PROCESS
- THE ARRAY REFLECTOR HAS A THICKNESS OF 0.032", THICKER HONEYCOMB – TYPE OF STRUCTURE IS NEEDED TO SUPPORT THE THIN FLAT ARRAY
- REQUIRED ANTENNA SURFACE ACCURACY ≤ 0.030"

Figure 5. Microstrip reflectarray for SCANSCAT.

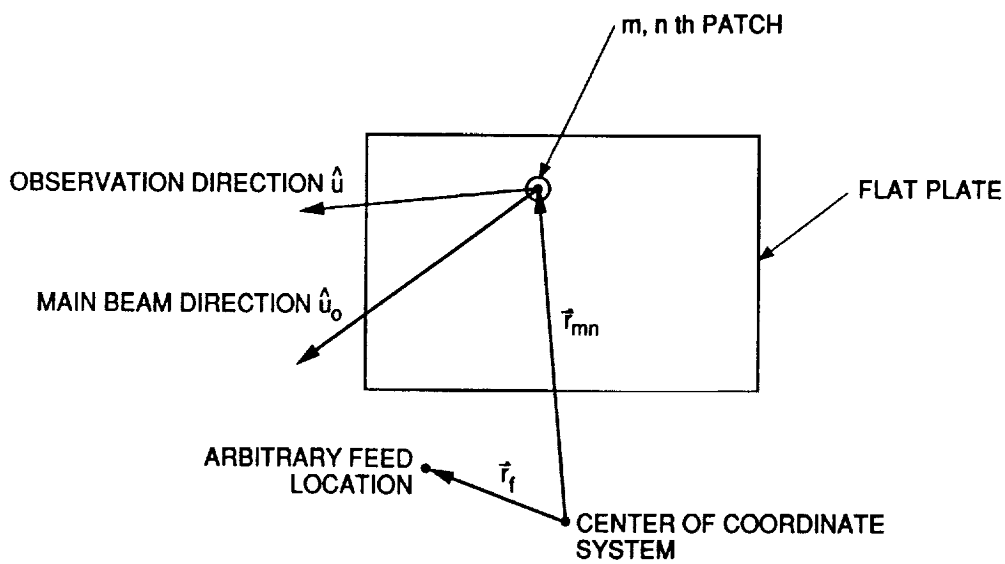


Figure 6. Coordinate system for array theory.

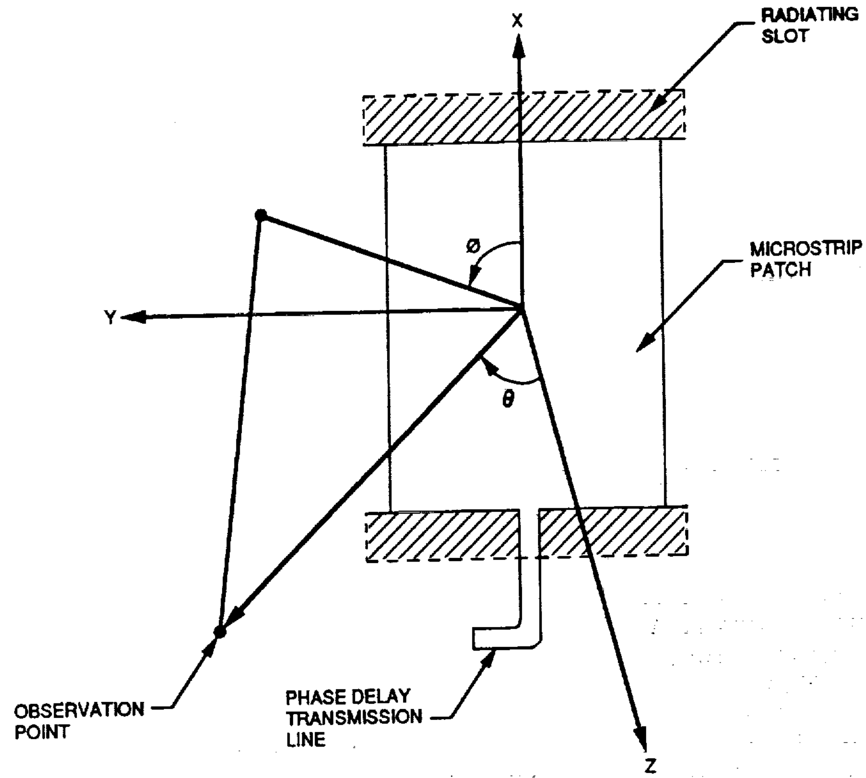


Figure 7. Microstrip patch dual-slot model.

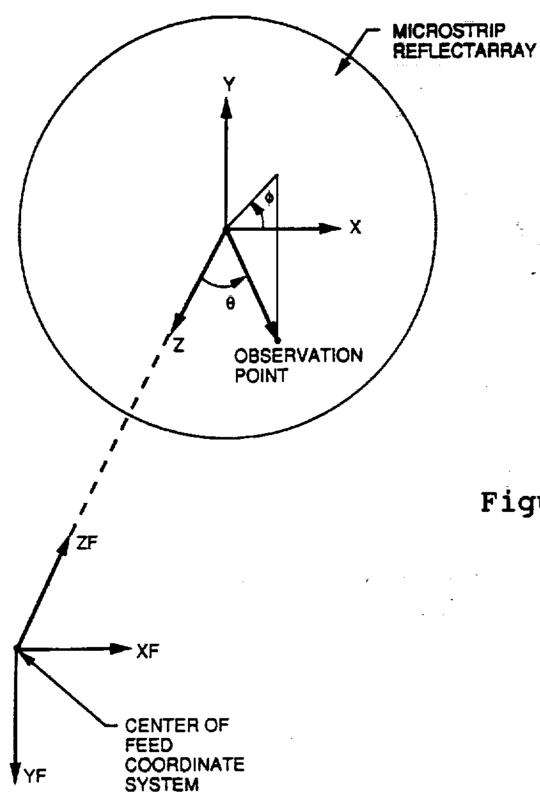


Figure 8. Microstrip reflectarray coordinate system.

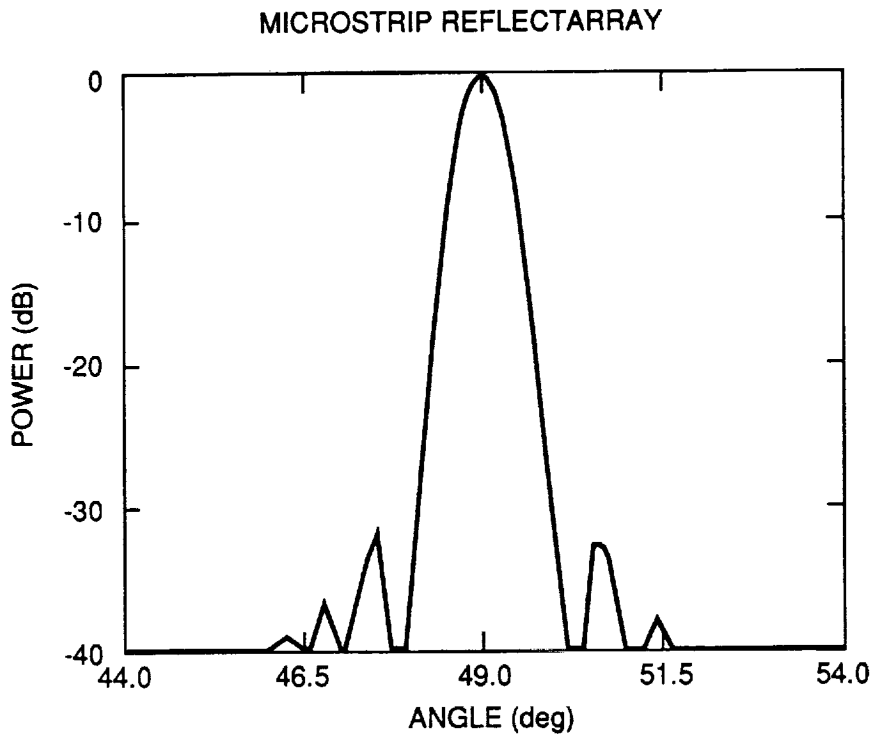


Figure 9. Calculated scan-plane pattern of the 49°-scanned beam.

