NATIONAL RADIO ASTRONOMY OBSERVATORY
GREEN BANK, WEST VIRGINIA

ELECTRONICS DIVISION INTERNAL REPORT No. 177

A DIRECTIONAL FILTER FOR LOCAL OSCILLATOR INJECTION IN A MILLIMETER-WAVE MIXER RADIOMETER

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AUGUST 1977

NUMBER OF COPIES: 150

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ABSTRACT

The advent of mixer radiometers with large tuning ranges operating at a wavelength of three millimeters creates the need for a local oscillator injection scheme which will provide low signal power and local oscillator power losses over the entire operating range of the receiver. The purpose of this paper is to report on the development of a directional filter for use in an 80-120 GHz mixer radiometer. A unique use of the mode properties of a resonant ring filter allows a very wide tuning range (85-115 GHz LO) with little degradation in filter performance. The directional nature of the filter, together with the resonant characteristic, provides both low signal path loss (0.2 dB) and low local oscillator path loss (4 dB).

I. BACKGROUND

The proposed radiometer will tune continuously from 80 to 120 GHz (signal frequency) with an IF frequency of 4.75 GHz and an instantaneous bandwidth of 650 MHz. The first stage of the receiver is a broadband diode mixer with no RF tuning, allowing both the signal and image bands to be down converted to the IF. The entire front end and first IF amplifier will be cooled to 20° K to improve the noise performance. A method of supplying the local oscillator power to the mixer is required. The injection scheme must provide a low loss path for the signal and the image simultaneously and should provide a reasonable loss in the local oscillator path because of local oscillator power limitations. The injection scheme must cover the entire operating range of the receiver and, if tunable, must be adjustable remotely without opening the dewar.

The traditional solution to the problem of local oscillator injection is presented in Figure 1. The directional coupler is chosen to provide the least signal loss due to coupling, consistent with available local oscillator power. A typical coupler for use in a 100 GHz receiver will have a -10 dB coupling factor and a mainline resistive loss of about 0.5 dB. The total signal power loss for this coupler is about 1 dB (0.55 dB coupling loss + 0.5 dB resistive loss), representing a significant decrease in receiver sensitivity. The local oscillator power loss is about 10 dB. The broadband nature of the coupling allows receiver operation over essentially the full waveguide band with no tuning required. The directional coupler represents an inexpensive, broadband solution to the problem of local oscillator injection; however, a solution yielding a lower signal path and local oscillator loss would be desirable. There exist several other techniques for injecting the local oscillator power, each with its attendant disadvantages.

II. RING FILTER

The proposed solution to the problem of local oscillator injection is presented in Figure 2. The injection filter is a 4-port device consisting of a traveling-wave resonant ring filter tuned to the local oscillator frequency and two directional couplers. The signal power is coupled from port 2 to port 3. The local oscillator power is coupled from port 1 to the resonant ring via one directional coupler and then to port 3 via the second directional coupler. The directional nature of the couplers prevents the flow of local oscillator power to ports 2 and 4, while the resonant ring prevents the coupling of signal power from port 2 to ports 1 and 4. Signal power loss is limited to resistive loss in the 2 to 3 path. There is virtually no signal loss due to coupling because of the resonant nature of the ring and the signal-local oscillator frequency separation. Local oscillator power loss is limited to the resistive loss in the resonant ring. The resonant frequency of the ring filter is varied by altering the guide wavelength in the waveguide forming the ring. This directional filter represents a low loss solution to the problem of local oscillator injection.

The design of the traveling-wave filter is based largely on the work of Coale (1) and Tischer (2). The ring is formed by a circular section of rectangular waveguide (TE_{10}) which is closed upon itself to form a ring. The waveguide ring is split along the center line of the broad wall of the waveguide. This allows the broad dimension, and hence the guide wavelength in the ring, to be varied for tuning. Power is coupled into and out of the ring through two narrow-wall multi-hole couplers. For a ring of broad dimension a and mean circumferential length, L, the resonant wavelength, λ, is given approximately by (1):

$$\lambda_{res} = \frac{1}{\sqrt{n^2/L^2 + 1/4a^2}}$$

where n represents the integer number of wavelengths around the ring at resonance. For a given guide width, a, there are an infinite number of resonances which will couple power from port 1 to port 3. The first few are shown in Figure 3. As we alter the guide width the "comb structure" representing the filter transmission modes moves along the frequency axis. One can operate the filter over any tuning range by increasing the ring waveguide width, a. There are three pertinent points to be noted.

The first point involves the restrictions which must be placed on the number of wavelengths, n, which one can fit around the ring. For a given guide wavelength there is a lower limit placed on the circumference of the ring, and hence n, by the requirement that two directional couplers be realized along this circumference. The upper limit is placed on n by the minimum mode spacing requirements and loss considerations. The longer the guide, the greater the local oscillator power transmission loss and the smaller the mode spacing.

The second point involves the allowable range of the guide width, a. If the guide width is too narrow the guide wavelength becomes too long to be of use and the loss increases. As the guide width is increased to effect the tuning of the filter a gap appears between the ring halves. As the width of the gap increases, power is coupled through the gap, representing a loss, significantly lowering the cavity Q thereby increasing the transmission loss of the filter.

The third point involves the presence of more than one transmission frequency or mode. Multiple modes do not seriously affect the local oscillator to mixer coupling; however, if a mode were to fall in either the signal or image frequency band some power would be coupled from port 2 to port 4 representing a loss in the input path, decreasing the receiver sensitivity.

The practical filter is limited in tuning range by the finite range of the guide width, a, and the limitations placed on the mode number, n. As an example consider the following design, based on the receiver requirements listed above. Consideration of the above points, in particular the third point, leads to the following choices for the ring parameters:

n = 16
L = 3"
a = .085" to .125" (.040" gap)

The tuning range of this filter will then be:

a = .085" = .126"   f = 93.7 GHz

a = .125" = .150"   f = 78.6 GHz

This represents a fractional tuning range of less than 20%, far short of the

40% (80-120 GHz) required for receiver operation. The gap of .040" would represent a large power loss, considerably affecting the transmission loss of the filter. The gap in the ring must be kept small.

One solution to this problem is to note that any of the resonances may be used. It is not necessary to move one resonance, as was done in the example above, to achieve the tuning range. It is necessary only to move the n^{th} resonance to the frequency location of the n+1 resonance. Since the entire comb moves, a large frequency range can be covered simply by choosing the proper mode and alterning the waveguide width to move that mode to the required frequency. In the example above, to move the n = 16 mode to the frequency of the n = 17 mode requires a change in guide width of .004 inches. This is a significant improvement in gap width. It is possible, using this technique, to construct a filter which has both low loss properties and a wide tuning range.

III. DESIGN

The first step in the design is the selection of the ring circumferential length, L, and the range of the ring guide width, a. The ring length is chosen to give the desired mode spacing consistent with coupler relizability. Care must be taken to assure that neither the image nor the signal band falls at the frequency of an adjacent mode. It is desirable to keep the ring as short as possible, in order to minimize loss. The ring waveguide width range, Δa, is chosen to give the tuning required to completely cover the region between the modes. Since the mode spacing and tuning rate are non-linear, care must be taken to assure that each mode covers its required range. It is desirable to choose values for a which yield a guide wavelength in a lower loss region of the guide attenuation curve.

The second step is the design of the couplers. It is usual to make the couplers identical. The following equation relates the transmission loss through the filter to the voltage coupling coefficient, C, and the loaded Q, Q_L, of the filter.

$$L \text{ (dB)} = 20 \log \frac{1 - (1 - C^2)\ C^{-\alpha L}}{C^2\ e^{-\alpha L/2}}$$

$$Q_L \cong n\pi/C^2\ 10^{\text{Loss (dB)}/20}$$

where α is the attenuation constant of the ring waveguide. The transmission loss of the filter is the more important of the two parameters in this case. Since we wish to minimize the local oscillator power loss the couplers will be designed accordingly. The accompanying decrease in the loaded Q is not a problem because of the high IF frequency. The coupler directivity requirement is determined from microwave circuit considerations for the case in question. The coupler is designed by any of the techniques presented in the literature.

IV. THE FILTER

The design of the filter proceeded as outlined above. To achieve a signal frequency range of 80-120 GHz the local oscillator must be tuned from about 85-115 GHz (LO above at the lower end and below at the upper end). A ring length of 3 inches was chosen to give the signal-LO-image relationship shown in Figure 4. Note that one mode has been allowed to fall between the LO (main mode) and the signal-image bands.

The couplers are chosen to each give a -10 dB coupling factor with a directivity in excess of 20 dB over the 85-115 GHz band, representing the best balance between loss and coupler relizability. The coupler design is based on the designs given by Levy (3). A Chebyshev tapered multi-hole array with circular apertures is chosen. Machining considerations dictate the use of the less efficient circular apertures. The coupling array is located in the very thin (.005 inch) common wall of the ring guide and signal/LO guides. The couplers are arranged symmetrically about the circular ring. Both couplers are mounted in the same half of the ring guide to allow for the tuning motion. The pertinent coupler dimensions are shown in Figure 5. Calculated coupler response is shown in Figures 5a and 5b.

The filter is fabricated of tellurium-copper, chosen because of its favorable machining characteristics. The filter is constructed in three pieces to allow for machining. The structure is aligned with steel guide pins. The rather odd waveguide pattern is chosen both for convenient final mounting considerations and to allow for relatively easy machining of the guides. The pattern is machined using an end mill equipped with a rotary table. The completed filter is gold plated for corrosion protection. Mechanical drawings and photographs of the filter are present in Appendix A.

The tuning of the filter presents special problems because of the high tuning sensitivity (600 GHz/inch) and the fact that the tuning must be accomplished at 20° Kelvin. The high tuning sensitivity leads to the use of a differential screw (400:1). The position of the screw is measured by a differential transformer, the core being connected to the high speed center screw of the differential pair. This type of position sensor gives the high resolution needed to measure the ring gap accurately and will operate at 20° Kelvin. A gear box is provided to interface the screw with the motor shaft in a convenient manner. Ball bearings are used throughout to minimize friction since no lubricant can be used. Careful choice of materials to minimize problems due to differential expansion is of the utmost importance.

Experience with the type of tuning mechanism described above leads to a decision to simplify the arrangement. While the above arrangement works adequately it is painfully slow. While the springs remove most of the backlash in the screw, stiction in the screw leads to a jerky tuning motion, making the tuning of the filter difficult in practice. An unexpected problem occurs when the servo fails. Since the servo remains on at all times any failure in the electronics causes the motor to drive the screw past the mechanical limits causing considerable damage to the tuning mechansim. In practice this has happened often enough to warrant attention. A step toward remedying these problems has been undertaken. Mechanical drawings and photographs of the tuning mechanism are present in Appendix B.

A new tuning mechanism is illustrated in Appendix C. The motion necessary to tune the ring is provided by a cam driven by a gear box. All gears, as well as the cam yoke, are spring loaded to remove backlash. The mechanism provides the required tuning resolution without the use of screws. The cam provides a very smooth movement without the binding tendency inherent in the differential screw. Since the cam is cyclical there are no mechanical limits which can be exceeded, causing damage to the mechanism, as with the differential screw arrangement. The mechanism is designed to be directly interchangeable with the existing mechanism. Tests on the new unit are not complete at this time.

V. ANALYSIS

A computer program to evaluate the performance of the filter is included in Appendix D. The program computes the amount of power coupled from the local oscillator port to the other three ports. An effort has been made to use the most appropriate model for the directional coupler and ring. The program is partitioned in the form of subroutines to provide for ease of implementation.

In addition to the main routines several utility routines have been included since they are not widely available. The usage should be clear from the listing. A sample problem is included. A description of each subroutine follows.

The subroutine CPLR calculates the complex reflection and coupling coefficients for two transmission lines coupled together periodically. The program utilizes a rigorous 4-port network analysis, rather than the usual weak coupling analysis, to yield accurate estimates of coupling and directivity. The analysis takes into account the dispersive nature of the transmission lines, transmission line losses, and the infinite number of waves being coupled back and forth by the coupler. The coupling coefficients of the apertures are based on Bethe's small hole theory as modified by Cohn to consider aperture resonance phenomena and the finite thickness of the wall containing the apertures. Aperture interaction due to evanescent modes is not considered. The true electrical length of the coupler is calculated to allow improved estimates of the resonant frequencies and mode spacings of the ring resonator. The analysis is based on articles by Riblat (4) and Levy (5). It should be noted that the use of this program is not limited to the coupler in question but may be used for any coupled transmission line problem by insertion of the appropriate expressions for the coupling reactances.

The conventions used are illustrated in Figure 6. Consider a wave of amplitude a_1 incident on port 1. With all ports terminated in the characteristic impedance of the transmission line the waves emerging from the four ports are as follows:

Port 1: $b_1 = R_0 \; a_1$

Port 2: $b_2 = KR \; a_1$

Port 3: $b_3 = KH \; a_1$

Port 4: $b_4 = T_{12} \; a_1$

where R_0, T_{12}, KR, and KH are the complex reflection and coupling coefficients. Since the coupler is symmetrical and reciprocity holds, any port may be taken as the input with the same results. Therefore, the reflection coefficient, R_0, for all ports is the same; the thru arm forward coupling, T_{12}, is the same as the thru arm reverse coupling, T_{21}, etc. An example of the application of these quantities for the coupler as it is excited in the filter is presented in Figure 7. The figure is self-explanatory.

The subroutine FILTER calculates the power delivered to each of the other three ports with a wave of unit amplitude entering port 1. All ports are assumed terminated in their characteristic impedance. The port numbering conventions are presented in Figure 2. The analysis considers waves traveling in both directions around the ring and resistive losses in the ring. A brief description of the method is presented.

The analysis is carried out in terms of the wave cascading matrix [R]. If the amplitudes of the incident waves are a_1 and a_2 and the amplitudes of outgoing waves are b_1 and b_2 as illustrated in Figure 8, then the waves are related as follows:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

The ring is divided into segments, each of which is characterized by its R-cascading matrix. Figure 9 illustrates the segmentation. The length of the coupler waveguides which are part of the ring is just the number of coupling holes times the hole spacing. The length of the waveguides which connect the two couplers to form the ring is half the balance necessary to make up the ring. Thus,

$$2\ (\#\text{ holes} \times \text{hole spacing} + \text{length connecting guide}) = L.$$

The upper directional filter is characterized as a 2-port with accompanying R matrix. This is allowed if we restrict incident waves to ports 1 and 2. The R matrix for this portion of the ring is:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{T_{12}} \begin{bmatrix} 1 & -R_0 \\ R_0 & T_{12}^2 - R_0^2 \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

where the quantities are defined as above.

The two sections of connecting waveguide are represented by:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} e^{\Gamma L} & 0 \\ 0 & e^{-\Gamma L} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

where $\Gamma = \alpha + j\beta$ is the complex propagation constant.

