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Title: PROGRAM "SCATTER" FOR THE ANALYSIS OF DIELECTRIC MATCHING LAYERS

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PROGRAM "SCATTER" FOR THE ANALYSIS OF DIELECTRIC MATCHING LAYERS

Nancyjane Bailey and A. R. Kerr

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INTRODUCTION

Program SCATTER, written by Rachael Padman to calculate the co-polar and cross-polar reflection and transmission characteristics of grooved dielectric panels, is now available on the NRAO Charlottesville Convex. The original program is fully described in [1]. Two errors in the original program description have been corrected, as described in Appendix I.

The program is interactive, prompting the user for information about the characteristics of the dielectric slab, the frequencies of interest and the orientation of the incident wave. The results are output directly to standard output, and a summary of the output data is also placed into an ASCII file. This data file follows the conventions of a Lotus 123.PRN file and may be imported directly into a Lotus worksheet.

DEFINITION OF THE PROBLEM

As shown in Figure 1, the x, y, and z directions are defined by the orientation of the incident wave to the dielectric slab. The xy plane is the plane of the surface of the dielectric, while the yz plane is the plane of incidence, containing both the incident ray and the normal to the dielectric surface. The angle of incidence, θ, is the angle the incident ray makes with the normal to the dielectric surface. The optic axis lies in the plane of the dielectric surface and is perpendicular to the grooves. The angle ϕ is that between the normal to the plane of incidence and the direction of the grooves. An incident wave is said to be TE if its E-field is perpendicular to the plane of incidence, and TM if its E-field lies in the plane of incidence. The output reflection and transmission coefficients are given as co-polar and cross-polar TE and TM components.

The co- and cross-polar reflection coefficients for incident TE and TM waves are complex quantities and are defined as follows:

R_{11} is the x-component of the reflected E-field when a pure TE wave, with $E_x = 1$, is incident on the slab.

R_{21} is the y-component of the reflected E-field when a pure TE wave, with $E_x = 1$, is incident on the slab.

R_{12} is the x-component of the reflected E-field when a pure TM wave, with $E_y = 1$, is incident on the slab.

R_{22} is the y-component of the reflected E-field when a pure TM wave, with $E_y = 1$, is incident on the slab.

The transmission coefficients T_{ij} are defined in an analogous way.

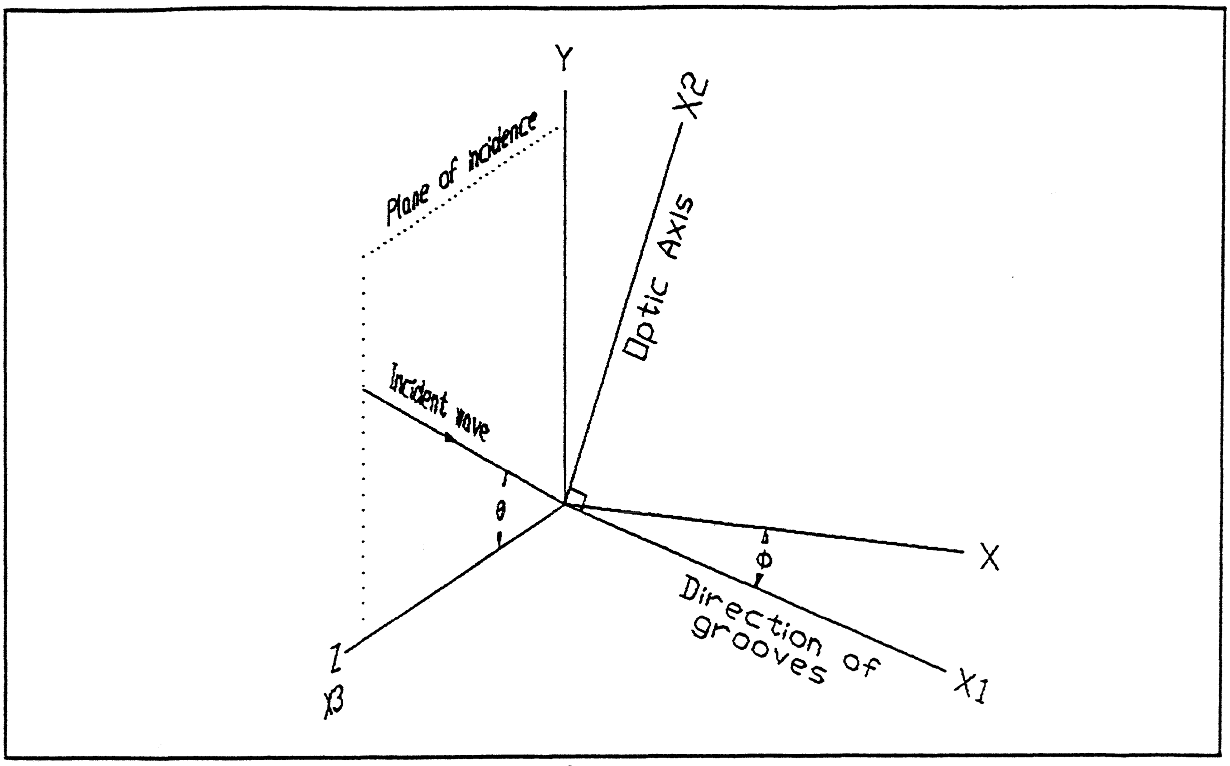

Fig. 1. Definition of axes and angles.