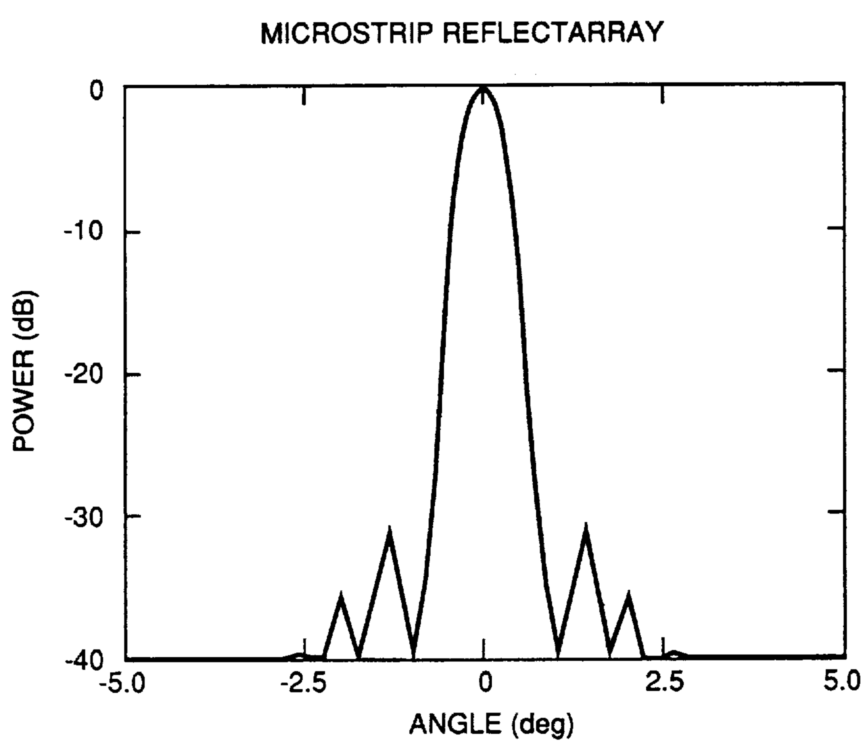


Figure 10. Calculated ϕ-plane pattern of the 49°-scanned beam.

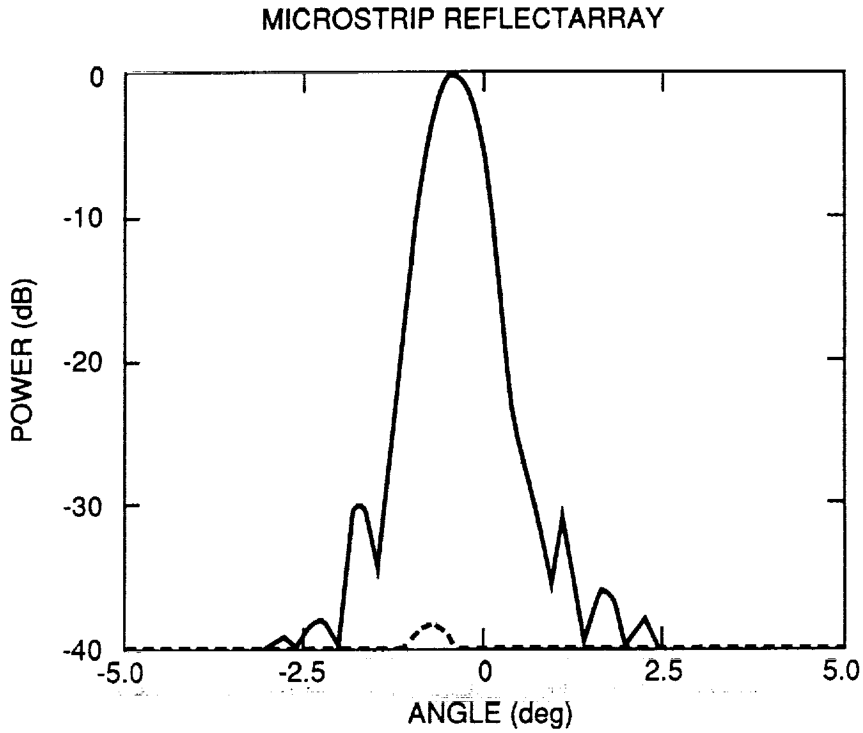


Figure 11. Calculated ϕ-plane pattern of the 49°-scanned beam when the feed is offset in y-direction by 0.4 wavelength.

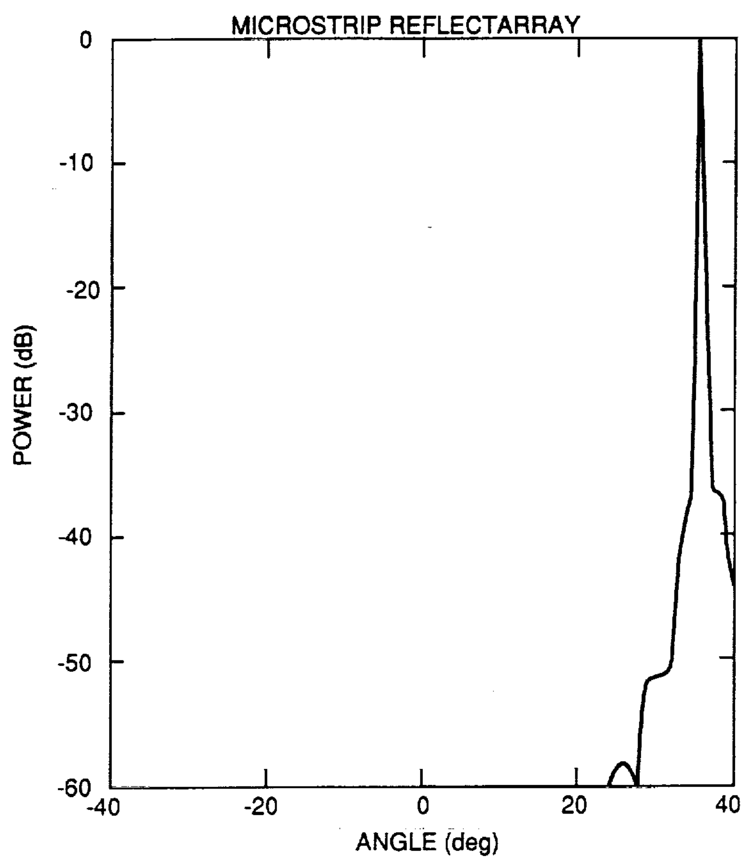


Figure 12. Calculated scan-plane pattern without including backscattered field components. Aperture diameter = 144 wavelengths.