These three elements of the ring are now cascaded to yield a representation of the upper half of the ring as illustrated in Figure 10. The R matrix for the entire structure is:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{T_{12}} \begin{bmatrix} e^{\Gamma L} & 0 \\ 0 & e^{-\Gamma L} \end{bmatrix} \begin{bmatrix} 1 & -R_0 \\ R_0 & T_{12}^2 - R_0^2 \end{bmatrix} \times$$

$$\times \begin{bmatrix} e^{\Gamma L} & 0 \\ 0 & e^{-\Gamma L} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

The upper portion of the ring is interfaced with the lower portion using the conventions illustrated in Figure 11. With the coupler parameters as defined above the relations among the various waves are:

$$\begin{aligned}
b_1 &= a_1\, R_0 + a_3\, KH + a_4\, KR \\
b_2 &= a_1\, T_{12} + a_3\, KR + a_4\, KH \\
b_3 &= a_1\, KH + a_3\, R_0 + a_4\, T_{12} \\
b_4 &= a_1\, KR + a_3\, T_{12} + a_4\, R_0
\end{aligned}$$

We now define the matrix:

$$\begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} = \frac{1}{T_{12}} \begin{bmatrix} e^{\Gamma L} & 0 \\ 0 & e^{-\Gamma L} \end{bmatrix} \begin{bmatrix} 1 & -R_0 \\ R_0 & T_{12}^2 - R_0^2 \end{bmatrix} \begin{bmatrix} e^{\Gamma L} & 0 \\ 0 & e^{-\Gamma L} \end{bmatrix} .$$

Then solving the following for a_3 and a_4

$$\begin{bmatrix} a_3 \\ b_3 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} b_4 \\ a_4 \end{bmatrix}$$

yields

$$a_3 = (R_{21} - R_{22}\, R_{11}/R_{12})\, b_4 + \frac{R_{22}}{R_{12}}\, b_3$$

$$a_4 = \frac{b_3 - R_{11}\, b_4}{R_{12}}$$

which when substituted in the set of four simultaneous equations above yields in matrix form:

$$\begin{bmatrix} -a_1 KR \\ -a_1 KH \\ -a_1 T_{12} \\ -a_1 R_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & (R_0/R_{12} + R_{22}\ T_{12}/R_{12}) & \left\{\left[T_{12}\left(R_{21} - \frac{R_{22}}{R_{12}} R_{11}\right) - \frac{R_0 R_{11}}{R_{12}}\right] - 1\right\} \\ 0 & 0 & (R_0\ R_{22}/R_{12} + T_{12}/R_{12} - 1) & \left[R_0\left(R_{21} - \frac{R_{22}}{R_{12}} R_{11}\right) - \frac{T_{12}R_{11}}{R_{12}}\right] \\ 0 & -1 & \left(\frac{KR\ R_{22}}{R_{12}} + \frac{KH}{R_{12}}\right) & \left[KR\left(R_{21} - \frac{R_{22}}{R_{12}} R_{11}\right) - \frac{KH\ R_{11}}{R_{12}}\right] \\ -1 & 0 & \left(\frac{KH\ R_{22}}{R_{12}} + \frac{KR}{R_{12}}\right) & \left[KH\left(R_{21} - \frac{R_{22}}{R_{12}} R_{11}\right) - \frac{R_{11}}{R_{12}} KR\right] \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

This represents a set of four simultaneous equations in four unknowns. If we call the 4 x 4 matrix BFM, then

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \left[BFM^{-1}\right] \begin{bmatrix} -a_1\ KR \\ -a_1\ KH \\ -a_1\ T_{12} \\ -a_1\ R_0 \end{bmatrix}$$

We now have an expression for the four waves necessary to completely characterize the filter. Waves b_3 and b_4 characterize the output side of the filter. Waves b_1 and b_2 characterize the input side of the filter. Output waves b_5 and b_6 can be found as follows: Waves b_3 and b_4 represent the waves at the exits of the input coupler. These waves are transformed around the ring to the input of the output coupler and then:

$$b_5 = a_4'\ KH + a_3'\ KR$$

$$b_6 = a_4'\ KR + a_3'\ KH$$

where the primed quantities are the waves after transformation around the ring as described above. Waves b_1 and b_2 are the outward flowing waves in the input coupler main line.

The quantities used in the above analysis are complex; consequently the programs are written to handle complex expressions. Several mathematical functions such as the complex hyperbolic sine and a routine for the inversion of a complex matrix were not available on the system used by myself. The subroutines were written and are included. The methods used are straightforward. The matrix inversion is accomplished using the standard Gauss-Jordon pivoted method, with thanks to IBM. These routines are general and may be useful elsewhere. Plotting routines have not been included as they are very system dependent.

VI. RESULTS

The measured response of the filter at room temperature is presented in Figures 12 and 13. No measurements of the antenna port to mixer port loss is included due to the difficulty of measuring these small quantities accurately in this frequency range. The signal loss is about .3 dB. There is a slight improvement in local oscillator transmission loss when the filter is cooled to 20° Kelvin. The filter response agrees fairly well with the design. The discrepancies are thought to be due largely to inaccuracies in the coupler design and the uncertainty in the high frequency value of the skin depth. The overall response of the filter is considered to be very good, representing a significant improvement over other injection schemes.

The choice of the mode spacing together with the mode characteristics of the filter yield a filter without spurious modes. This property allows for ease of tuning. Mechanical limits prevent the filter from being tuned more than one mode spacing. This assures that at any operating frequency the filter need be tuned only to the closest mode without fear of reduced filter performance due to mode selection errors. In practice one need not be concerned with which mode he is operating on.

This injection filter represents an improved solution to the problem of local oscillator injection in millimeter wave radiometers. The filter gives excellent electrical and mechanical performance and can be implemented with moderate efforts, as compared to other schemes. In addition to use an an LO injection filter, this type of filter has many other uses. Filters of this type are currently in use in receivers of the NRAO at Kitt Peak, Arizona.

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge the help and encouragement of Drs. S. Weinreb and A. R. Kerr and the machinists, on whose patience and skill so much depended, W. Luckado and Garnet Taylor.

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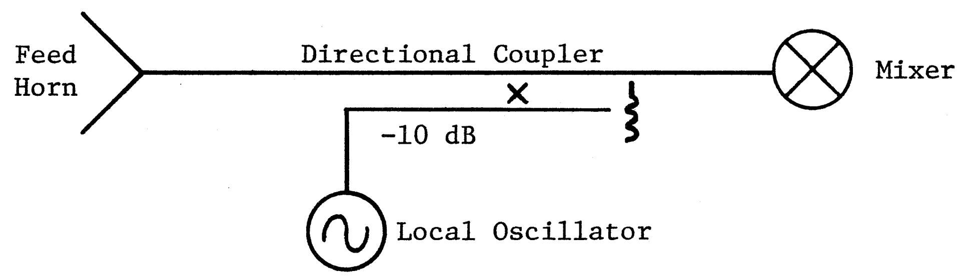


Figure 1: Directional coupler used in local oscillator injection scheme.

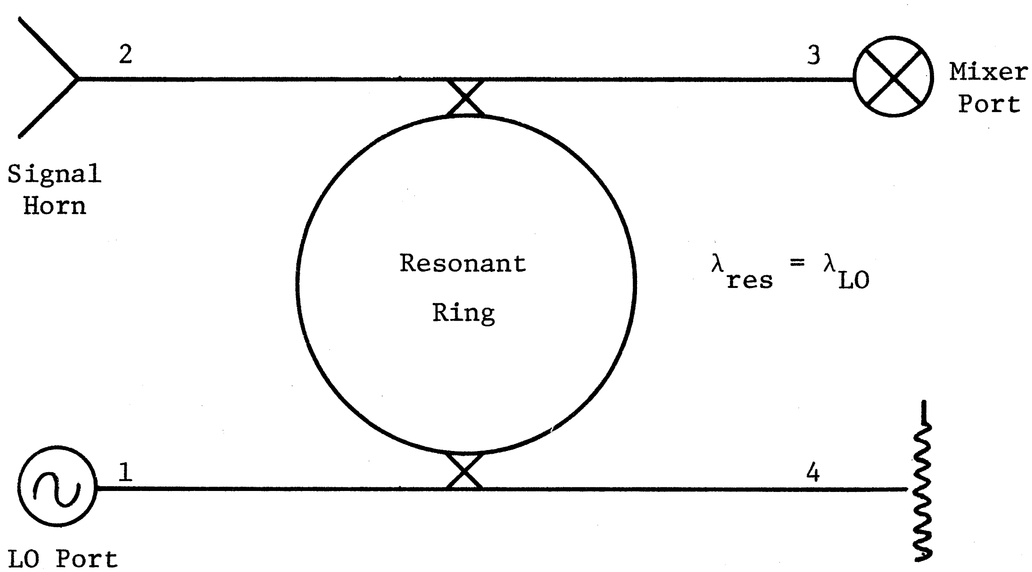
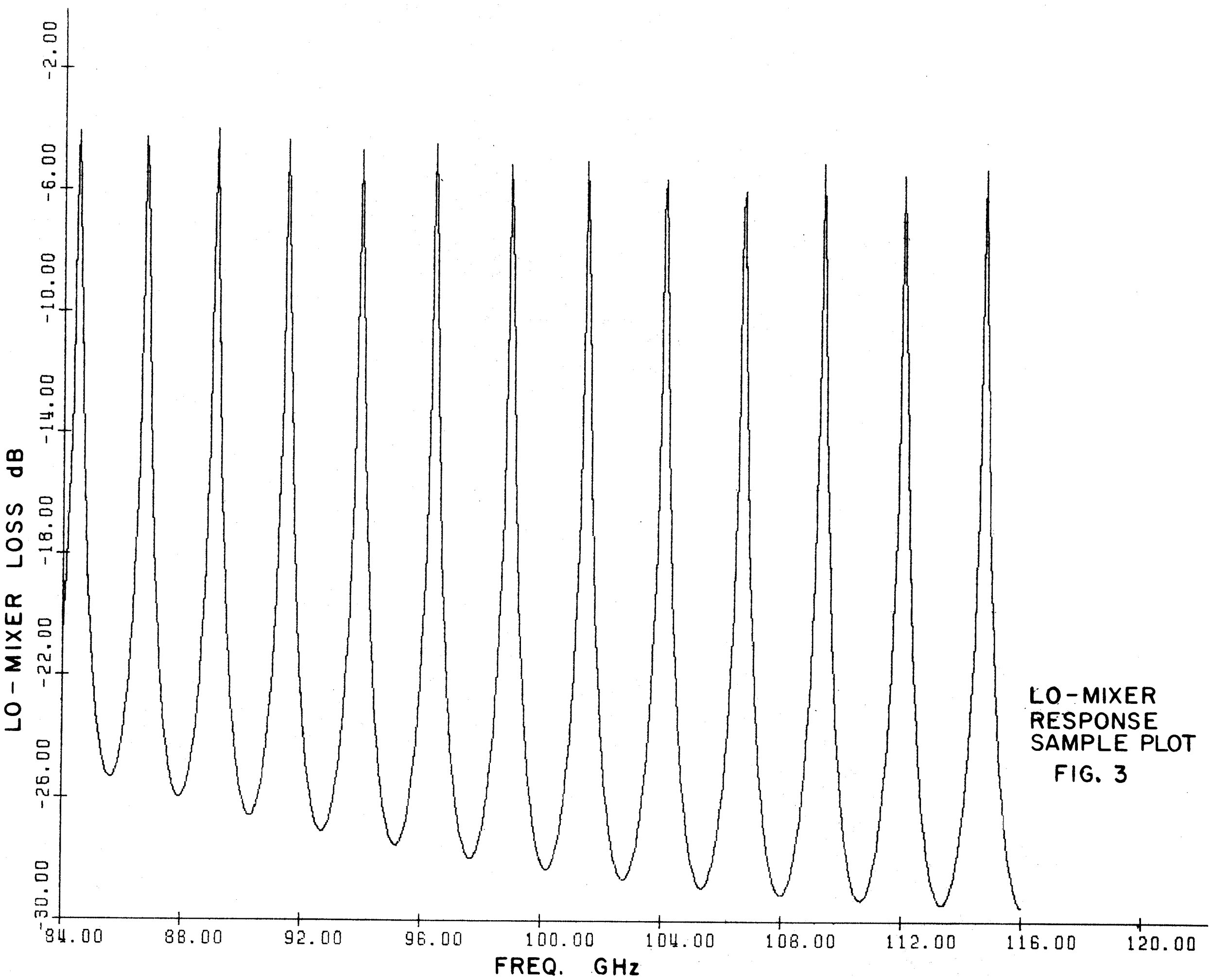
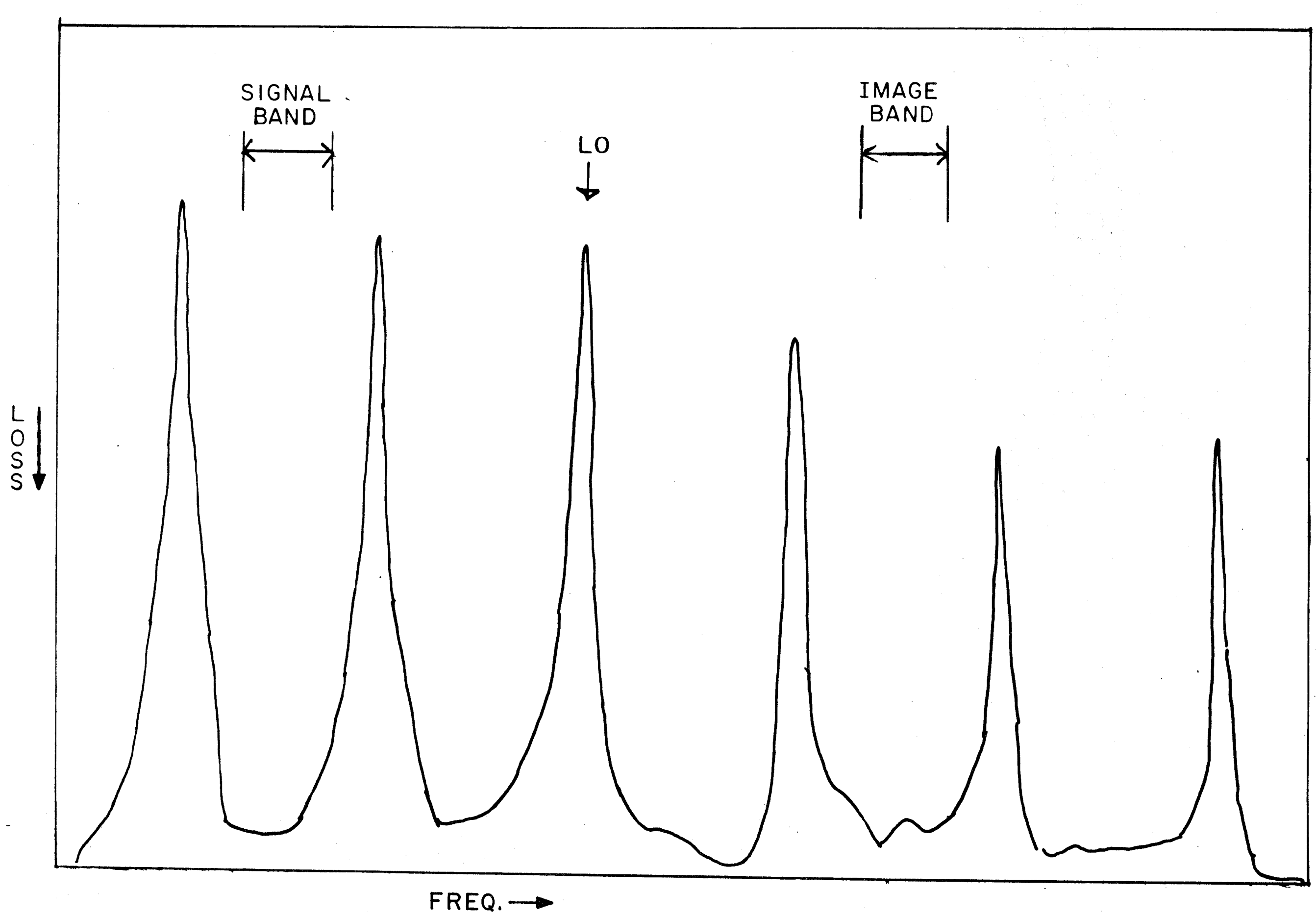