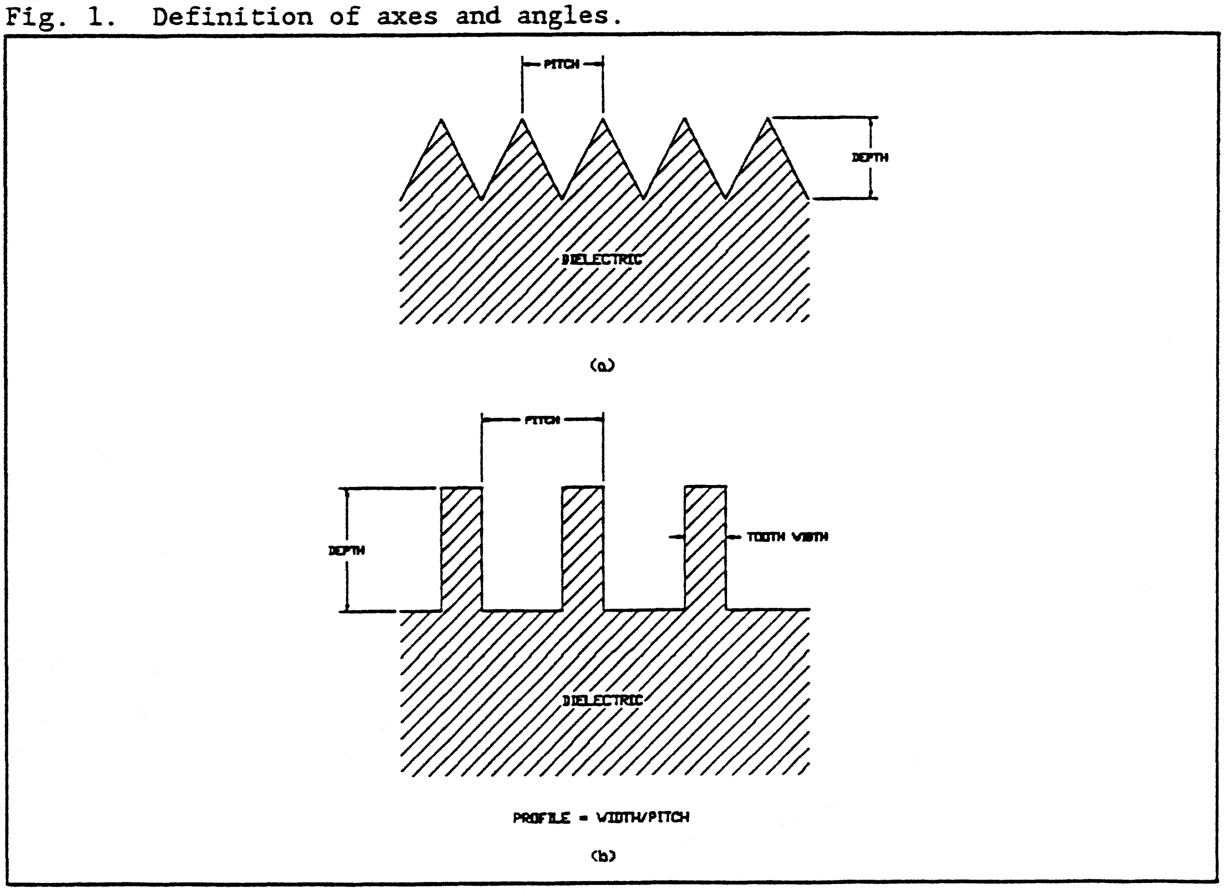

Fig. 2. Triangular and rectangular grooves.

PROGRAM "SCATTER" FOR TRIANGULAR AND RECTANGULAR GROOVES

SCATTER was designed to be quite general, computing the reflection and transmission coefficients of an anisotropic layer whose dielectric tensor varies with z in an arbitrary manner. The version obtained from Padman was a modified version of the original SCATTER of [1], and was configured to analyze a dielectric slab with triangular grooves (Figure 2(a)). Subroutine GROOVE defines the variation of the dielectric tensor with depth. By making a change in the function PROFILE (called by subroutine GROOVE), it was possible to modify the program to analyze a slab with rectangular grooves (Figure 2(b)). Both versions are on the NRAO Charlottesville Convex. SCATTER12 is for triangular grooves and SCATTER13 is for rectangular grooves. SCATTER12 and SCATTER13 differ only in the definition of the function PROFILE(z), whose value gives the ratio of the width of the tooth to the tooth spacing (pitch), as a function of distance z normal to the slab. Both versions of the code are reasonably well documented; code originally written by Padman but incompatible with the Convex was simply commented out and remains in the source code.

Appendix I describes corrections to the original SCATTER report and Fortran code [1].