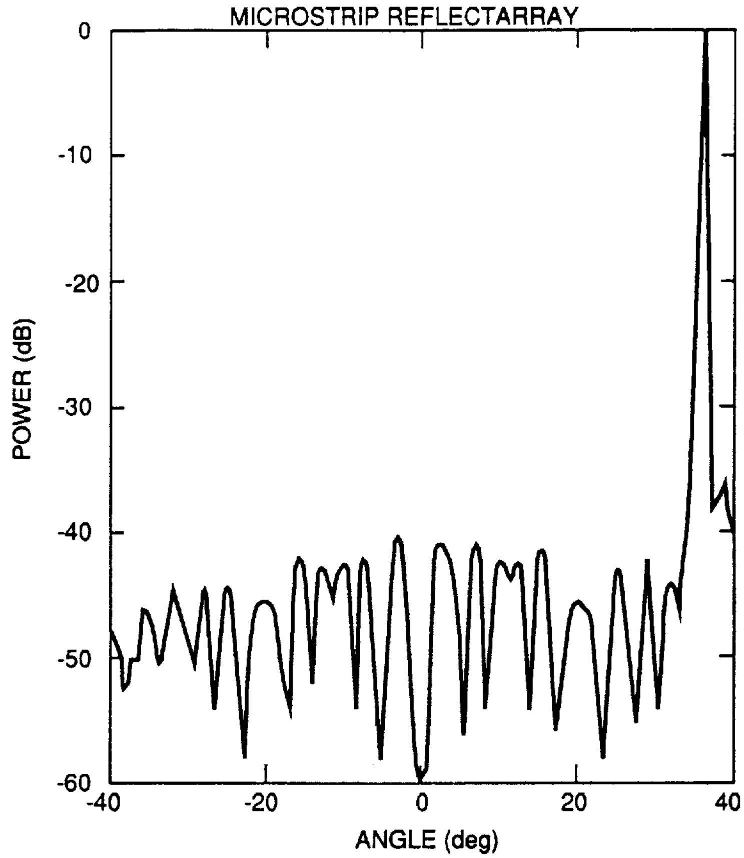


Figure 13. Calculated scan-plane pattern with backscattered fields included. Aperture diameter = 144 wavelength.

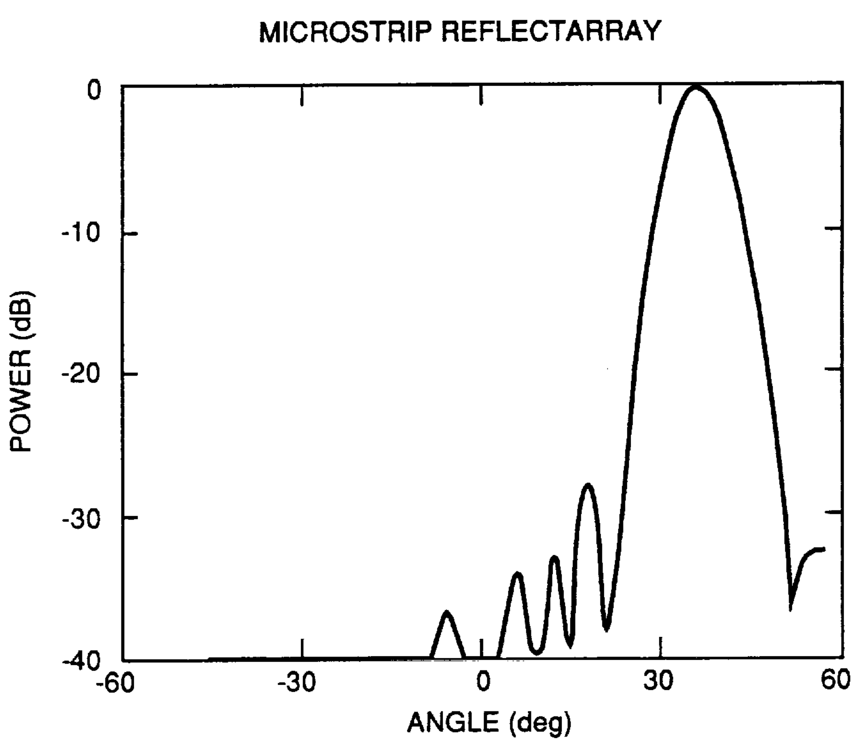


Figure 14. Calculated scan-plane pattern without including backscattered field components. Aperture diameter = 10 wavelengths.

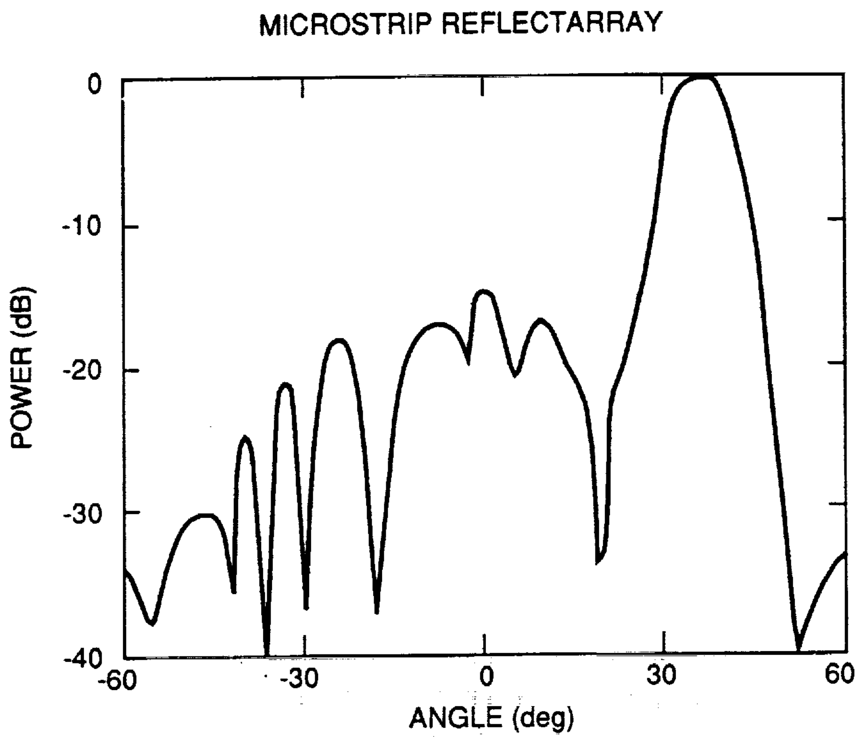


Figure 15. Calculated scan-plane pattern with backscattered fields included. Aperture diameter = 10 wavelengths.

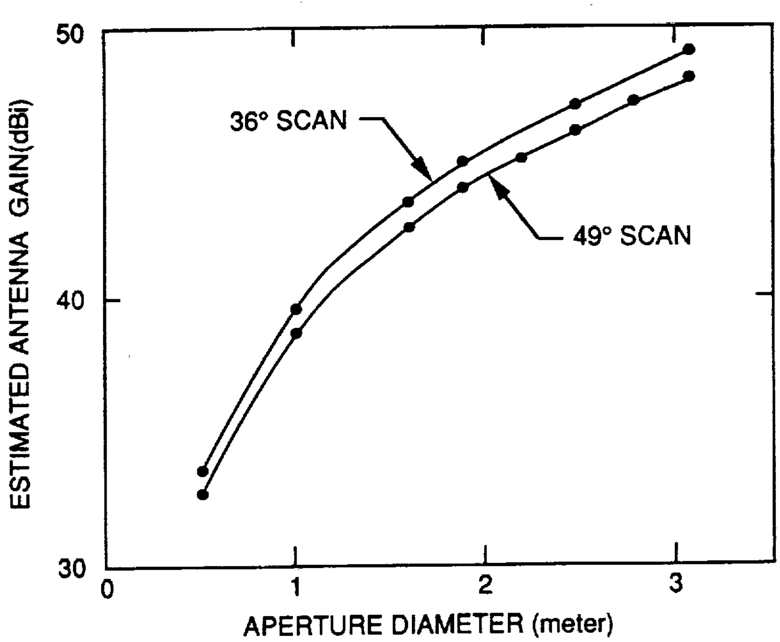


Figure 16. Calculated microstrip reflectarray antenna gain versus aperture size.