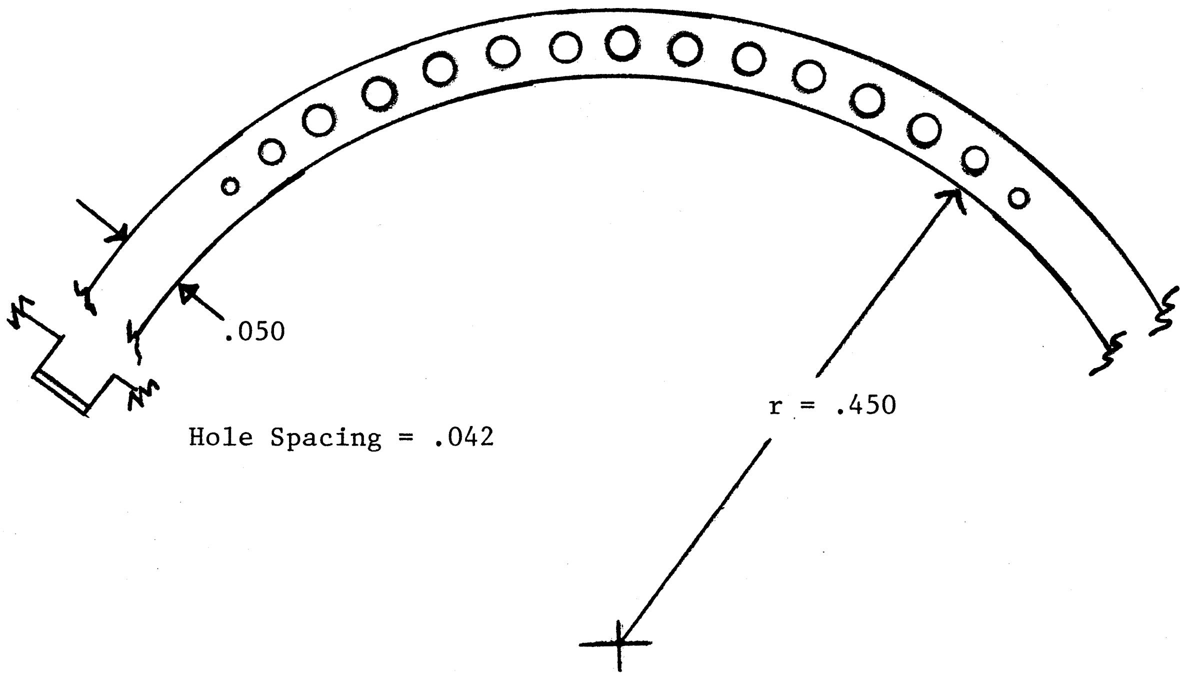
Figure 2: Resonant ring filter used for local oscillator injection.



LO-MIXER RESPONSE SAMPLE PLOT
FIG. 3



SIGNAL & IMAGE BAND RELATIONSHIPS
FIG. 4



#	Dia. (in.)
1	.018
2	.028
3	.034
4	.036
5	
6	
7	
8	
9	
10	
11	
12	.036
13	.034
14	.028
15	.018

Figure 5: Directional coupler dimensions for 10 dB coupling, 85-115 GHz.

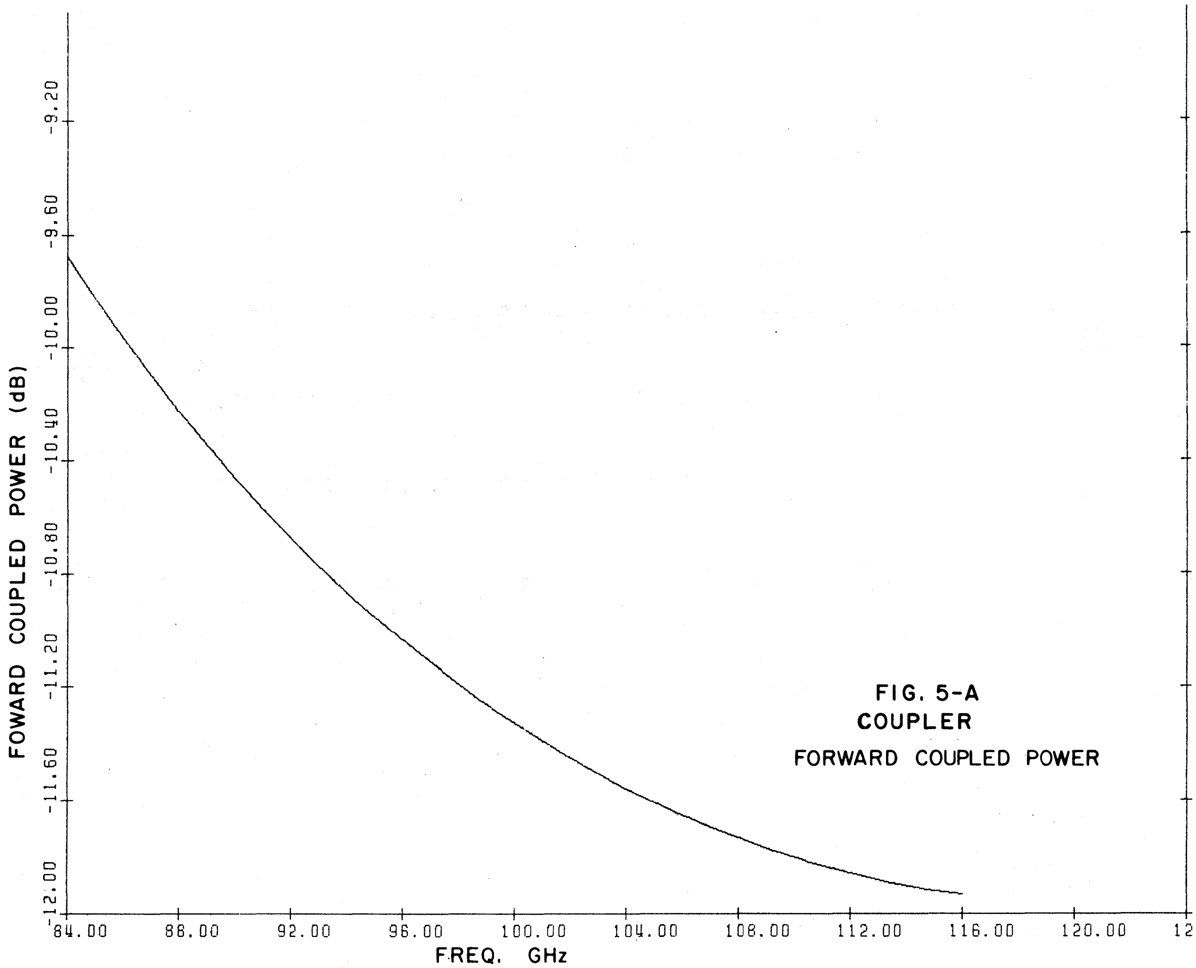


FIG. 5-A
COUPLER
FORWARD COUPLED POWER

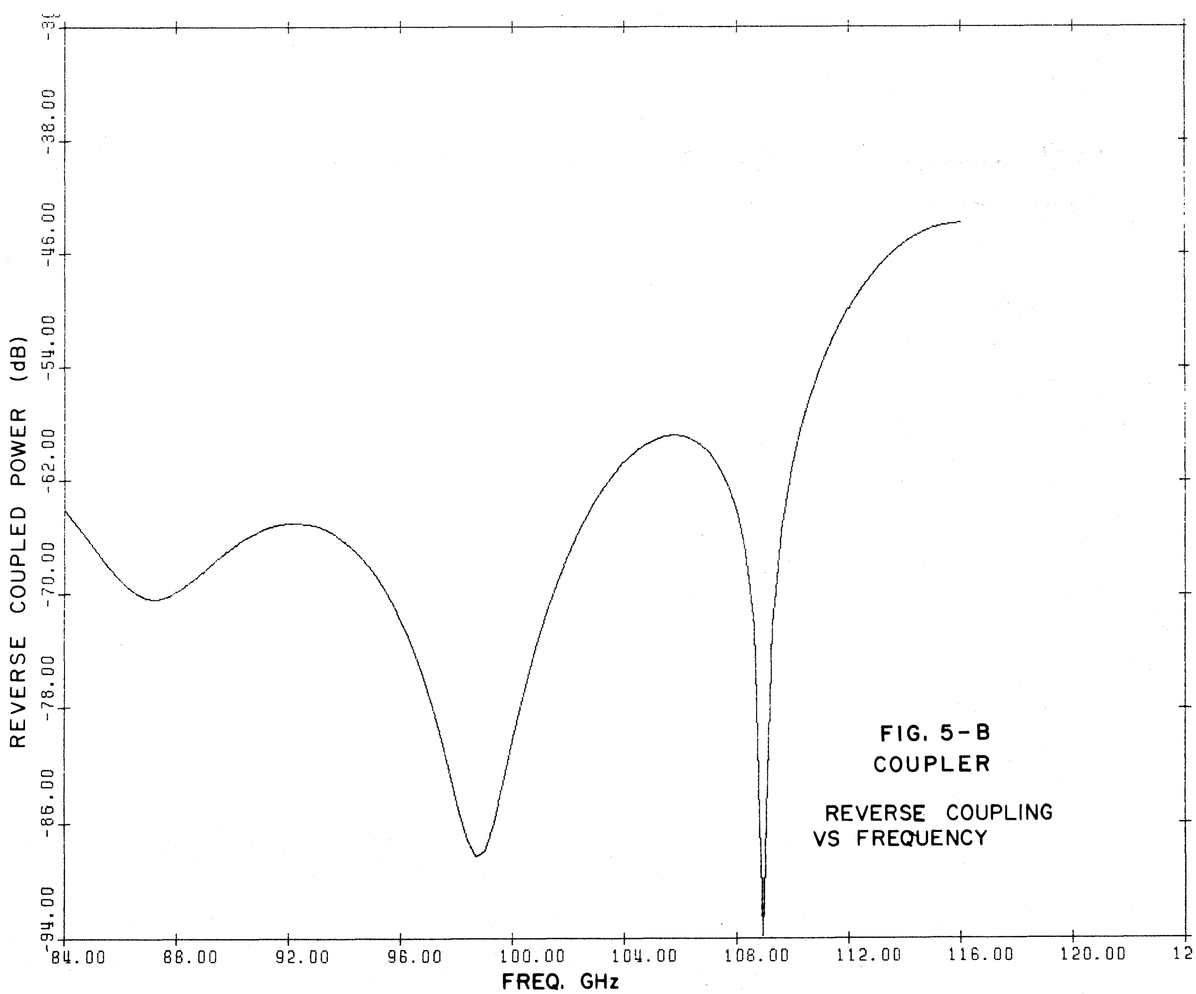


FIG. 5-B
COUPLER
REVERSE COUPLING
VS FREQUENCY

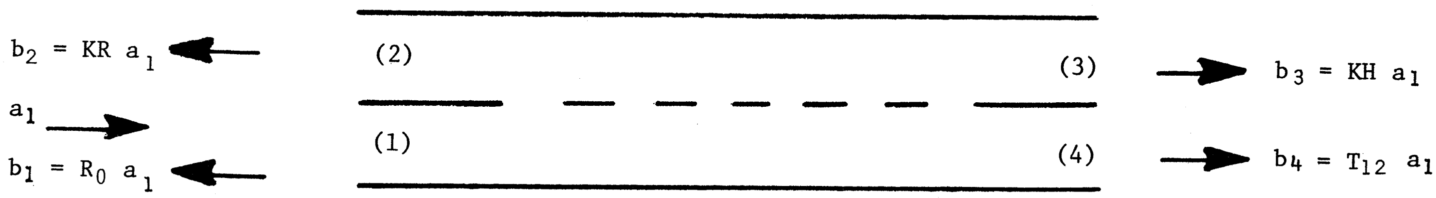
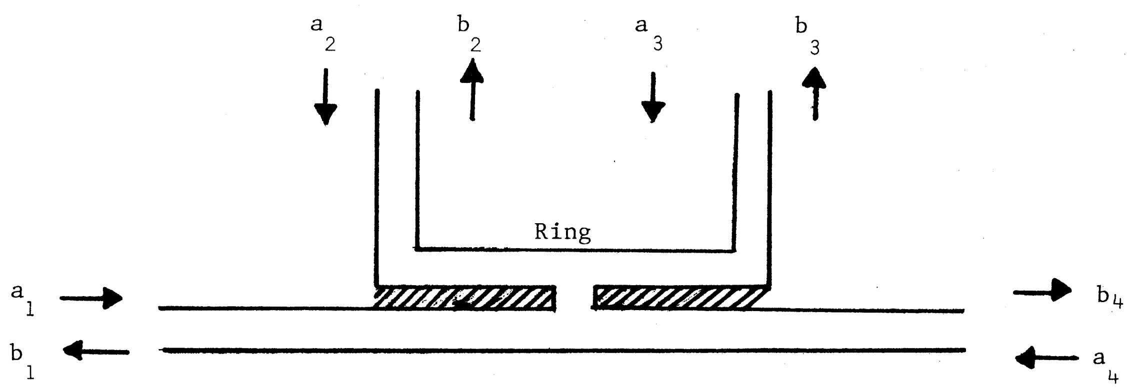


Figure 6: Coupler wave conventions.



$b_1 = a_1 R_0 + a_2 KR + a_3 KH + a_4 T_{12}$

$b_2 = a_1 KR + a_2 R_0 + a_2 T_{12} + a_4 KH$

$b_3 = a_1 KH + a_2 T_{12} + a_3 R_0 + a_4 KR$

$b_4 = a_1 T_{12} + a_2 KH + a_3 KR + a_4 R_0$

R_0 = Reflection coefficient.

KR = Reverse coupling.

KH = Forward coupling.

T_{12} = Thru arm coupling.

Figure 7: Power flow in coupler.