EXAMPLES

Example 1 -- Verification of program SCATTER at normal incidence

To check operation of the program, it was used to analyze a thick slab of PTFE ($\epsilon_r = 2.1$) with rectangular grooves designed to provide perfect matching at 230 GHz to a normally incident wave with E-field perpendicular to the grooves. This occurs when the effective dielectric constant of the grooved layer is SQRT(2.1) and the groove depth = λ_0/SQRT(2.1). The tooth width is chosen to give the desired effective dielectric constant using the series capacitor analogy, which is valid provided the groove pitch << $\lambda_0/2$. Specifically the following parameter values were used:

Dielectric constant $\epsilon_r = 2.1$
Angle between x-axis and grooves $\phi = 0$
Angle of incidence $\theta = 0$
Total slab thickness = 1.5 cm
Groove depth = 0.0271 cm
Groove pitch = 0.0065 cm
Tooth width = 0.0038 cm
Grooves on two surfaces not crossed

Figure 3 shows the results for R_{11} and R_{22} computed by SCATTER13. As expected, R_{22} becomes extremely small at 230 GHz. The interference between reflections from the two sides of the slab are seen as the fast ripple superimposed on the slower frequency response of the individual grooved layers. Appendix II shows the dialogue with the program, and the results displayed on the monitor screen for this example.

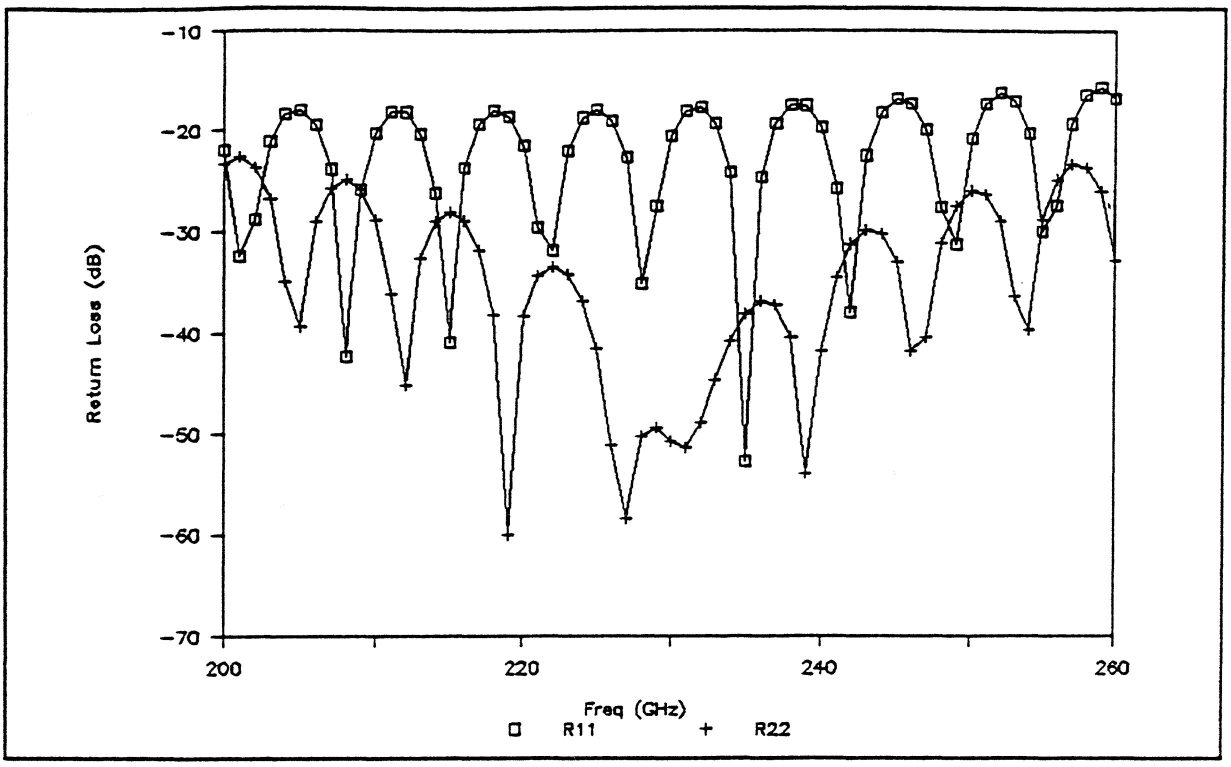

Fig. 3. Example 1: Test of program SCATTER using a PTFE window with parallel rectangular grooves on both faces. The grooves are designed to be perfectly matched for normal incidence at 230 GHz when the E-field is perpendicular to the grooves.