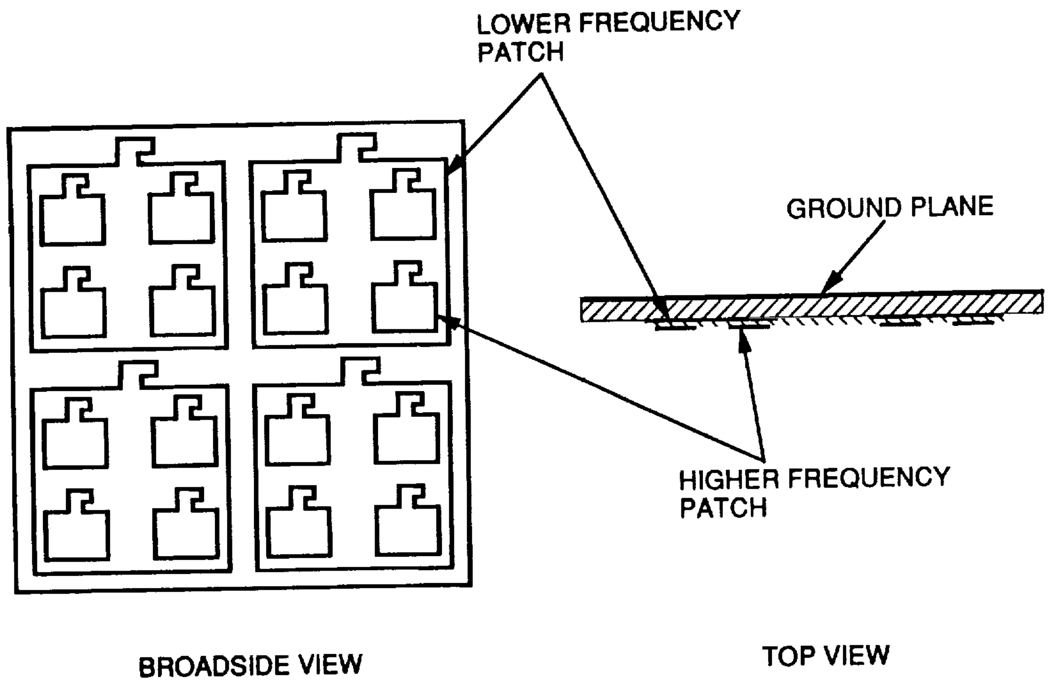


Figure 17. Dual-frequency double-layer microstrip reflectarray concept.