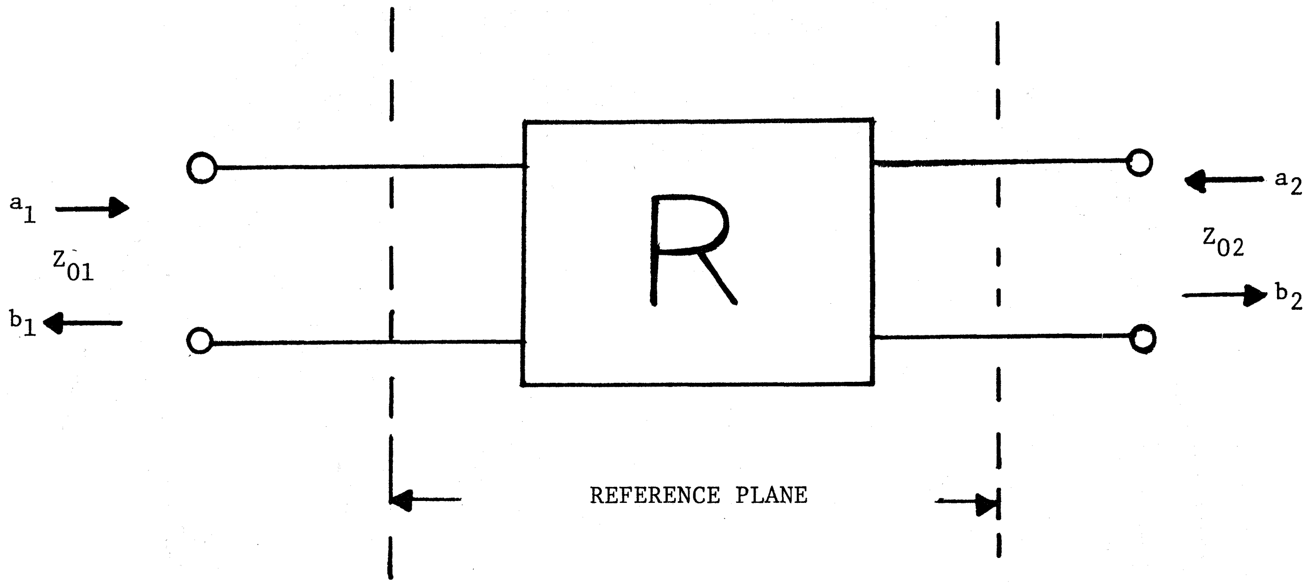
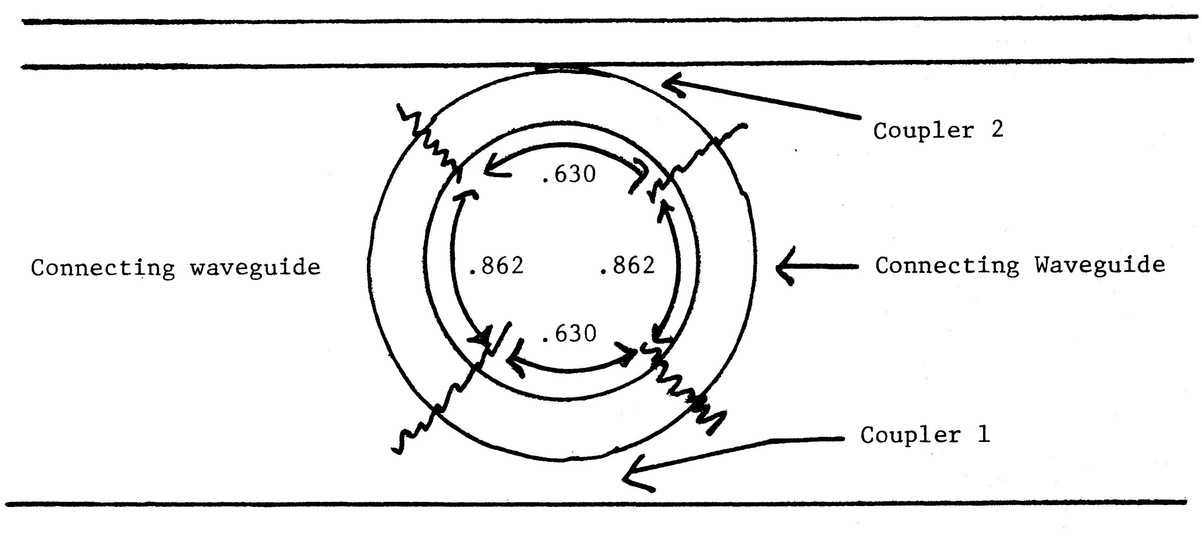


Figure 8. Wave Cascading Matrix Conventions.



Waveguide lengths are as in example.

.630 = 15 (holes) x .042 (hole) spacing

Figure 9: Segmentation of filter.

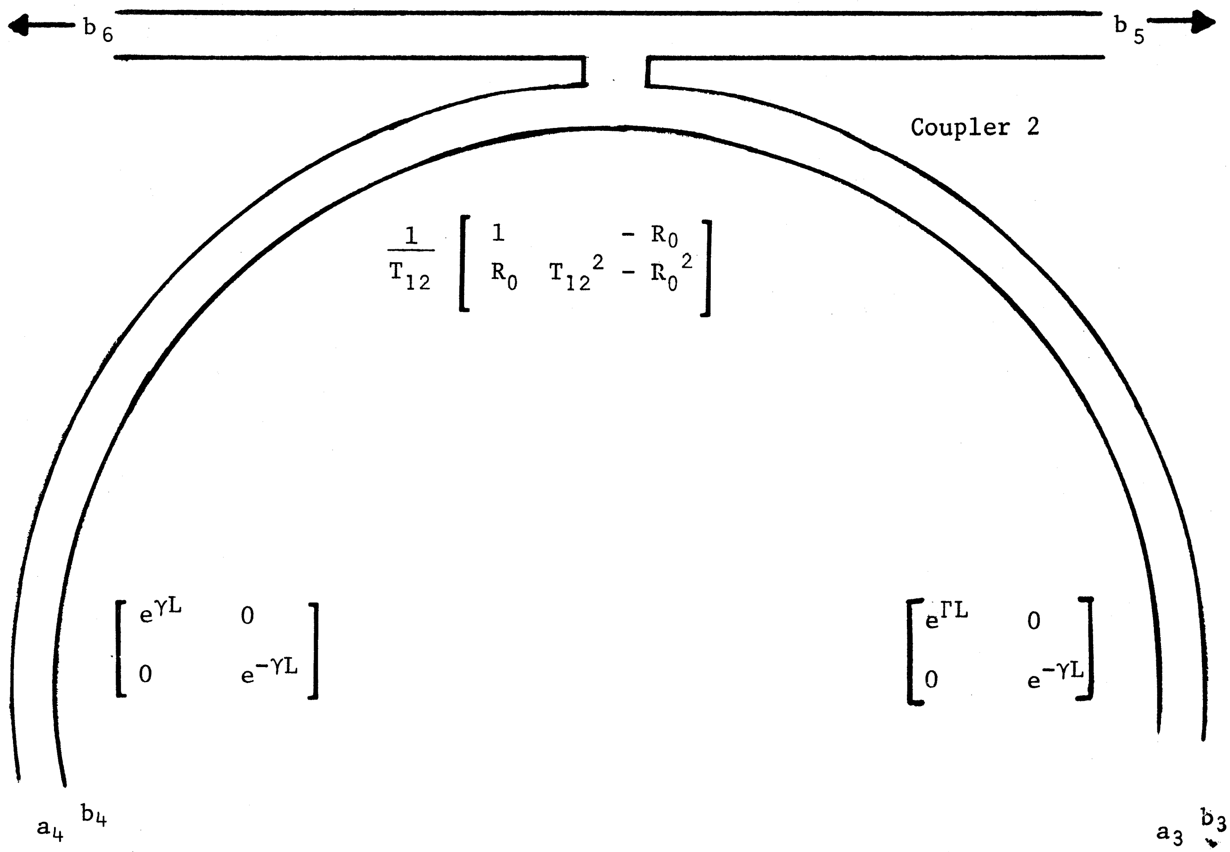


Figure 10: Representation of upper ring and coupler.

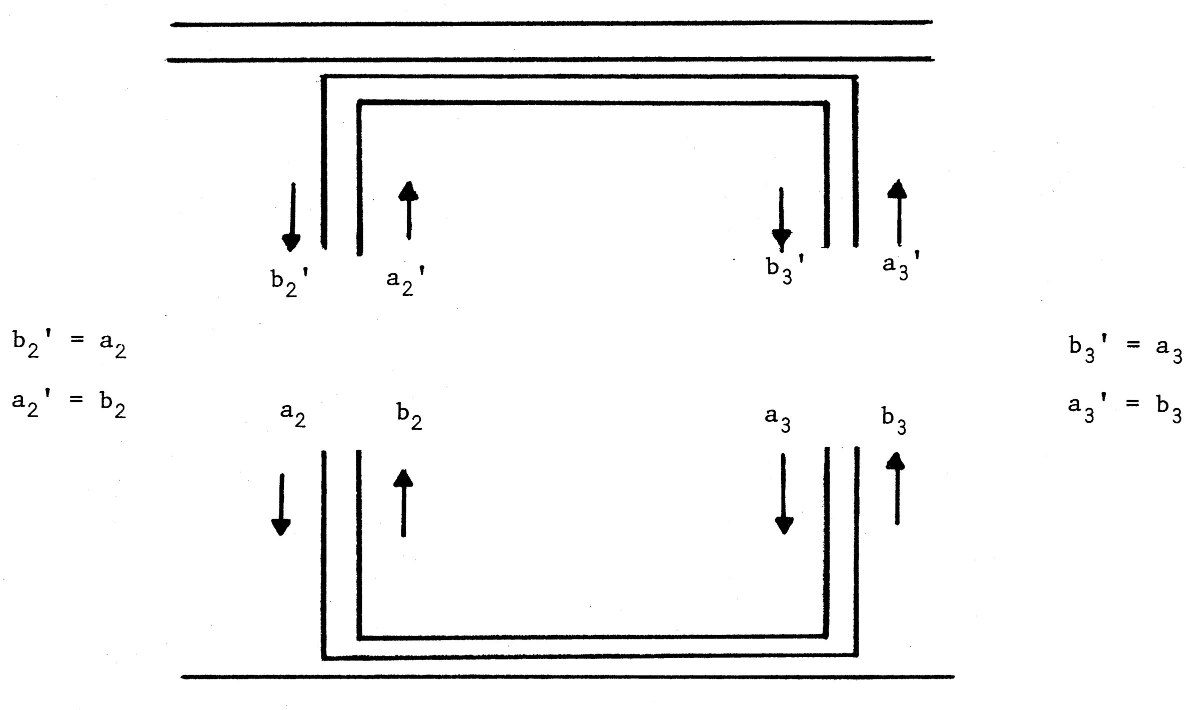
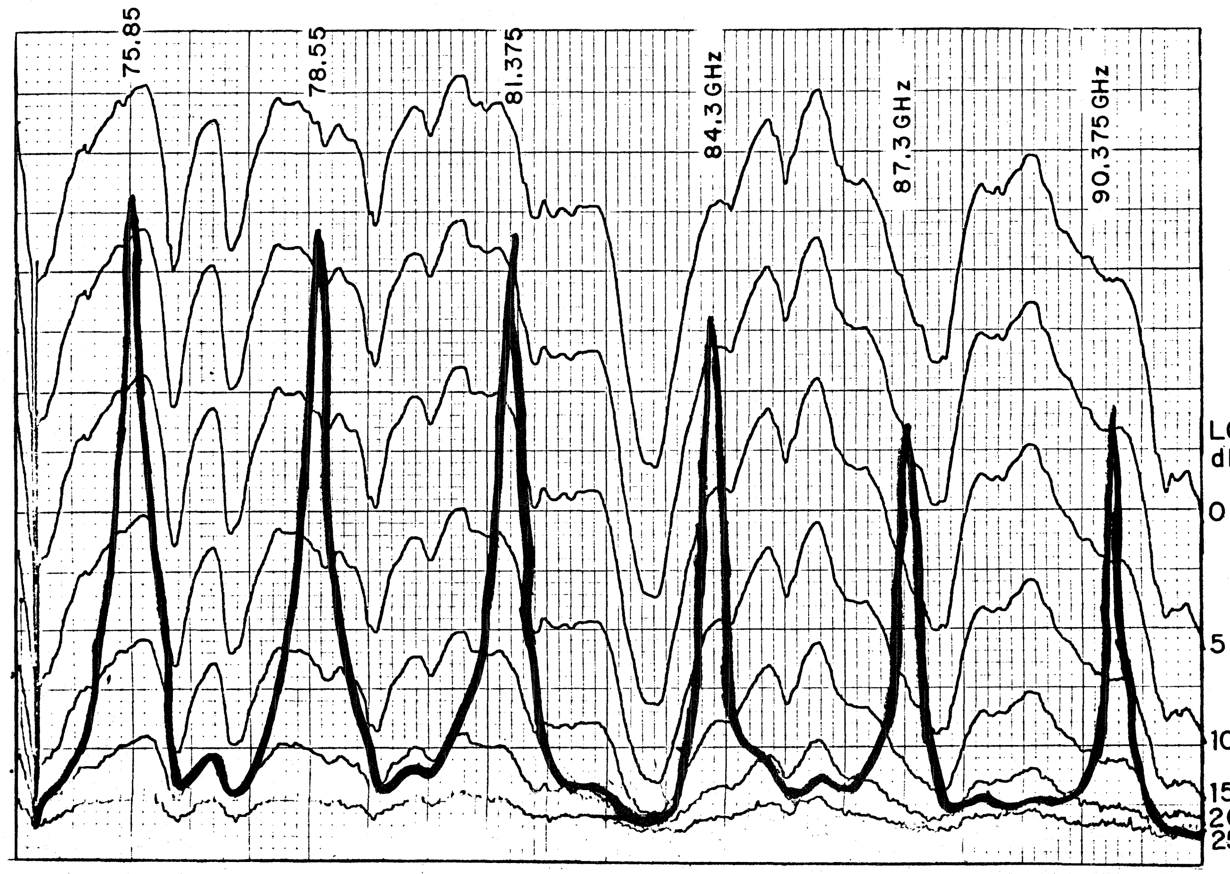


Figure 11: Wave conventions for ring connections.