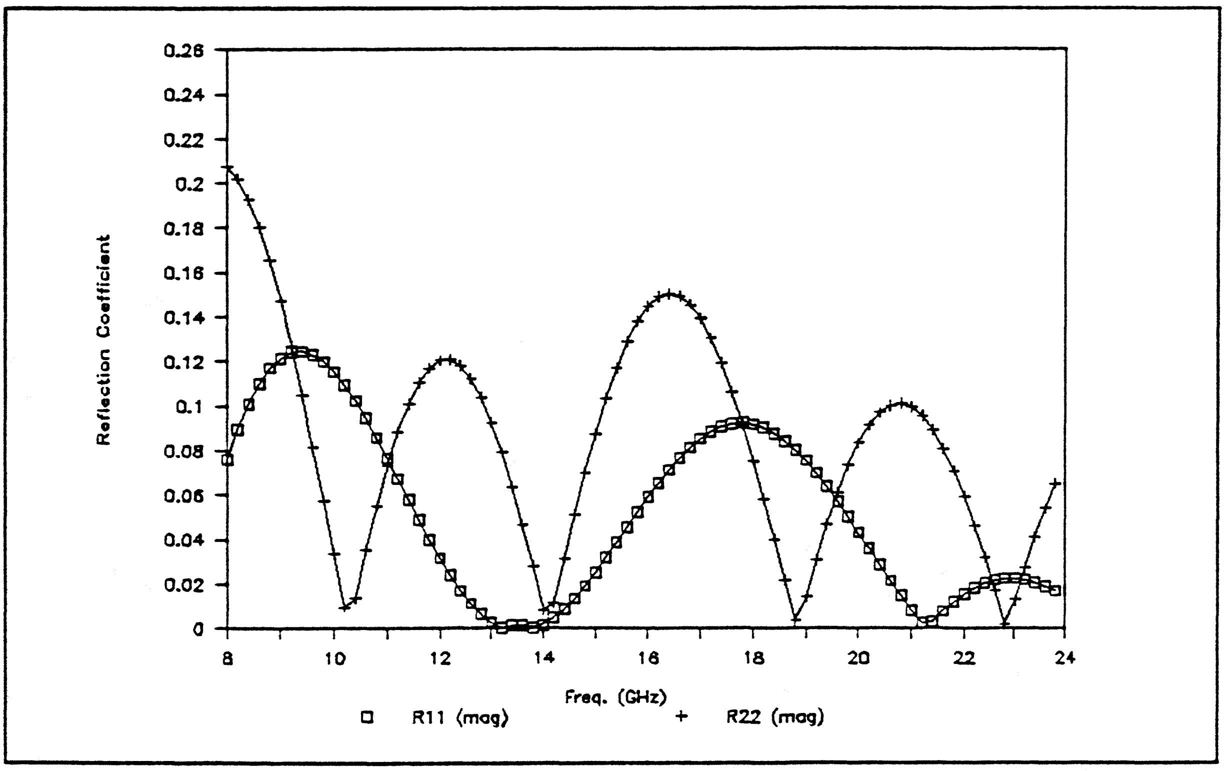

Fig. 4. Example 2: Verification of the program using Padman's results in [2]. Compare with Fig. 1 of [2].

Example 2 -- Verification of Padman's results in reference [2].

This example reproduces the results of Padman's IEEE-AP paper [2] using SCATTER12. The results in Figure 4 are in close agreement with the published results.

Example 3 -- A 230-GHz PTFE window with triangular grooves for use at normal incidence.

This window has parallel grooves on the two surfaces. The depth and pitch of the triangular grooves were chosen to give acceptably low reflections for both polarizations -- a tool angle of 23° is used in this example:

Dielectric constant $\epsilon_r = 2.1$
Angle between x-axis and grooves $\phi = 0$
Angle of incidence $\theta = 0$
Total slab thickness = 0.4666 cm
Groove depth = 0.1066 cm
Groove pitch = 0.0432 cm
Grooves on two surfaces not crossed

The computed values of R_{11} and R_{22} for this window are shown in Figure 5.

Example 4 -- A 230-GHz PTFE window with rectangular grooves for use at normal incidence.

It is of interest to compare the window with triangular grooves in example 3 with one using rectangular grooves of comparable pitch. Following example 1, the tooth width was chosen to give PROFILE = 0.592, and the groove depth was λ_0/SQRT(2.1). Thus:

Dielectric constant $\epsilon_r = 2.1$
Angle between x-axis and grooves $\phi = 0$
Angle of incidence $\theta = 0$
Total slab thickness = 0.4666 cm
Groove depth = 0.0271 cm
Groove pitch = 0.0432 cm
Tooth width = 0.0256 cm
Grooves on two surfaces not crossed

The values of R_{11} and R_{22} computed using SCATTER13 are shown in Figure 6. Figure 7 shows the effect on R_{22} of changing the groove depth by ± 20% (± 0.0054 cm). For comparison, Figure 8 shows the effect of a ± 0.0213 cm (± 20% of groove depth) change of position of the grooving tool on the window with triangular grooves in Example 3. Note that, with a triangular grooving tool, making the grooves too deep while maintaining constant pitch and groove angle is equivalent to reducing the slab thickness. Clearly, the window with triangular grooves is much less sensitive to groove depth errors than the one with rectangular grooves.