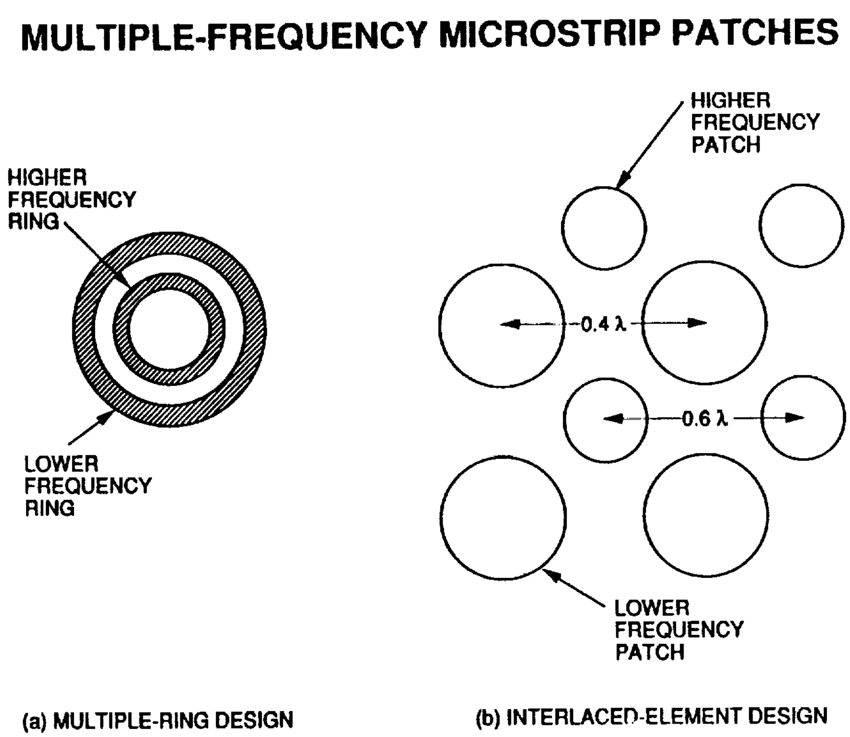


Figure 18. Multiple-frequency microstrip reflectarray designs.

```
3313929*SCAN(1).SCAT(42)
C...THIS PROGRAM COMPUTES THE RADIATION PATTERN OF A LARGE
C...MICROSTRIP REFLECTARRAY WITH CIRCULAR APERTURE, ALL INPUT
C...LENGTHS ARE IN WAVELENGTH.  PROGRAMMED BY DR. JOHN HUANG
C...AT JET PROPULSION LABORATORY, 12/12/1989.
      DIMENSION DBT(500),DBP(500),XAX(500),XX(2),YY(2)
      COMPLEX CJ,CJJ,EXX,EYY,EZZ,FACP,EX,EY,EZ,ETH,EPH
      COMPLEX ETHR,EPHR,ETHD,EPHD
      COMMON/DD1/EPS,T,WT2,THIR,PHIR,THOR,PHOR,SSP
      COMMON/DD2/CJ,PI,TPI,DPR
      COMMON/DD3/XPS,YPS,FX,FY,FZ,IP
      CJ=(0.,1.)
      PI=3.14159265
      TPI=2.*PI
      DPR=180./PI
      CJJ=(1.E-15,1.E-15)
C      WRITE(6,11)
C 11   FORMAT(' MICROSTRIP A & B DIMENSIONS=?')
      READ(5,99)AX,BY
 99   FORMAT()
C     WRITE(6,12)
C12   FORMAT(' SUBSTRATE DIELECTRIC CONSTANT & THICKNESS=?')
      READ(5,99)EPS,T
C     WRITE(6,13)
C13   FORMAT(' ELEMENT SPACING & ARRAY APERTURE RADIUS=?')
      READ(5,99) DX,DY,RA
C     WRITE(6,14)
C14   FORMAT(' FEED LOCATION & FEED COSINE Q FACTORS=?')
      READ(5,99)FX,FY,FZ,QX,QY
C     WRITE(6,15)
C15   FORMAT(' FEED POLARIZATION, IF X IP=1,  IF Y IP=2')
      READ(5,99)IP
C...IF IP=1, BEAM NEEDS TO SCAN TO Y DIRECTION OR PHS=90 DEG FOR
C...HH POLARIZATION, SCAN TO X DIRECTION OR PHS=0 DEG FOR VV
C...POLARIZATION,,,,IP=2 BEAM NEEDS TO SCAN TO X DIRECTION OR PHS=0
C...DEG FOR HH POLARIZATION, SCAN TO Y DIRECTION OR PHS=90 DEG
C...FOR VV POLARIZATION.
C     WRITE(6,16)
C16   FORMAT(' REQUIRED BEAM SCAN ANGLE=?')
      READ(5,99)THS,PHS
C     WRITE(6,7)
C7    FORMAT(' PLOT X-AXIS & Y-AXIS LENGTH IN INCH=?')
      READ(5,99)XDIM,YDIM
C     WRITE(6,17)
C17   FORMAT(' PATTERN CUT ANGLE, THETA IC=1,,, PHI IC=2')
      READ(5,99)IC
C     WRITE(6,18)
C18   FORMAT(' LEFT BOUND, RIGHT BOUND, INCREMENT OF PLOT=?')
      READ(5,99)THL,THR,ITH,PHL,PHR,IPH
C     WRITE(6,19)
C19   FORMAT(' WRITE OUT REQUIRED ELEMENT PHASE, IF YES, IW=1')
      READ(5,99)IW
C     WRITE(6,26)
C26   FORMAT(' GTD GROUND PLANE EFFECT, IF YES, IGD=1')
      READ(5,99)IGD
      THSR=THS/DPR
      PHSR=PHS/DPR
```

```
      SAI=ATAN(RA/FZ)
      CSAI=COS(SAI)
      CSA2=COS(SAI/2.)
      EK1=QX*ALOG10(CSAI)
      EK=EK1/2./ALOG10(CSA2)
      EFF1=(1.-CSA2**(2.*EK))/EK/TAN(SAI/2.)
      EFF=(2.*EK+1.)*EFF1*EFF1
      EFS=1.-CSA2**(2.*(2.*EK+1.))
      EFI=EFF/EFS
C     WRITE(6,58)EFS,EFI,EFF
C58   FORMAT(' SPILL-OVER, ILLUMINATION, TOTAL EFF.=',3F9.3)
      Q1=QX-1
      TQ1=2.*QX+1.
      EFS=1.-CSAI**TQ1
      EF1=(1.-CSAI**QX)/QX
      EF2=(1.-CSAI**Q1)/Q1
      EF3=(1.-CSAI**TQ1)/TQ1
      EFI=((EF1+EF2)**2.)/EF3
      EFI=EFI/2./TAN(SAI)/TAN(SAI)
      EFF=EFI*EFS
      WRITE(6,59)EFS,EFI,EFF
 59   FORMAT(' SPILL-OVER, ILLUMINATION, TOTAL EFF.=',3F9.3)
      NX=INT(RA*2.0000001/DX)+1
      NY=INT(RA*2.0000001/DY)+1
      NX1=NX-1
      NY1=NY-1
      HFX=FLOAT(NX-1)/2.*DX
      HFY=FLOAT(NY-1)/2.*DY
      IF(IC.EQ.2)GO TO 65
      IA=ITH+1
      DAN=(THR-THL)/FLOAT(ITH)
      GO TO 66
 65   IA=IPH+1
      DAN=(PHR-PHL)/FLOAT(IPH)
 66   DO 500 IJ=1,IA
      EXX=CJJ
      EYY=CJJ
      EZZ=CJJ
      IF(IC.EQ.2)GO TO 67
      THPL=THL+(IJ-1)*DAN
      PHPL=PHL
      GO TO 68
 67   THPL=THL
      PHPL=PHL+(IJ-1)*DAN
 68   IY=0
      ICOUNT=0
      THPR=ABS(THPL)/DPR
      PHPR=PHPL/DPR
      IF(THPL.LT.0.)PHPR=PHPL/DPR+PI
      CT=COS(THPR)
      CP=COS(PHPR)
      ST=SIN(THPR)
      SP=SIN(PHPR)
 31   YP=FLOAT(NY-IY-1)*DY-HFY
      IX=0
      IY=IY+1
 32   XP=-FLOAT(NX-IX-1)*DX+HFX
```

```
      IF(ABS(XP).LT.1.E-8)XP=1.E-8
      IF(ABS(YP).LT.1.E-8)YP=1.E-8
      RP=SQRT(XP*XP+YP*YP)
      RAP=RA+0.0000001
      IF(RP.GT.RAP)GO TO 62
      ICOUNT=ICOUNT+1
      SX=XP-FX
      SY=YP-FY
      SZ=-FZ
      S=SQRT(SX*SX+SY*SY+SZ*SZ)
      UX=SX/S
      UY=SY/S
      UZ=SZ/S
      SXY=SQRT(SX*SX+SY*SY)
      THF=ACOS(FZ/S)
      PHF=ATAN2(UY,UX)
      IF(PHF.LT.0.)PHF=PHF+TPI
      EPAT=COS(PHF)*COS(PHF)*(COS(THF))**QX+SIN(PHF)*SIN(PHF)*
     &(COS(THF))**QY
      SS=SQRT(SZ*SZ+RP*RP)
      SFAC=SS-FZ
      SFA=FLOAT(INT(SFAC))
      PHAS1=TPI*(SFAC-SFA)
      PHN=ATAN2(YP,XP)
      IF(PHN.LT.0.)PHN=PHN+TPI
      PHAS2=TPI*RP*COS(PHSR-PHN)*SIN(THSR)
      PHASR=PHAS2-PHAS1
      TES=PHASR/TPI
      ITES=INT(TES)
      PHASD=(TES-FLOAT(ITES))*TPI*DPR
      IF(IJ.EQ.1.AND.IW.EQ.1)WRITE(6,*)XP,YP,PHASD
C    ABOVE ARE PATCH LOCATION AND REQUIRED PHASE DELAY
      IF(IP.EQ.2)GO TO 61
      WT2=BY+T
      DO 36 I=1,2
      XPS=XP-(AX+T)/2.
      IF(I.EQ.2)XPS=XP+(AX+T)/2.
      YPS=YP
      XS=FX-XPS
      YS=FY-YPS
      ZS=FZ
      SSP=SQRT(XS*XS+YS*YS+ZS*ZS)
      UXS=XS/SSP
      UYS=YS/SSP
      UZS=ZS/SSP
      PHIR=ATAN2(-UYS,-UXS)+PI
      IF(PHIR.LT.0.)PHIR=PHIR+TPI
      THIR=ACOS(UZS)
      RSP=SQRT(XS*XS+YS*YS)
      PHNN=ATAN2(-UYS,-UXS)
      IF(PHNN.LT.0.)PHNN=PHNN+TPI
      PHASO=TPI*RSP*COS(PHPR-PHNN)*SIN(THPR)
      FACP=CEXP(CJ*(PHASO-PHASR))*EPAT
      THOR=THPR
      PHOR=PHPR
      CALL SOURCE(EXP,EYP,EZP)
      CALL SLOTX(EXP,EYP,EZP,EX,EY,EZ)
```

```
      EXX=EXX+EX*FACP
      EYY=EYY+EY*FACP
      EZZ=EZZ+EZ*FACP
   36 CONTINUE
      GO TO 62
   61 WT2=AX+T
      DO 37 I=1,2
      XPS=XP
      YPS=YP-(BY+T)/2.
      IF(I.EQ.2)YPS=YP+(BY+T)/2.
      XS=FX-XPS
      YS=FY-YPS
      ZS=FZ
      SSP=SQRT(XS*XS+YS*YS+ZS*ZS)
      UXS=XS/SSP
      UYS=YS/SSP
      UZS=ZS/SSP
      PHIR=ATAN2(-UYS,-UXS)+PI/2.
      IF(PHIR.LT.0.)PHIR=PHIR+TPI
      THIR=ACOS(UZS)
      RSP=SQRT(XS*XS+YS*YS)
      PHNN=ATAN2(-UYS,-UXS)
      IF(PHNN.LT.0.)PHNN=PHNN+TPI