ROOM TEMP. MAY 7, 1975 J. DAVIS 80-120 COOLED RX. INJECTION FILTER INSERTION LOSS VS FREQUENCY L.O. TO MIXER PATH OTHER PORTS TERMINATED

FIG. 12-A

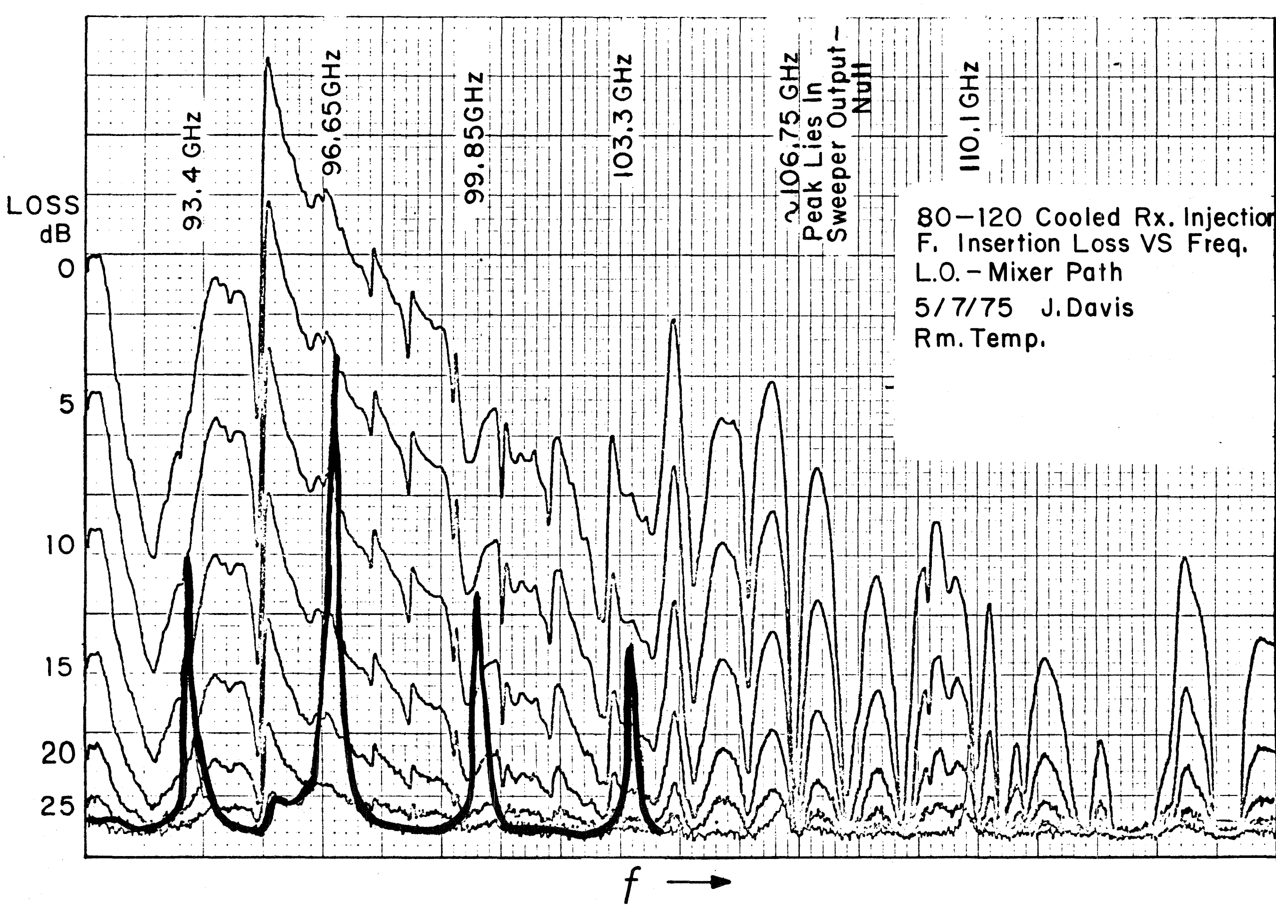
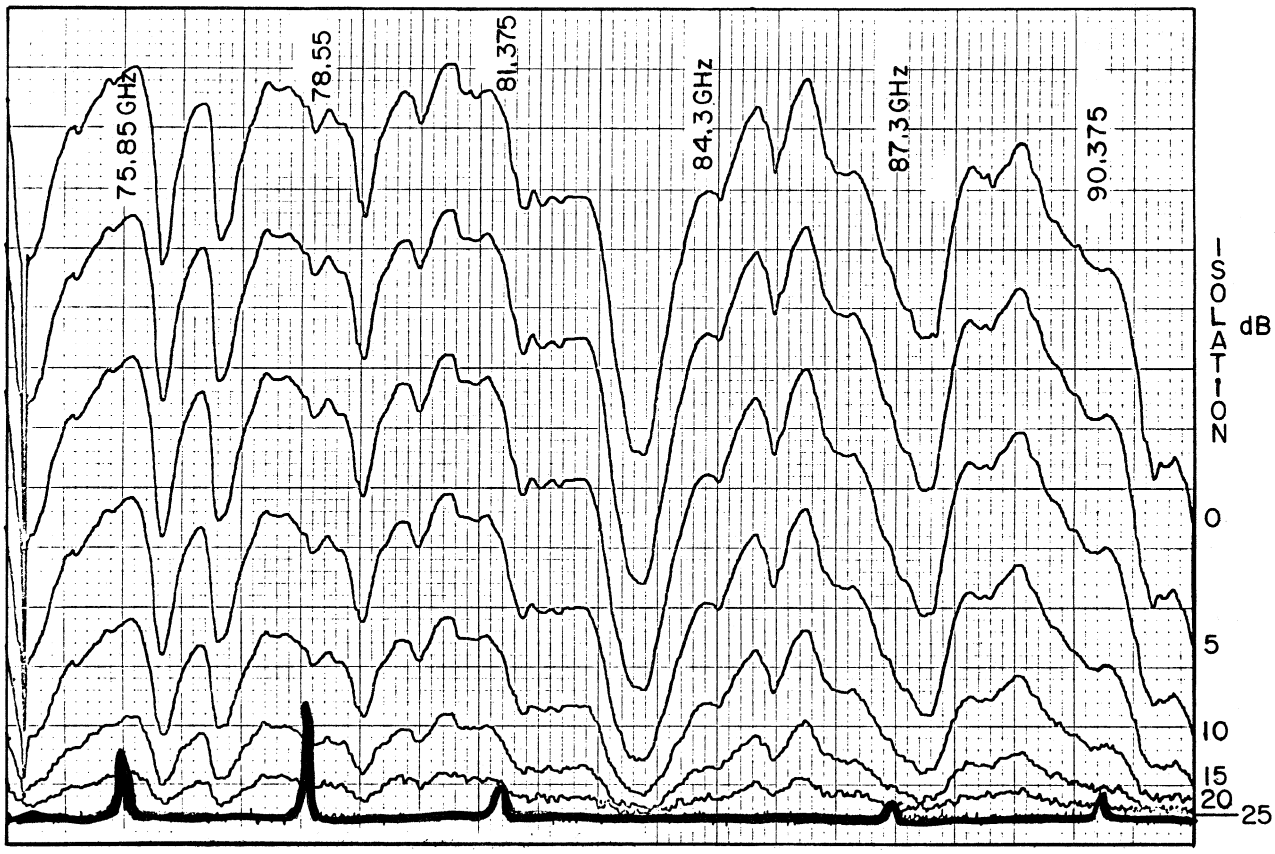


FIG. 12-B



80-120 GHz Cooled Rx. Injection Filter
L.O. — ANT. Path Isolation VS Freq.

5/7/75 J. Davis
Rm. Temp.

FIG. 13—A

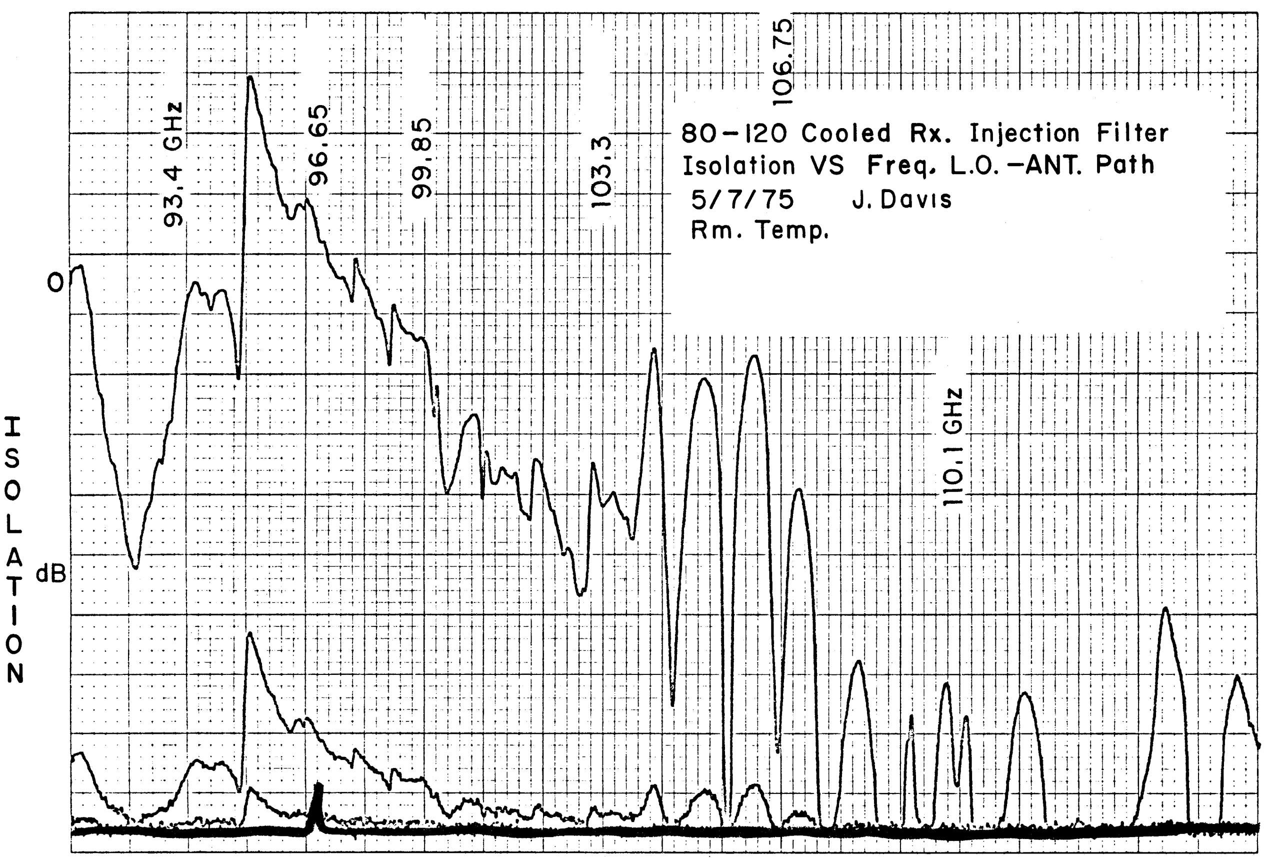


FIG. 13—B

APPENDIX A

MECHANICAL DRAWINGS:

INJECTION FILTER

APPENDIX A

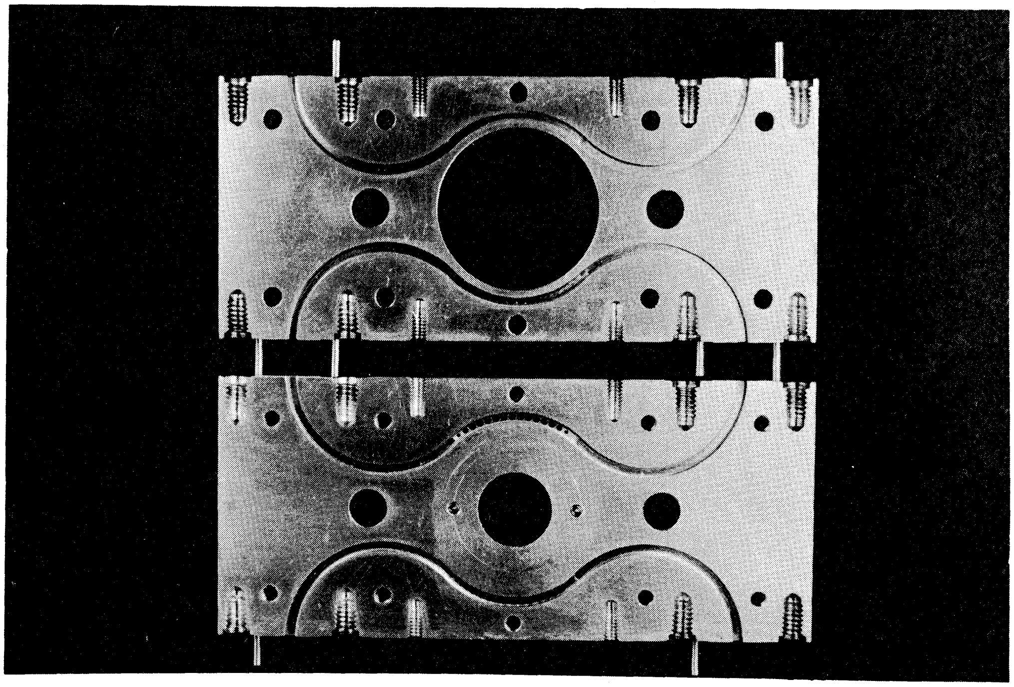


Photo 1: Injection Filter, Internal View.

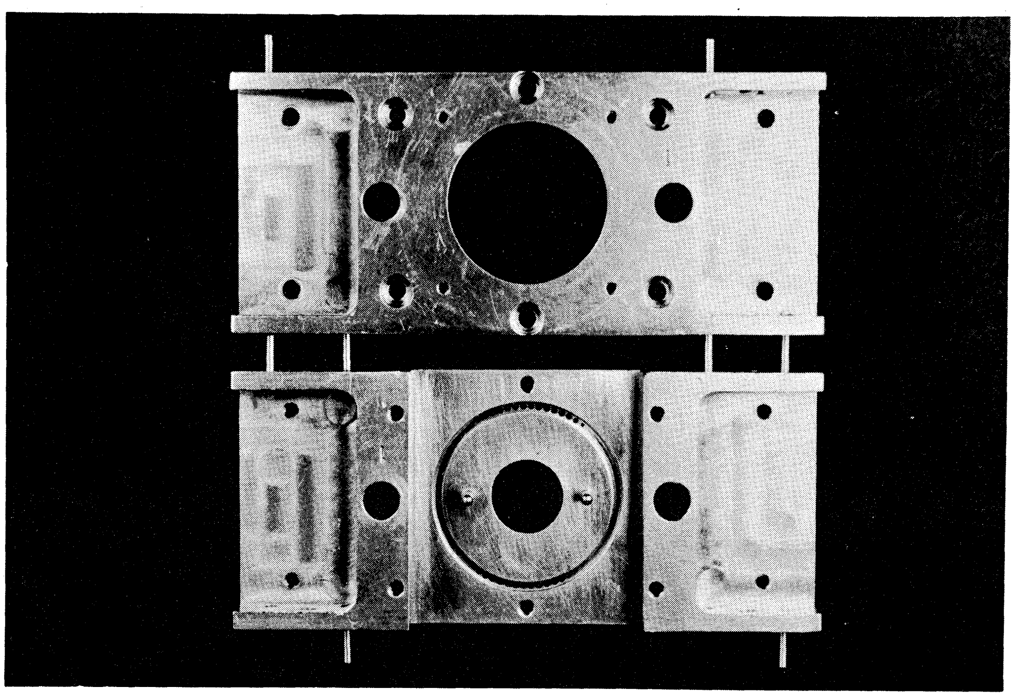


Photo 2: Injection Filter, External View.