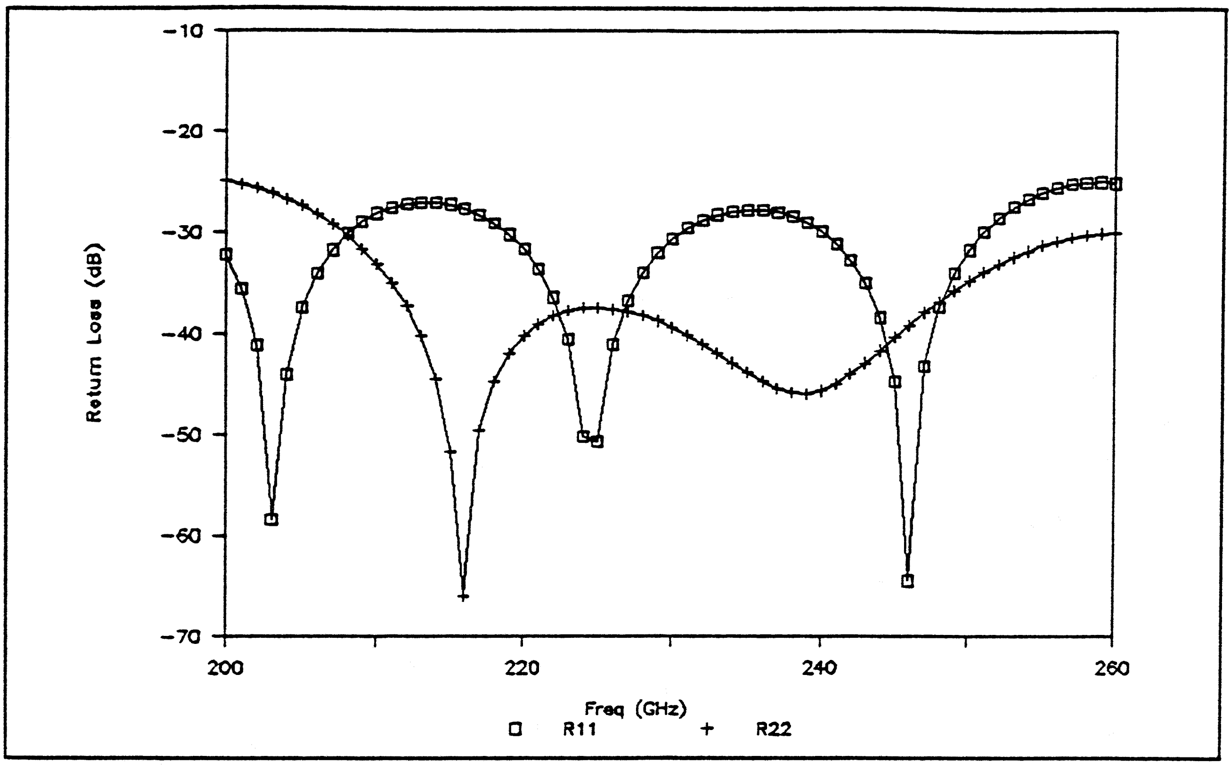

Fig. 5. Example 3: A 230 GHz PTFE window with triangular grooves parallel on the two faces.

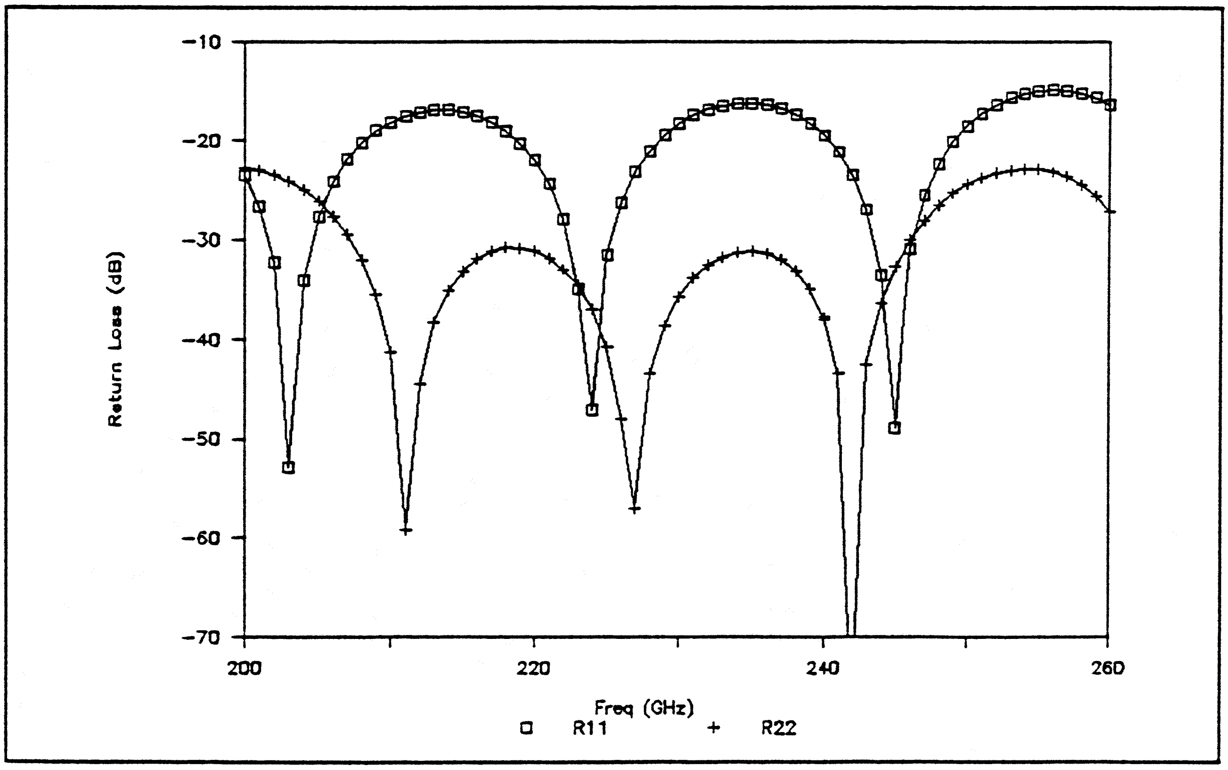

Fig. 6. Example 4: A 230 GHz PTFE window with rectangular grooves parallel on the two faces.