      PHASO=TPI*RSP*COS(PHPR-PHNN)*SIN(THPR)
      FACP=CEXP(CJ*(PHASO-PHASR))*EPAT
      THOR=THPR
      PHOR=PHPR-PI/2.
      IF(PHOR.LT.0.)PHOR=PHOR+TPI
      CALL SOURCE(EXP,EYP,EZP)
      CALL SLOTX(EXP,EYP,EZP,EX,EY,EZ)
      EXX=EXX-EY*FACP
      EYY=EYY+EX*FACP
      EZZ=EZZ+EZ*FACP
   37 CONTINUE
   62 IX=IX+1
      IF(IY.GT.NY)GO TO 81
      IF(IX.GT.NX1)GO TO 31
      GO TO 32
   81 ETH=EXX*CP*CT+EYY*SP*CT-EZZ*ST
      EPH=-EXX*SP+EYY*CP
      IF(IGD.GT.1)GO TO 82
      IF(IC.EQ.2)GO TO 82
      IF(ABS(PHS).GT.0.01)GO TO 82
      IF(ABS(THPL).LT.2.)GO TO 82
      ETHR=CJJ
      EPHR=CJJ
      RD=FZ*TAN(THPR)
      IF(RD.GT.RA)GO TO 83
      XPS=RD
      IF(THPL.LT.0.)XPS=-RD
      YPS=0.
      SSP=FZ/COS(THPR)
      FAC=CEXP(-CJ*TPI*SSP)
      EPAT=COS(THPR)**QX
      PHASO=TPI*XPS*SIN(THPR)
      IF(THPL.LT.0.)PHASO=-PHASO
      FACP=CEXP(CJ*PHASO)*EPAT*FAC
```

```
      CALL SOURCE(EXP,EYP,EZP)
      EXX=-EXP
      EYY=-EYP
      EZZ=EZP
      ETHR=(EXX*CP*CT+EYY*SP*CT-EZZ*ST)*FACP
      EPHR=(-EXX*SP+EYY*CP)*FACP
 83   THOR=THPR
      PHOR=PHPR
      CALL EDGE(RA,QX,ETHD,EPHD)
      ETH=ETH+ETHR+ETHD
      EPH=EPH+EPHR+EPHD
 82   AET=CABS(ETH)
      AEP=CABS(EPH)
      IF(AET.LT.1.E-15)AET=1.E-15
      IF(AEP.LT.1.E-15)AEP=1.E-15
      DBT(IJ)=20.*ALOG10(AET)
      DBP(IJ)=20.*ALOG10(AEP)
      XAX(IJ)=THPL
      IF(IC.EQ.2)XAX(IJ)=PHPL
      WRITE(6,77)XAX(IJ),DBT(IJ),DBP(IJ)
 77   FORMAT(' ANGLE=',F12.5,3X,'DBT=',F12.5,3X,'DBP=',F12.5)
 500  CONTINUE
      WRITE(6,97)ICOUNT
 97   FORMAT(' TOTAL NUMBER OF ELEMENTS= ',I5)
      YMT=-1000.
      YMP=-1000.
      DO 22 I=1,IA
      IF(YMT.LT.DBT(I))YMT=DBT(I)
      IF(YMP.LT.DBP(I))YMP=DBP(I)
 22   CONTINUE
      YMX=YMT
      IF(YMT.LT.YMP)YMX=YMP
      DO 21 I=1,IA
      DBT(I)=DBT(I)-YMX
      DBP(I)=DBP(I)-YMX
      IF(DBT(I).LT.-60.)DBT(I)=-60.
      IF(DBP(I).LT.-60.)DBP(I)=-60.
 21   CONTINUE
      CALL BGNPLT
      CALL PLFORM('LINLIN',XDIM,YDIM)
      XX(1)=THL
      XX(2)=THR
      IF(IC.EQ.2)XX(1)=PHL
      IF(IC.EQ.2)XX(2)=PHR
      YY(1)=-60.
      YY(2)=0.
      CALL PLSCAL(XX,2,040504,YY,2,060506)
      CALL PLGRAF('MICROSTRIP REFLECTARRAY','ANGLE','DB')
      CALL PLCURV(XAX,DBP,IA,0,0)
      CALL PLNUP
      CALL PLNTYP(5)
      CALL PLNDN(0.,0.)
      CALL PLCURV(XAX,DBT,IA,0,0)
      CALL ENDPLT
      STOP
      END
```

```
3313929*SCAN(1).SLOTX(5)
      SUBROUTINE SLOTX(EXP,EYP,EZP,EX,EY,EZ)
C...THIS SUBROUTINE GIVES RE-RADIATED FIELD FROM ONE EDGE SLOT
C...OF A MICROSTRIP PATCH
      COMPLEX CJ,FAC,EX,EY,EZ
      COMMON/DD1/EPS,T,HL,THIR,PHIR,THOR,PHOR,RI
      COMMON/DD2/CJ,PI,TPI,OPR
      SPS=SQRT(EPS)
      A=T/2.
      B=HL/2.
      CPHI=COS(PHIR)
      SPHI=SIN(PHIR)
      CTHI=COS(THIR)
      STHI=SIN(THIR)
      ARG1=TPI*A*CPHI*STHI*SPS
      ARG2=TPI*B*SPHI*STHI*SPS
      IF(ARG1.LT.1.E-4)GO TO 11
      F1=SIN(ARG1)/ARG1
      GO TO 12
   11 F1=1.
   12 IF(ABS(ARG2-PI/2.).LT.1.E-4)GO TO 13
      F2=COS(ARG2)/(ARG2*ARG2-PI*PI/4.)
      GO TO 14
   13 F2=-1./PI
   14 EPH=F1*F2*SPHI*CTHI
      ETH=-F1*F2*CPHI
      EXT=ETH*CTHI*CPHI-EPH*SPHI
      EYT=ETH*CTHI*SPHI+EPH*CPHI
      EZT=-ETH*STHI
C     EII=EXP*EXT
      EII=EXP*EXT+EYP*EYT+EZP*EZT
      CPH=COS(PHOR)
      SPH=SIN(PHOR)
      CTH=COS(THOR)
      STH=SIN(THOR)
      ARG1=TPI*A*CPH*STH*SPS
      ARG2=TPI*B*SPH*STH*SPS
      IF(ARG1.LT.1.E-4)GO TO 17
      F1=SIN(ARG1)/ARG1
      GO TO 18
   17 F1=1.
   18 IF(ABS(ARG2-PI/2.).LT.1.E-4)GO TO 19
      F2=COS(ARG2)/(ARG2*ARG2-PI*PI/4.)
      GO TO 20
   19 F2=-1./PI
   20 EPH=EII*F1*F2*SPH*CTH
      ETH=EII*(-F1*F2*CPH)
      FAC=CEXP(-CJ*TPI*RI)/RI
      EX=(ETH*CTH*CPH-EPH*SPH)*FAC
      EY=(ETH*CTH*SPH+EPH*CPH)*FAC
      EZ=-ETH*STH*FAC
      RETURN
      END

@PRT,S TT.SOURCE
```

```
3313929*SCAN(1).SOURCE(1)
              SUBROUTINE SOURCE(EXP,EYP,EZP)
        C...THIS SUBROUTINE GIVES SOURCE FIELD IN PATCH COORDINATE SYSTEM
              COMMON/DD3/XP,YP,FX,FY,FZ,IP
              IF(IP.EQ.1)GO TO 11
              SX=XP-FX
              SY=FZ
              SZ=YP-FY
              GO TO 12
         11   SX=FZ
              SY=YP-FY
              SZ=XP-FX
         12   SS=SQRT(SX*SX+SY*SY+SZ*SZ)
              UXS=SX/SS
              UYS=SY/SS
              UZS=SZ/SS
              THR=ACOS(UZS)
              PHR=ATAN2(UYS,UXS)
              IF(PHR.LT.0.)PHR=PHR+TPI
              EX=-COS(THR)*COS(PHR)
              EY=-COS(THR)*SIN(PHR)
              EZ=SIN(THR)
              IF(IP.EQ.1)GO TO 14
              EXP=EZ
              EYP=-EX
              EZP=-EY
              GO TO 15
         14   EXP=EZ
              EYP=EY
              EZP=-EX
         15   RETURN
              END

@PRT,S TT.EDGE
```

```
3313929*SCAN(1).EDGE(4)
            SUBROUTINE EDGE(RA,QX,EPND,EPRD)
      C...SINGLE EDGE DIFFRACTED FIELDS
            COMPLEX CJ,EPND,EPRD,FACP,FAC
            COMPLEX DS,DH,DPS,DPH
            COMMON/DD1/EPS,T,HL,THIR,PHIR,THOR,PHOR,RI
            COMMON/DD2/CJ,PI,TPI,DPR
            COMMON/DD3/XP,YP,FX,FY,FZ,IP
            XP=RA
            YP=0.
            CALL SOURCE(EX,EY,EZ)
            THOR=ATAN(FZ/RA)
            EPAT=COS(PI/2.-THOR)**QX
            EPNI=EX*SIN(THOR)+EZ*COS(THOR)
            EPRI=EY
            R=RA/COS(THOR)
            FAC=CEXP(-CJ*TPI*R)/R*EPAT
            PHP=THOR*DPR
            PH=THOR*DPR+90.
            IF(PHOR.GT.0.01)PH=90.-THOR*DPR
            CALL DW(DS,DH,DPS,DPH,R,PH,PHP,90.,2.)
            ENI=COS(THOR)
            ENS=COS(PI/2.-THOR)
            IF(PHOR.GT.0.01)ENS=COS(PI/2.+THOR)
            SGD=(1./R)-((ENI-ENS)/RA)
            RHO=ABS(1./SGD)