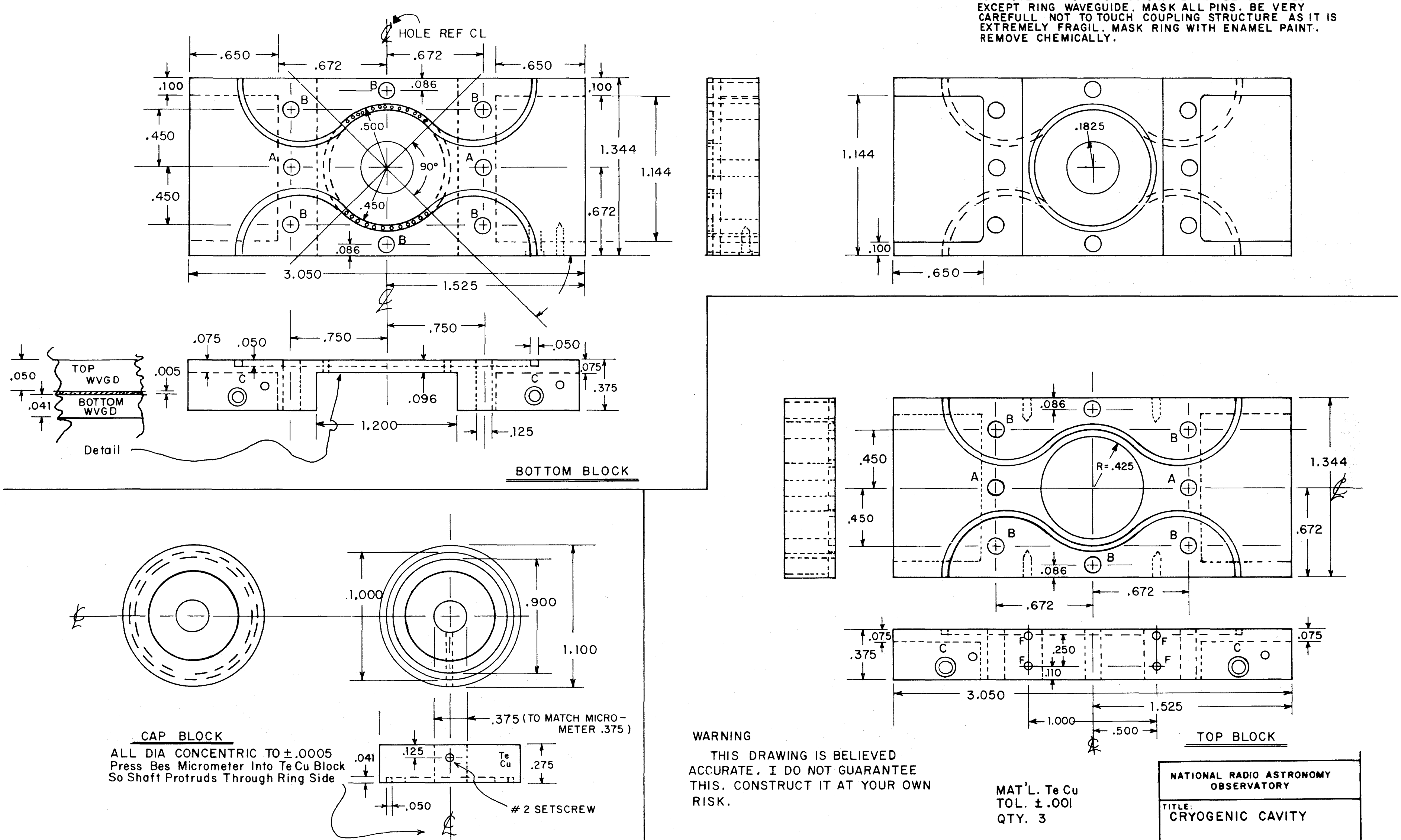
COUPLING HOLES
Spaced Center To Center .042 On WVGD Centerline

HOLE DIAMETERS PLACE CENTER HOLE ON CENTERLINE
DO NOT BREAK THRU BETWEEN HOLES.

SEE ATTACHED SHEET FOR HOLE SIZES

5.06° BETWEEN CENTERS ON ROLAY TABLE
5° 3' 36"

NOTES:
A: 1/8" ST. ALIGN PIN 2PLCS.
TO WVGD TO ±.001
B: #2 CLEAR IN TOP HALF THREADED IN BOTTOM 6PLCS.
C: STANDARD WVGD FLANGE 4PLCS.
D: ALL WAVEGUIDES INNER RADIUS .450; OUTER RADIUS .500
CENTERS OF CURVATURE LOCATED AT BLOCK CENTER &
.672 X AND Y MOVEMENT FROM CENTER.
F: #2-56 X .150 DEEP 4 EACH SIDE (ON BOTH SIDES, 8 TOTAL)
G: PLATE 2 MICRONS COPPER COVERED BY 1/2 MICRON GOLD
TO PROTECT FROM CORROSION. PLATE ALL SURFACES
EXCEPT RING WAVEGUIDE. MASK ALL PINS. BE VERY
CAREFULL NOT TO TOUCH COUPLING STRUCTURE AS IT IS
EXTREMELY FRAGIL. MASK RING WITH ENAMEL PAINT.
REMOVE CHEMICALLY.



WARNING
THIS DRAWING IS BELIEVED ACCURATE. I DO NOT GUARANTEE THIS. CONSTRUCT IT AT YOUR OWN RISK.

MAT'L. Te Cu
TOL. ±.001
QTY. 3

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: CRYOGENIC CAVITY	
DSGN. BY: J. DAVIS	DATE: 5/25/73
APPD. BY:	DR. BY:
DWG. NO. B 2576 M18	

APPENDIX B

MECHANICAL DRAWINGS:

DIFFERENTIAL SCREW AND GEAR BOX

APPENDIX B

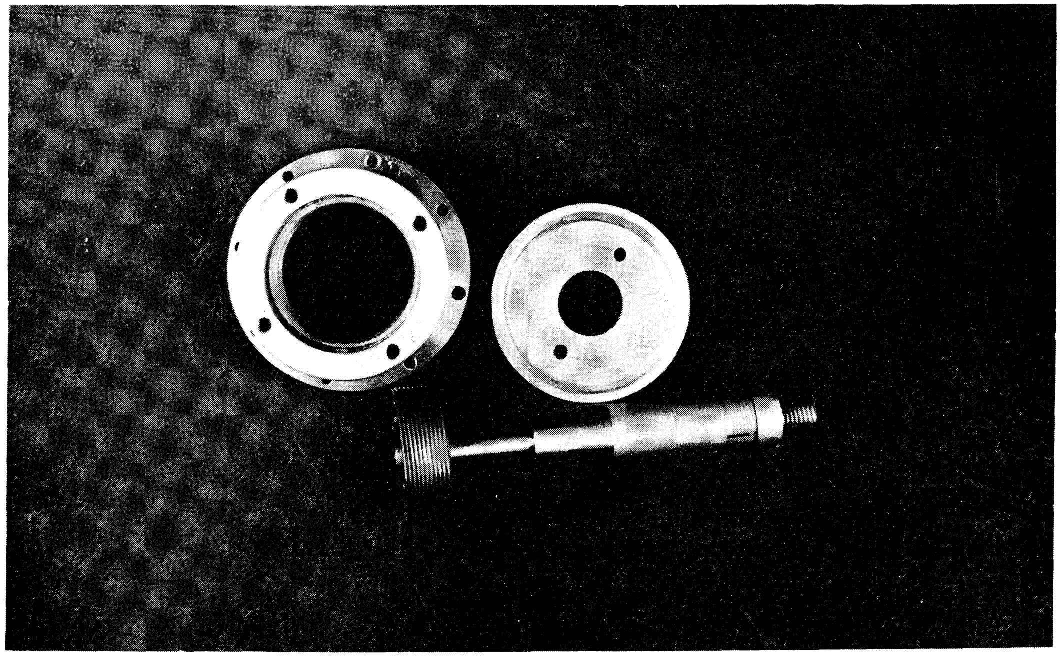


Photo 1: Differential Screw and Cap Block.

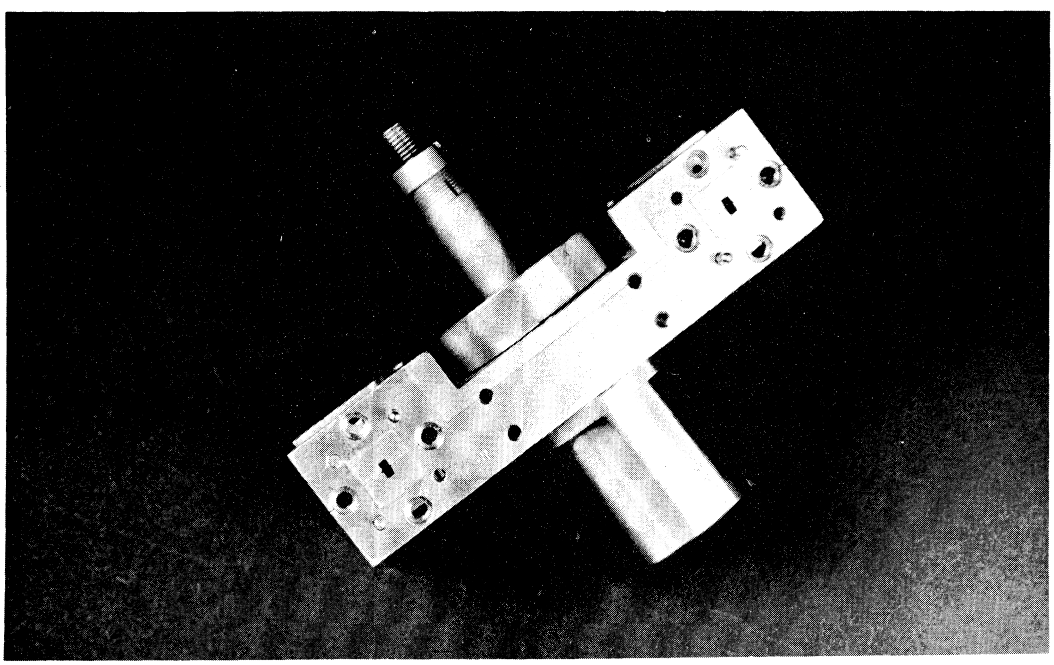
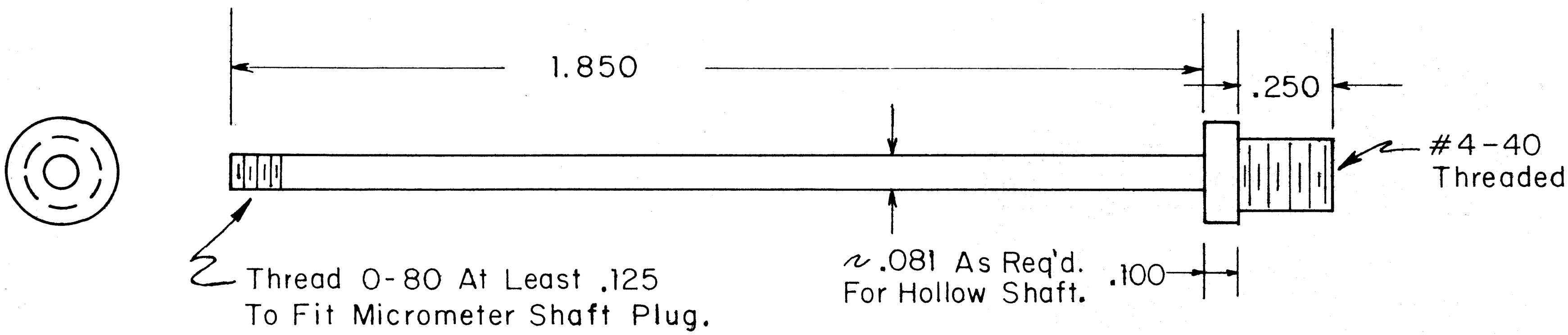
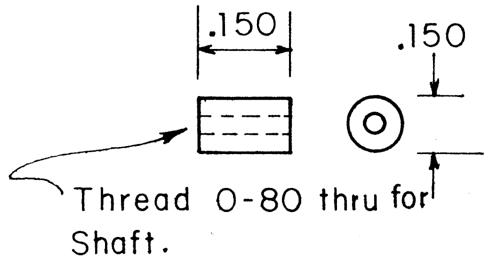


Photo 2: Cavity with Differential Screw and Cap Block Attached.



Make from AL.

SENSOR ROD 2 REQ'D.



Make from Brass

Press into micrometer shaft.

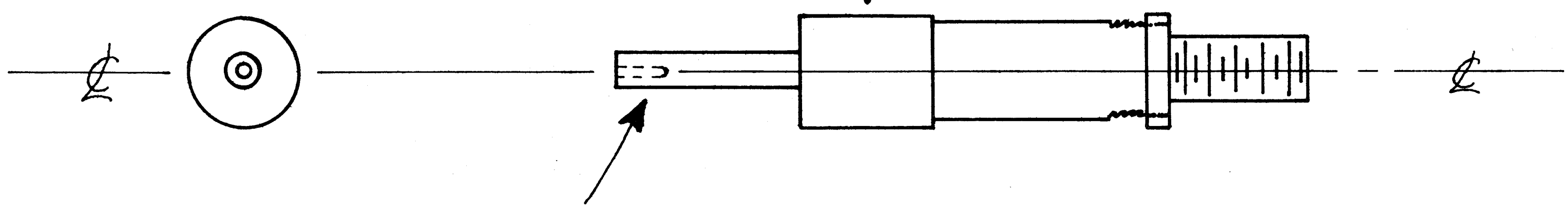
(NOT USED IN FINAL DESIGN)

THREADED PLUG 2 REQ'D.