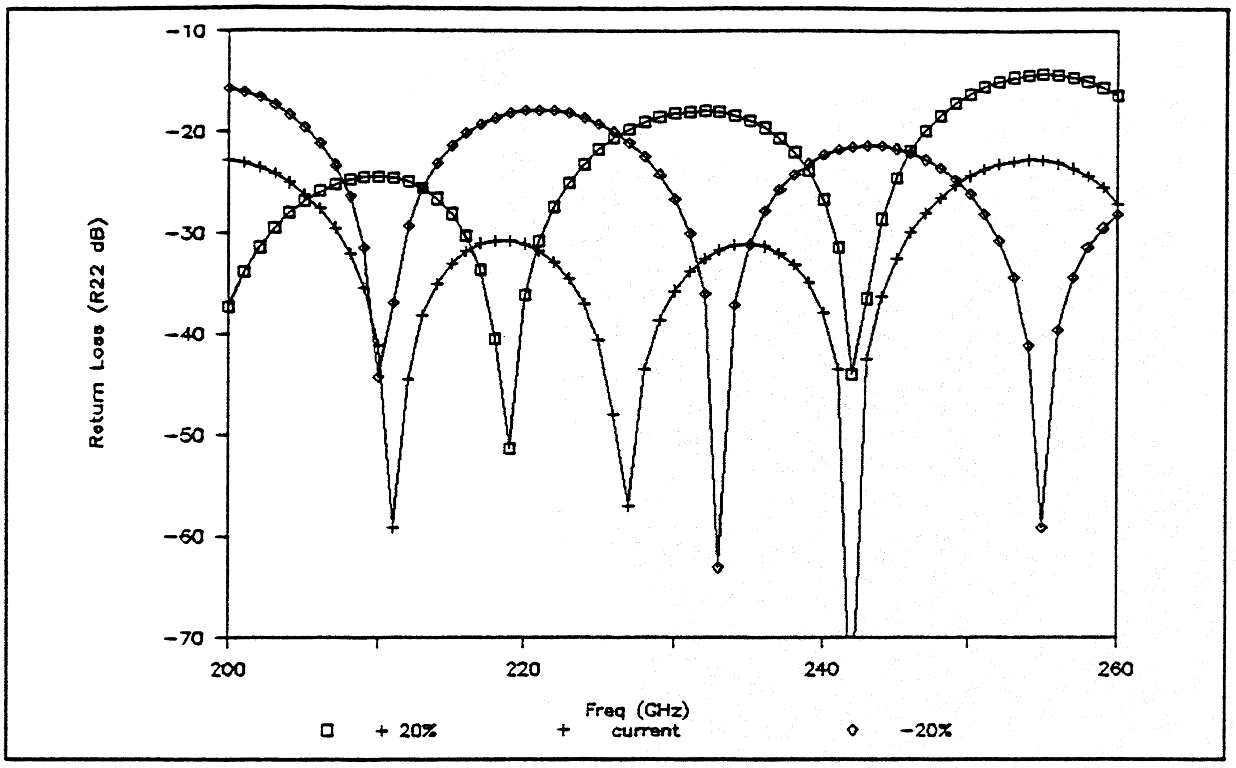

Fig. 7. Example 4: R_{22} for the rectangular grooved window of Fig. 6. The curves show the effect of a 20% change in groove depth.