            FACP=CEXP(CJ*TPI*RA*SIN(THOR))
            IF(PHOR.GT.0.01)FACP=CEXP(-CJ*TPI*RA*SIN(THOR))
            EPND=EPNI*FAC*DH*SQRT(RHO)*FACP
            EPRD=EPRI*FAC*DS*SQRT(RHO)*FACP
            IF(SGD.LT.0.)EPND=EPND*CJ
            IF(SGD.LT.0.)EPRD=EPRD*CJ
            XP=-RA
            CALL SOURCE(EX,EY,EZ)
            EPNI=EX*SIN(THOR)-EZ*COS(THOR)
            EPRI=EY
            PH=90.-THOR*DPR
            IF(PHOR.GT.0.01)PH=THOR*DPR+90.
            CALL DW(DS,DH,DPS,DPH,R,PH,PHP,90.,2.)
            ENS=COS(PI/2.+THOR)
            IF(PHOR.GT.0.01)ENS=COS(PI/2.-THOR)
            SGD=(1./R)-((ENI-ENS)/RA)
            RHO=ABS(1./SGD)
            FACP=CEXP(-CJ*RA*TPI*SIN(THOR))
            IF(PHOR.GT.0.01)FACP=CEXP(CJ*RA*TPI*SIN(THOR))
            EPND=EPND+EPNI*FAC*DH*SQRT(RHO)*FACP
            EPRD=EPRD+EPRI*FAC*DS*SQRT(RHO)*FACP
            IF(SGD.LT.0.)EPND=EPND*CJ
            IF(SGD.LT.0.)EPRD=EPRD*CJ
            RETURN
            END

@PRT,S TT.DW
```

```
3313929*SCAN(1).DW(0)
            SUBROUTINE DW(DS,DH,DPS,DPH,R,PH,PHP,BO,FN)
      C *** WEDGE DIFFRACTION AND SLOPE DIFFRACTION COEFFICIENT ***
      C *** FOR THE SOFT AND HARD B.C. ***
            COMPLEX DIN,DIP,DPN,DPP,DS,DH,DPS,DPH
            BETN=PH-PHP
            CALL DI(DIN,R,BETN,BO,FN)
            CALL DPI(DPN,R,BETN,BO,FN)
            IF(ABS(PHP).GT.2.5E-4.AND.ABS(PHP).LT.(FN*180.-2.5E-4)
           &)GO TO 10
            DS=(0.,0.)
            DH=DIN
            DPS=DPN
            DPH=(0.,0.)
            RETURN
      10    CONTINUE
            BETP=PH+PHP
            CALL DI(DIP,R,BETP,BO,FN)
            CALL DPI(DPP,R,BETP,BO,FN)
            DS=DIN-DIP
            DH=DIN+DIP
            DPS=DPN+DPP
            DPH=DPN-DPP
            RETURN
            END

@PRT,S TT.DI
```

```
3313929*SCAN(1).DI(2)
                 SUBROUTINE DI(DIR,R,BET,BO,FN)
          C ***  INCIDENT (BET=PH-PHP) OR REFLECTED (BET=PH+PHP) ***
          C ***  PART OF WEDGE DIFFRACTION COEFFICIENT ***
                 COMPLEX TOP,COM,EX,UPPI,UNPI,FA,DIR
                 DATA PI,TPI,DPR/3.14159265,6.2831853,57.29577958/
                 ANG=BET/DPR
                 TOP=-CEXP(CMPLX(0.,-PI/4.))
                 DEM=2.*TPI*FN*SIN(BO/DPR)
                 COM=TOP/DEM
                 SQR=SQRT(TPI*R)
                 DNS=(PI+ANG)/(2.0*FN*PI)
                 SGN=SIGN(1.,DNS)
                 N=IFIX(ABS(DNS)+0.5)
                 DN=SGN*N
                 A=1.0+COS(ANG-2.0*FN*PI*DN)
                 BOTL = 2.0*SQRT(ABS(R*A))
                 EX=CEXP(CMPLX(0.0,TPI*R*A))
                 CALL FRNELS (C,S,BOTL)
                 C=SQRT(PI/2.0)*(0.5-C)
                 S= SQRT(PI/2.0)*(S-0.5)
                 FA=CMPLX(0.,2.)*SQR*EX*CMPLX(C,S)
                 RAG=(PI+ANG)/(2.0*FN)
                 TSIN=SIN(RAG)
                 TS=ABS(TSIN)
                 IF(TS.GT.1.E-5) GO TO 442
                 COTA=-SQRT(2.0)*FN*SIN(ANG/2.0-FN*PI*DN)
                 IF(COS(ANG/2.0-FN*PI*DN).LT.0.0) COTA=-COTA
                 GO TO 443
          442    COTA=SQRT(A)*COS(RAG)/TSIN
          443    UPPI=COM*COTA*FA
                 DNS=(-PI+ANG)/(2.0*FN*PI)
                 SGN=SIGN(1.,DNS)
                 N=IFIX(ABS(DNS)+0.5)
                 DN=SGN*N
                 A=1.0+COS(ANG-2.0*FN*PI*DN)
                 BOTL = 2.0*SQRT(ABS(R*A))
                 EX=CEXP(CMPLX(0.0,TPI*R*A))
                 CALL FRNELS (C,S,BOTL)
                 C=SQRT(PI/2.0)*(0.5-C)
                 S= SQRT(PI/2.0)*(S-0.5)
                 FA=CMPLX(0.,2.)*SQR*EX*CMPLX(C,S)
                 RAG=(PI-ANG)/(2.0*FN)
                 TSIN=SIN(RAG)
                 TS=ABS(TSIN)
                 IF(TS.GT.1.E-5) GO TO 542
                 COTA= SQRT(2.0)*FN*SIN(ANG/2.0-FN*PI*DN)
                 IF(COS(ANG/2.0-FN*PI*DN).LT.0.0) COTA=-COTA
                 GO TO 123
          542    COTA=SQRT(A)*COS(RAG)/TSIN
          123    UNPI=COM*COTA*FA
                 DIR=UPPI+UNPI
                 RETURN
                 END


@PRT,S TT.DPI
```

```
3313929*SCAN(1).DPI(0)
      SUBROUTINE DPI(DPIR,R,BET,BO,FN)
C *** INCIDENT (BET=PH-PHP) OR REFLECTED (BET=PH+PHP) ***
C *** PART OF WEDGE SLOPE DIFFRACTION COEFFICIENT ***
      COMPLEX TOP,COM,EX,UPPI,UNPI,FPA,DPIR
      DATA PI,TPI,DPR/3.14159265,6.2831853,57.29577958/
      ANG=BET/DPR
      SBO=SIN(BO/DPR)
      TOP=CEXP(CMPLX(0.,-PI/4.))
      DEM=4.*TPI*FN*FN*SBO*SBO
      COM=TOP/DEM
      DNS=(PI+ANG)/(2.0*FN*PI)
      SGN=SIGN(1.,DNS)
      N=IFIX(ABS(DNS)+0.5)
      DN=SGN*N
      A=1.0+COS(ANG-2.0*FN*PI*DN)
      BOTL = 2.0*SQRT(ABS(R*A))
      EX=CEXP(CMPLX(0.0,TPI*R*A))
      CALL FRNELS (C,S,BOTL)
      C=SQRT(PI/2.0)*(0.5-C)
      S= SQRT(PI/2.0)*(S-0.5)
      FPA=TPI*R*(CMPLX(0.,2.)+4.*SQRT(ABS(TPI*R*A))*EX*CMPLX(C,S))
      RAG=(PI+ANG)/(2.0*FN)
      TSIN=SIN(RAG)
      TS=TSIN*TSIN
      IF(TS.GT.1.E-5) GO TO 442
      CSCA=-2.*FN*FN*COS(ANG-TPI*FN*DN)/COS((PI+ANG)/FN)
      GO TO 443
  442 CSCA=A/TS
  443 UPPI=COM*CSCA*FPA
      DNS=(-PI+ANG)/(2.0*FN*PI)
      SGN=SIGN(1.,DNS)
      N=IFIX(ABS(DNS)+0.5)
      DN=SGN*N
      A=1.0+COS(ANG-2.0*FN*PI*DN)
      BOTL = 2.0*SQRT(ABS(R*A))
      EX=CEXP(CMPLX(0.0,TPI*R*A))
      CALL FRNELS (C,S,BOTL)
      C=SQRT(PI/2.0)*(0.5-C)
      S= SQRT(PI/2.0)*(S-0.5)
      FPA=TPI*R*(CMPLX(0.,2.)+4.*SQRT(ABS(TPI*R*A))*EX*CMPLX(C,S))
      RAG=(PI-ANG)/(2.0*FN)
      TSIN=SIN(RAG)
      TS=TSIN*TSIN
      IF(TS.GT.1.E-5) GO TO 542
      CSCA=-2.*FN*FN*COS(ANG-TPI*FN*DN)/COS((PI-ANG)/FN)
      GO TO 123
  542 CSCA=A/TS
  123 UNPI=COM*CSCA*FPA
      DPIR=UPPI-UNPI
      RETURN
      END

@PRT,S TT.FRNELS
```