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: CRYOGENIC CAVITY 80–120 GHz SENSOR BITS & PIECES	
DSGN. BY: J. DAVIS	DATE: 7-30-73
APPD. BY:	DR. BY:
DWG. NO. A2576M25-1	

Turn Down First .300 of barrel until concentric with shaft ±.0005

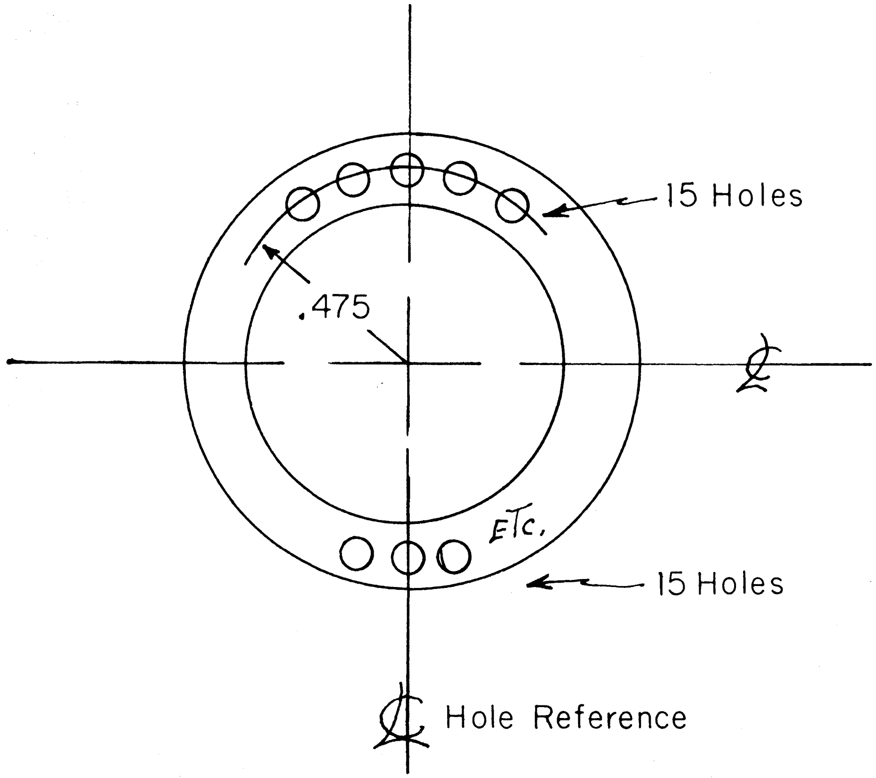
Make cap block to match - OR - turn down sufficeintly to press brass sleeve on barrel and then turn brass sleeve to .375 dia. ±.0005



Soften micrometer shaft
Tap and thread end #0-80 x .100 DP to receive sensor rod. concentric ±.001

Centerline is defined to be centerline of rotation of .195 dia. micrometer shaft.
All rotating parts of differential screw refer to this ℄.

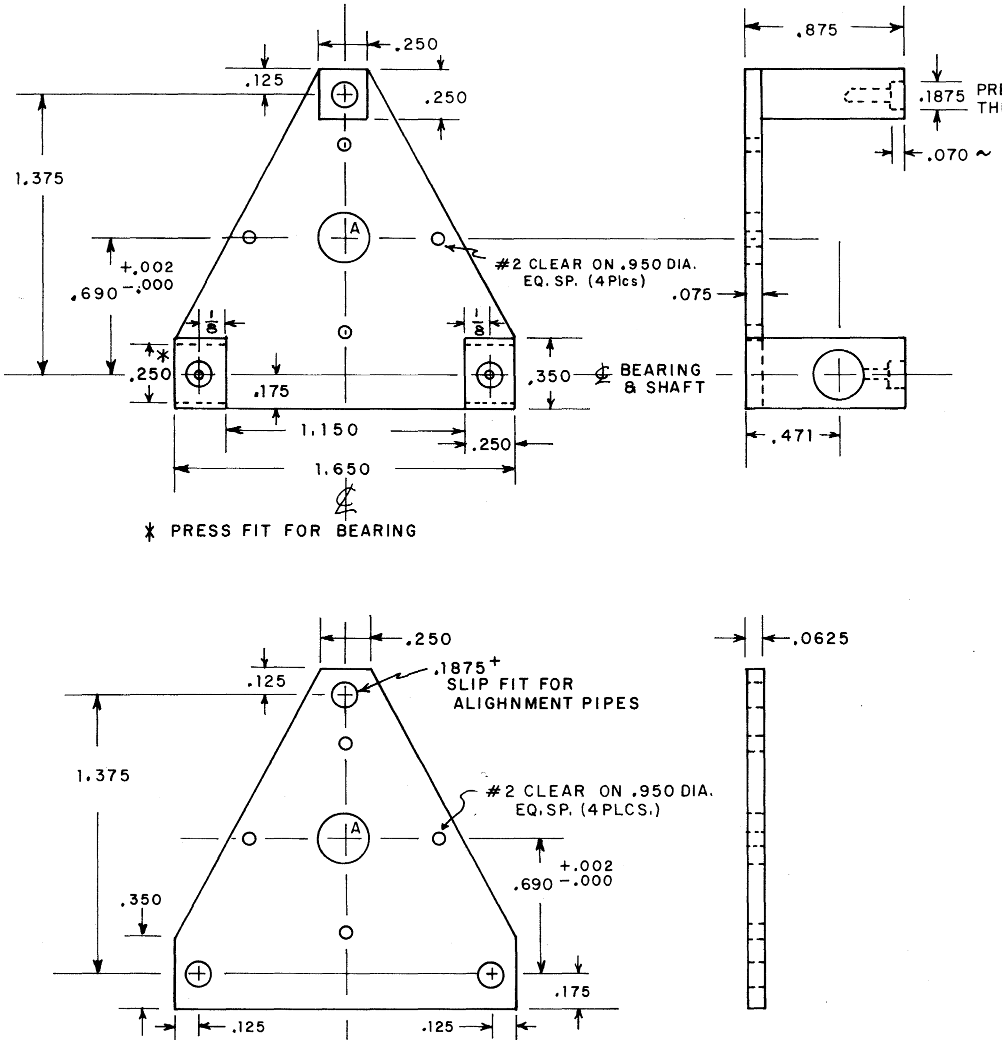
NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: Modifications to Micrometer for 80–120 Cooled Injection Filter	
DSGN. BY: J. DAVIS	DATE: 7/75
APPD. BY:	DR. BY:
DWG. NO. A2576 M25-2	



Coupling holes: Set up Rotary table so the Zero Degree – 180° line is colinear with Reference ℄ (See dwg. no. B2576M18 Hole Ref. ℄) then place holes on .475 radius about Block ℄'s according to following table. Rotate block 180° and Repeat

ANGLE	DIAMETER
146° 55' 0"	.018
151 59 0	.028
159 3 0	.034
162 7 0	.036
167 11 0	.036
172 15 0	.036
177 19 0	.036
182 23 0	.036
187 27 0	.036
192 31 0	.036
197 35 0	.036
202 39 0	.036
207 43 0	.034
212 47 0	.028
217 51 0	.018

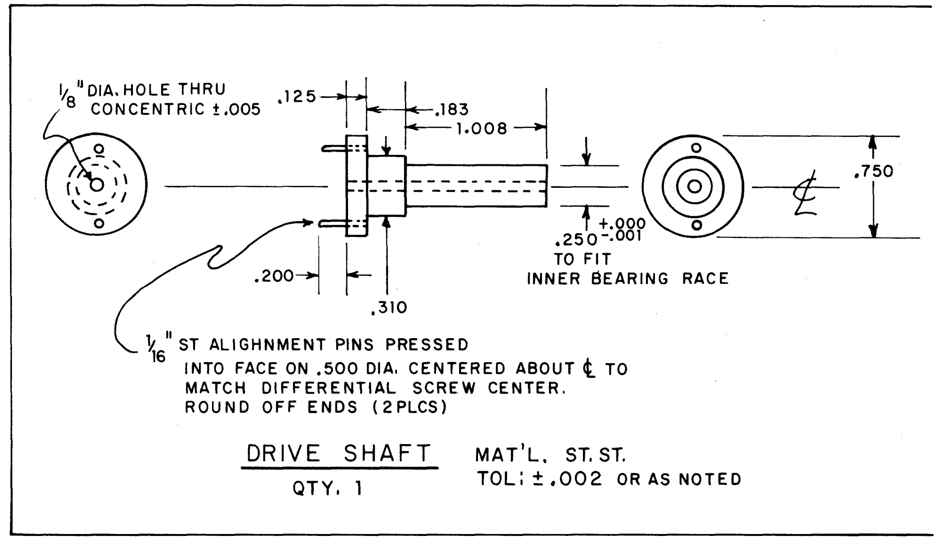
NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: COUPLER DETAIL	
DSGN. BY: J. DAVIS	DATE: 7/75
APPD. BY:	DR. BY:
DWG. NO. A2576 M25 – 3	



NOTE A: BORE TO .3750
PRESS FIT FOR E2-8 BALL BEARINGS.

GEAR BOX
QTY. 3

MAT'L. AL
TOL: ±.002
OR AS NOTED

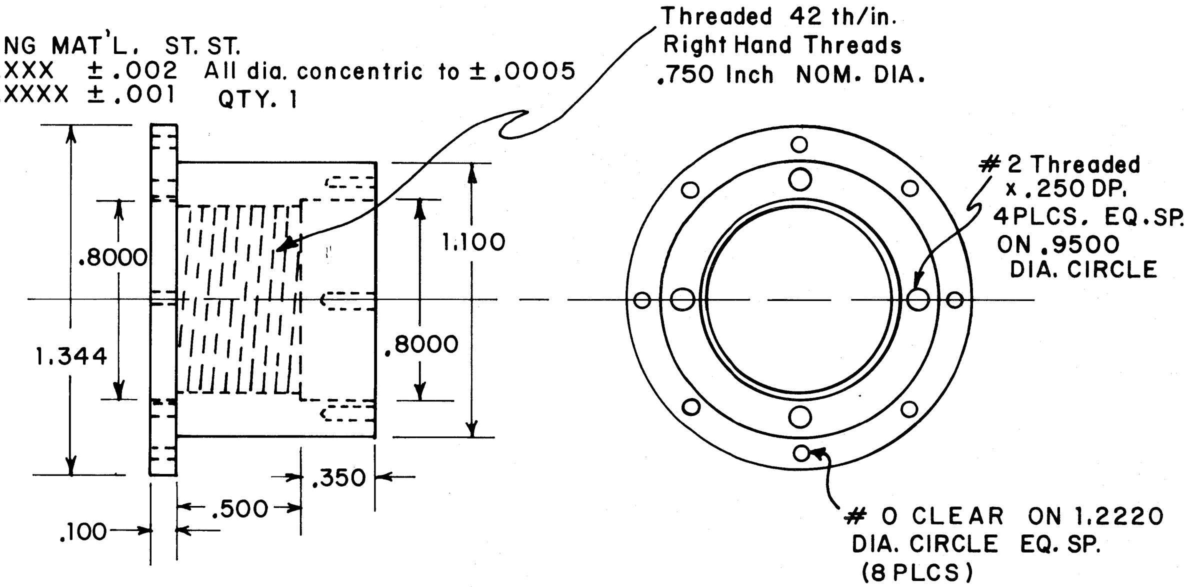


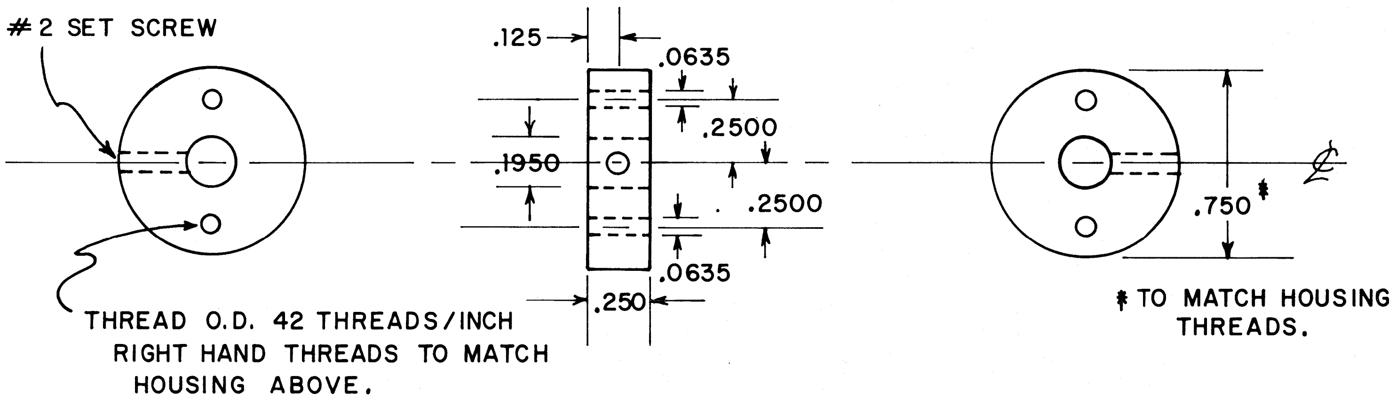
DRIVE SHAFT
QTY. 1

MAT'L. ST. ST.
TOL: ±.002 OR AS NOTED

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: GEAR BOX & DRIVE SHAFT	
DSGN. BY: J. DAVIS	DATE: 9/11/73
APPD. BY:	DR. BY:
DWG. NO. B2576M19	

HOUSING MAT'L. ST. ST.
TOL:.XXX ±.002 All dia. concentric to ±.0005
.XXXX ±.001 QTY. 1





KEEP PLUG AND HOUSING AXIS CONCENTRIC
TO WITHIN ±.001 OR ±.002 IF POSSIBLE
THREADS SHOULD BE A SMOOTH EASY TURNING FIT
AXIAL SLOP <.001

DIFFERENTIAL SCREW CENTER QTY. 1
MAT'L. BRASS
TOL.: .XXX ±.002 ALL DIA. CONCENTRIC
.XXXX ±.001 TO ±.0005

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: SCREW DRIVE & CAP BLOCK	
DSGN. BY: J. DAVIS	DATE: 5/31/73
APPD. BY:	DR. BY:
DWG. NO. B2576 M20	

APPENDIX C

MECHANICAL DRAWINGS:

PRECISION MOVER

APPENDIX C

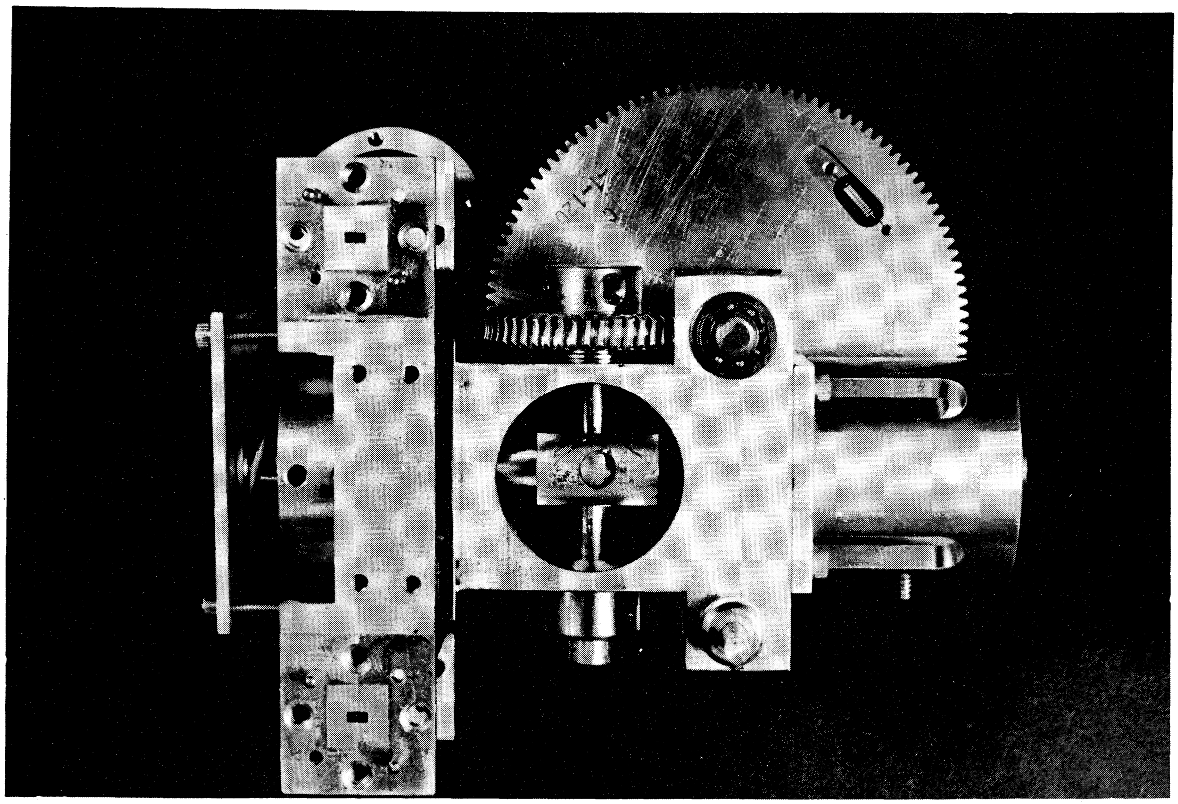
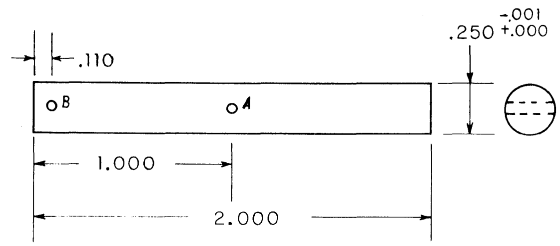


Photo 1: Cavity with Precision Mover Attached.