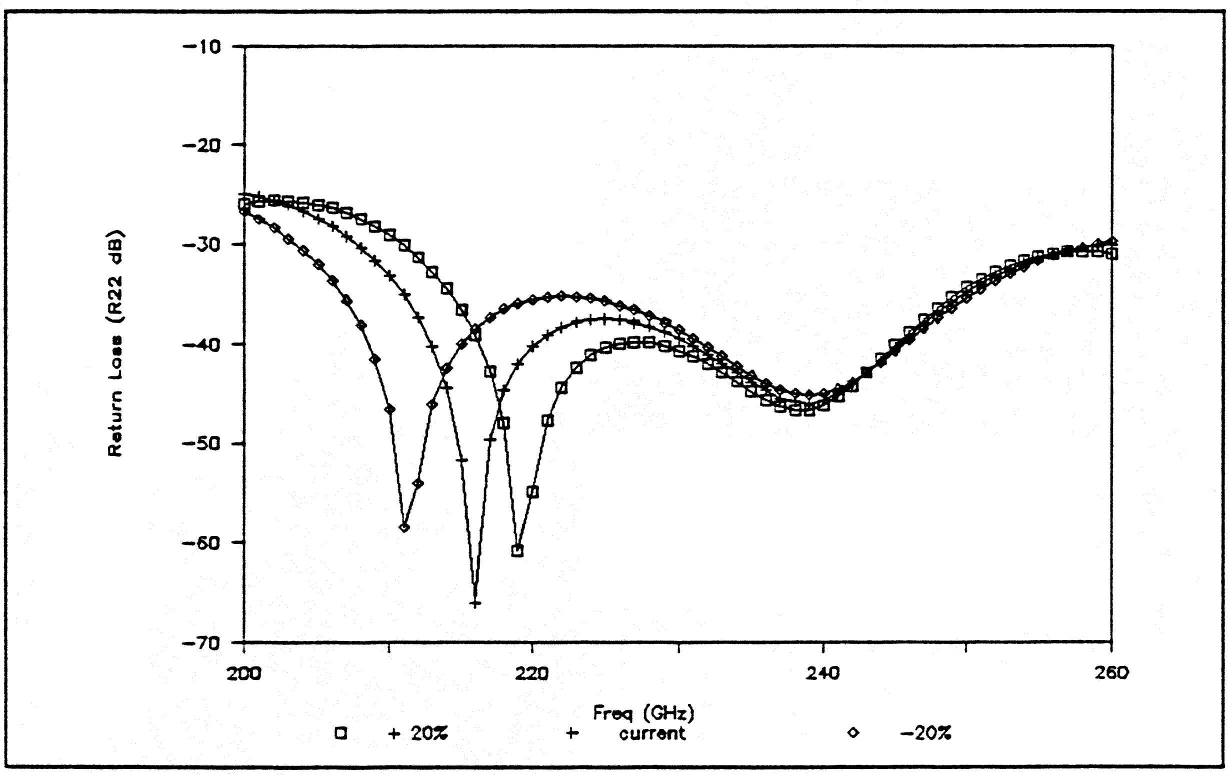

Fig. 8. R_{22} for the triangular grooved window of Fig. 5. The curves show the effect of an error in depth of the grooving tool equal to 20% of the groove depth.

ACKNOWLEDGEMENT

We thank Rachael Padman for providing us with the original version of SCATTER, and for her invaluable assistance with the program.

REFERENCES:

[1] R. Padman, "Program SCATTER - A Program for the Calculation of Plane-Wave Propagation in a Stratified Anisotropic Dielectric," CSIRO Division of Radiophysics Internal Report RPP 2031(L), December 1976.

[2] R. Padman, "Reflection and Cross Polarization Properties of Grooved Dielectric Panels," *IEEE Trans. Antennas Prop.*, vol. AP-26, pp. 741-743.

APPENDIX I: CORRECTIONS TO THE ORIGINAL SCATTER REPORT AND CODE

One correction is necessary in the original Fortran code of program SCATTER [1]: At the beginning of the listing of SCATTER, a comment defining PHI should be changed to read "PHI, ANGLE BETWEEN THE NORMAL TO THE PLANE OF INCIDENCE (X-AXIS) AND THE GROOVES." In the current NRAO working versions of SCATTER, a corresponding change has been made in the question which asks for PHI.

On page 3 of ref. [1], item (iii) should read "The optic axis is parallel to the surface of the dielectric and is at the same angle $(\pi/2 - \phi)$ to the x-axis for all values of z...."

The example at the top of page 3 is made more consistent with the ensuing discussion if it is changed to read "....if $\epsilon^*_{11} = \epsilon^*_{33}$ the optic axis of the dielectric lies in the x_2 direction."

On page 16, the meaning is clearer if near the middle of the page, "...$\epsilon_{22} = \epsilon_{33}$..." is changed to read "...$\epsilon_{11} = \epsilon_{22} = \epsilon_{33} = \epsilon$ (all derivatives equal to zero)..."