313929*SCAN(1).FRNELS(0)

```
      SUBROUTINE FRNELS(C,S,XS)
C     THIS IS THE FRESNEL INTEGRAL SUBROUTINE WHERE THE INTEGRAL IS FROM
C     U=0 TO XS, THE INTEGRAND IS EXP(-J*PI/2.*U*U),AND THE OUTPUT IS
C     C(XS)-J*S(XS).
      DIMENSION A(12),B(12),CC(12),D(12)
      DATA A/1.595769140,-0.000001702,-6.808568854,-0.000576361,6.920691
     *902,-0.016898657,-3.050485660,-0.075752419,0.850663781,-0.02563904
     *1,-0.150230960,0.034404779/
      DATA B/-0.000000033,4.255387524,-0.000092810,-7.780020400,-0.00952
     *0895,5.075161298,-0.138341947,-1.363729124,-0.403349276,0.70222201
     *6,-0.216195929,0.019547031/
      DATA CC/0.,-0.024933975,0.000003936,0.005770956,0.000689892,-0.009
     *497136,0.011948809,-0.006748873,0.000246420,0.002102967,-0.0012179
     *30,0.000233939/
      DATA D/0.199471140,0.000000023,-0.009351341,0.000023006,0.00485146
     *6,0.001903218,-0.017122914,0.029064067,-0.027923955,0.016497308,-0
     *.005598515,0.000838386/
      DATA PI/3.14159265/
      IF(XS.LE.0.0) GO TO 414
      X=XS
      X = PI*X*X/2.0
      FR=0.0
      FI=0.0
      K=13
      IF(X-4.0) 10,40,40
   10 Y=X/4.0
   20 K=K-1
      FR=(FR+A(K))*Y
      FI=(FI+B(K))*Y
      IF(K-2) 30,30,20
   30 FR=FR+A(1)
      FI=FI+B(1)
      C=(FR*COS(X)+FI*SIN(X))*SQRT(Y)
      S=(FR*SIN(X)-FI*COS(X))*SQRT(Y)
      RETURN
   40 Y=4.0/X
   50 K=K-1
      FR=(FR+CC(K))*Y
      FI=(FI+D(K))*Y
      IF(K-2) 60,60,50
   60 FR=FR+CC(1)
      FI=FI+D(1)
      C=0.5+(FR*COS(X)+FI*SIN(X))*SQRT(Y)
      S=0.5+(FR*SIN(X)-FI*COS(X))*SQRT(Y)
      RETURN
  414 C=-0.0
      S=-0.0
      RETURN
      END
```

TP=10.368 SUP=6.107 CPU=.009 IO=2.609 CC-ER=3.488

BRKPT PRINTS

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16. Abstract

This publication presents an antenna system that has been proposed as one of the candidates for the SCANSCAT (Scanned Scatterometer) radar application. It is the mechanically steered planar microstrip reflectarray. Due to its thin, lightweight structure, the antenna's mechanical rotation will impose minimum angular momentum for the spacecraft. Since no power-dividing circuitry is needed for its many radiating microstrip patches, this electrically large array antenna demonstrates excellent power efficiency. In addition, this fairly new antenna concept can provide many significant advantages over a conventional parabolic reflector.

The basic formulation for the radiation fields of the microstrip reflectarray is presented. This formulation is based on the array theory augmented by the Uniform Geometrical Theory of Diffraction (UTD). A computer code for analyzing the microstrip reflectarray's performances, such as far-field patterns, efficiency, etc., is also listed in this report. It is proposed here that a breadboard unit of this microstrip reflectarray should be constructed and tested in the future to validate the calculated performance. The antenna concept presented here can also be applied in many other types of radars where a large array antenna is needed.

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