APPENDIX II: DIALOGUE WITH SCATTER13 DURING EXECUTION OF EXAMPLE 1.

```
% scatter13
This is scatter 13, used to analyze dielectrics with
rectangular grooves.
What is the angle between the X axis and the grooves (in deg.)?
0
Angle of incidence?
0
Number of steps for integration?
50
Dielectric constant?
2.1
Total slab thickness (cm.)?
1.5
Groove depth (cm) ?
.0271
Groove pitch (cm) ?
.0065
What is the tooth width (cm.) ?
.0038
type the name of the output file (8 char with .prn)
fig3.prn
Are the grooves crossed (y/n) ?
n
Print dielectric constant profile (y/n) ?
n
Start frequency (GHz)?
200
End frequency (GHz) ?
260
frequency increment?
30


Scattering parameters of grooved dielectric window:
 - normal to plane of incidence at          0.     degrees from groove axis
 - angle of incidence  =                    0.     degrees

Window details:
 - Grooves on opposite faces are Parallel
 - Dielectric constant =    2.100000
 - Groove depth        =   2.7100001E-02 cm
 - Groove pitch        =   6.5000001E-03 cm
 - Slab thickness      =    1.500000     cm
 - Tooth Width         =   3.8000001E-03 cm

Calculation details:
 - Start frequency     =    200.0000    GHz
 - Finish frequency    =    260.0000    GHz
 - Frequency step      =    30.00000    GHz
 - coupled PDEs solved by numerical integration in          50 steps
Frequency =    200.0000     GHz
FY(0) = (  1.000000      ,          0.     ) FX(0) =
 (  1.000000      ,         0.     )
HX(0) = (  1.000000      ,          0.     ) HY(0) =
 ( -1.000000      ,         0.     )
Power check:
 - Perpendicular polarization =    1.000083
 - Parallel polarization      =   0.9999956
Transmission matrix coefficients:
 - T11 =  (-0.9013337    ,-0.4257584    ) = ( 0.9968313    , -154.7156    )
 - T12 =  (        0.    ,        0.    ) = (        0.    ,        0.   )
 - T21 =  (        0.    ,        0.    ) = (        0.    ,        0.   )
 - T22 =  (-0.8097652    ,-0.5827530    ) = ( 0.9976576    , -144.2591    )
```

```
Co-polar transmission losses:
 - TX11 =   2.7566694E-02 dB
 - TX22 =   2.0369722E-02 dB
Reflection matrix coefficients:
 - R11 = (-3.4194946E-02, 7.2398214E-02) = ( 8.0067453E-02,  115.2822     )
 - R12 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R21 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R22 = (-3.9935470E-02, 5.5498242E-02) = ( 6.8373213E-02,  125.7381     )
Co-polar reflection losses:
 - RX11 =    21.93088     dB
 - RX22 =    23.30228     dB
 - VSWRX =    1.174072
 - VSWRY =    1.146782
Frequency =    230.0000     GHz
FY(0) = (  1.000000     ,        0.     ) FX(0) =
 (  1.000000     ,       0.     )
HX(0) = (  1.000000     ,        0.     ) HY(0) =
 ( -1.000000     ,       0.     )
Power check:
 - Perpendicular polarization =    1.000231
 - Parallel polarization      =    1.000175
Transmission matrix coefficients:
 - T11 = (-0.8169441    , 0.5692861    ) = ( 0.9957331     ,  145.1294     )
 - T12 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - T21 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - T22 = (-0.9253492    , 0.3793353    ) = (  1.000083     ,  157.7095     )
Co-polar transmission losses:
 - TX11 =   3.7141792E-02 dB
 - TX22 =  -7.2270620E-04 dB
Reflection matrix coefficients:
 - R11 = (-5.3473592E-02,-7.6729770E-02) = ( 9.3524761E-02, -124.8730     )
 - R12 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R21 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R22 = ( 1.1129379E-03, 2.7239709E-03) = ( 2.9425578E-03,  67.77647     )
Co-polar reflection losses:
 - RX11 =    20.58147     dB
 - RX22 =    50.62550     dB
 - VSWRX =    1.206348
 - VSWRY =    1.005903
Frequency =    260.0000     GHz
FY(0) = (  1.000000     ,        0.     ) FX(0) =
 (  1.000000     ,       0.     )
HX(0) = (  1.000000     ,        0.     ) HY(0) =
 ( -1.000000     ,       0.     )
Power check:
 - Perpendicular polarization =    1.000238
 - Parallel polarization      =    1.000271
Transmission matrix coefficients:
 - T11 = ( 6.7534151E-02, 0.9873560    ) = ( 0.9896629     ,  86.08714     )
 - T12 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - T21 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - T22 = (-0.1676458    , 0.9857202    ) = ( 0.9998746     ,  99.65221     )
Co-polar transmission losses:
 - TX11 =   9.0254329E-02 dB
 - TX22 =   1.0893499E-03 dB
Reflection matrix coefficients:
 - R11 = (-0.1439046    , 9.8483772E-03) = ( 0.1442412     ,  176.0850     )
 - R12 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R21 = (       0.     ,       0.     ) = (       0.     ,        0.    )
 - R22 = (-2.2512555E-02,-3.8339820E-03) = ( 2.2836692E-02, -170.3351     )
Co-polar reflection losses:
 - RX11 =    16.81821     dB
 - RX22 =    32.82734     dB
 - VSWRX =    1.337107
 - VSWRY =    1.046741
Do you want to run again (y/n)?
n
```

APPENDIX III: .PRN FILE PRODUCED BY SCATTER13 DURING EXECUTION OF EXAMPLE 1.

```
"This is scatter 13, used to analyze dielectrics with"
"rectangular grooves."
" - normal to plane of incidence at ",        0.     ,"degrees from groove axis"
" - Angle of incidence is ",                  0.
"Window details:"
" - Grooves on opposite faces are Parallel "
" - Dielectric constant = ",   2.100000
" - Groove depth        = ",  2.7100001E-02," cm"
" - Groove pitch        = ",  6.5000001E-03," cm"
" - Slab thickness      = ",   1.500000    ," cm"
" - Tooth Width         = ",  3.8000001E-03" cm"
"Calculation details:"
" - Start frequency     = ",   200.0000    ," GHz"
"- Finish frequency    = ",   260.0000    ," GHz"
" - Frequency step      = ",   30.00000    ," GHz"
" - coupled PDEs solved by numerical integration in ",          50," steps"

"Freq. GHz.", "magT11", "magT12", "magT21", "magT22", "magR11", "magR12", "magR21", "magR22"
200.00, 0.9968, 0.0000, 0.0000, 0.9977, 0.0801, 0.0000, 0.0000, 0.0684
230.00, 0.9957, 0.0000, 0.0000, 1.0001, 0.0935, 0.0000, 0.0000, 0.0029
260.00, 0.9897, 0.0000, 0.0000, 0.9999, 0.1442, 0.0000, 0.0000, 0.0228
```