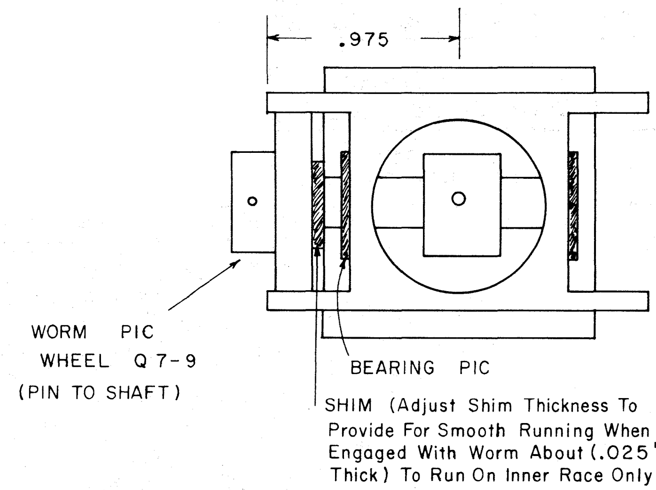


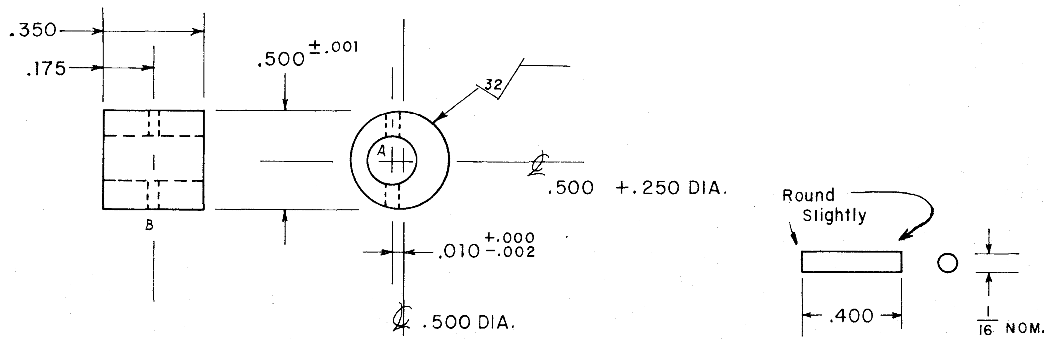
NOTES

A. Slip Fit For 1/16" ST ST PIN ON Dia. To Match CAM.

B. Slip Fit For 1/16" ST ST PIN To Match Worm Wheel.

SHAFT — MAT. ST. ST. TOL. ± .005





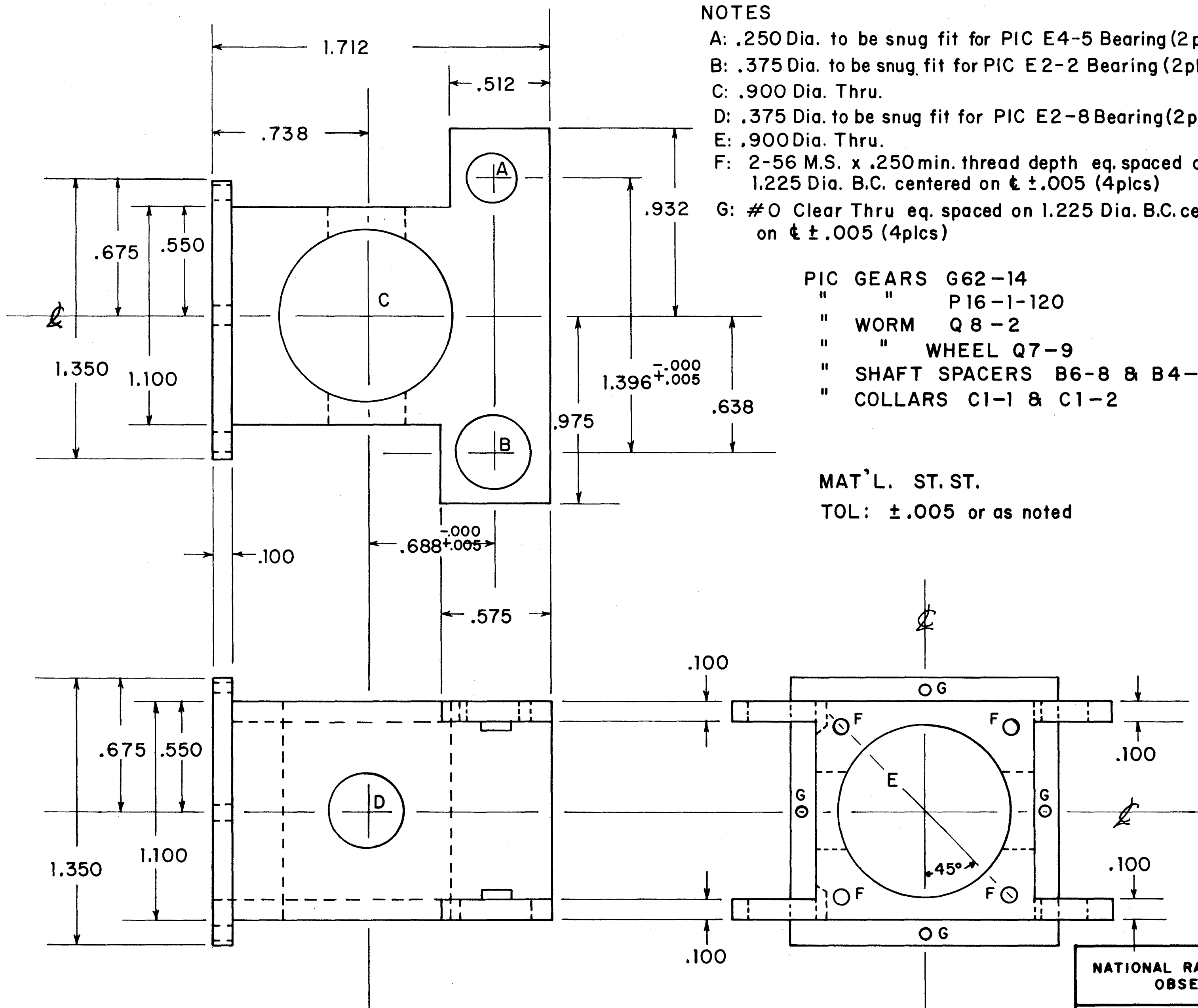
A: Bore .250 Dia. Hole To Be Slip Fit Over .250 Dia. Shaft, Above.
Center of Bore is offset by .010 from center of .500 Dia. to form cam.
inside surface RMS 32μ INCH OR Better.

B: Hole for 1/16" PIN to match shaft above. To be slip fit one side and snug fit other side holes located on diameter of .250 Hole.

NOTE This cam is to give about .016 mils. of travel for yoke rod when shaft is rotated.

CAM — MAT. ST. ST. TOL. ± .005

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: SHAFT / CAM / SHIMS / & ASS'Y.	
DSGN. BY: J. DAVIS	DATE:
APPD. BY:	DR. BY:
DWG. NO.	



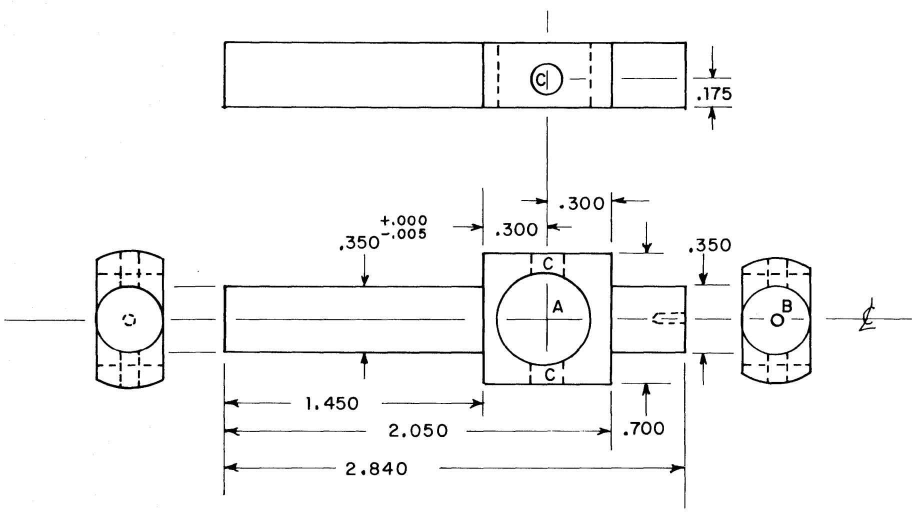
NOTES

A: .250 Dia. to be snug fit for PIC E4-5 Bearing (2 plcs)
B: .375 Dia. to be snug fit for PIC E2-2 Bearing (2 plcs)
C: .900 Dia. Thru.
D: .375 Dia. to be snug fit for PIC E2-8 Bearing (2 plcs)
E: .900 Dia. Thru.
F: 2-56 M.S. x .250 min. thread depth eq. spaced on 1.225 Dia. B.C. centered on ℄ ±.005 (4 plcs)
G: #0 Clear Thru eq. spaced on 1.225 Dia. B.C. centered on ℄ ±.005 (4 plcs)

PIC GEARS G62-14
" " P16-1-120
" WORM Q8-2
" " WHEEL Q7-9
" SHAFT SPACERS B6-8 & B4-8
" COLLARS C1-1 & C1-2

MAT'L. ST. ST.
TOL: ±.005 or as noted

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: PRECISION MOVER BODY BLOCK	
DSGN. BY: J. DAVIS	DATE:
APPD. BY:	DR. BY:
DWG. NO.	



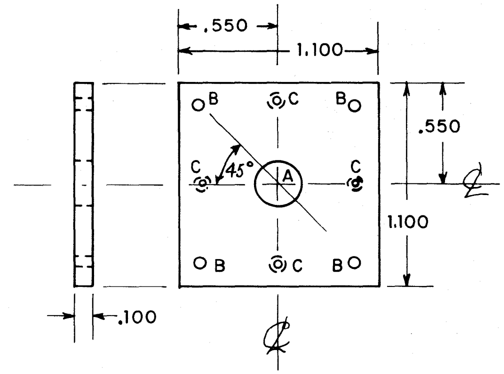
NOTES

A: .562 ± .005 DIA. THRU; INSIDE SURFACE TO BE 32 μ in. RMS OR BETTER, AXIS OF HOLE TO BE ⊥ TO AXIS OF .350 DIA. TO WITHIN ±.5 DEG.

B: THREADED 6-40 NF X .250 MIN. THREAD DEPTH, SURFACE OF .350 DIA. TO BE FINISHED TO RMS 32 μ in. OR BETTER.

C: .187 DIA. THRU.

YOKE MAT'L. ST. ST. QTY. 1 TOL: ±.005 OR AS NOTED



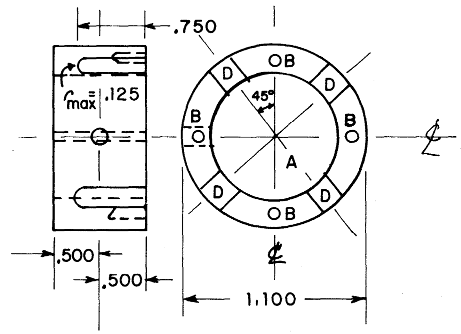
END PLATE MAT'L. AL. TOL: ±.005 QTY. 1

NOTES

A: .350 $^{-.000}_{+.005}$ TO BE EASY SLIP FIT WITH YOKE

B: #2 CLEAR THRU, 4 Plcs. EQ. SP. ON 1.225 DIA. ON ℄ ± .005

C: #2 CLEAR THRU & C/B FOR FH SCREW REVERSE SIDE, 4 Plcs. EQ. SP. ON .956 DIA. ON ℄ ± .005



SENSOR MTG. MAT'L. AL. QTY. 1 TOL: ±.005

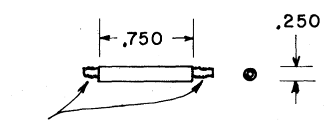
NOTES:

A: .820 $^{-.000}_{+.010}$ DIA. THRU

B: #2-56 x .200 MIN. THREAD DEPTH 4 Plcs. EQ. SP. ON .956 DIA. ON ℄ ± .005

D: .250 ± .005 WIDE SLOT x .750 DEEP 4 Plcs. EQ. SP. AROUND PART.

C: #4-40 THRU ON DIA. THRU ℄.



THREAD # 6-40 BOTH ENDS
MIN. THREAD LENGTH = .200 MAX. .250

SENSOR ROD MAT'L. BRASS OR AL. QTY. 1 TOL: ±.005

NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: YOKE, END PLATE, SENSOR MTG. & SENSOR ROD	
DSGN. BY: J. DAVIS	DATE: OCT. 1, '76
APPD. BY:	DR. BY:
DWG. NO.	

APPENDIX D

COMPUTER PROGRAMS

```
    C   PROGRAM DIRCOUP(INPUT,OUTPUT,HAFWAY,TAPE5=HAFWAY)
        DIMENSION FWD(503),REV(503),R(103),T(103),K1(103),K2(103),F(503)
        DIMENSION D(20)
        COMMON A,B,D,X,TH,LEN,N,ALPHA,K
        REAL K1,K2,K,LEN
        COMPLEX RO,T12,KR,KH
        READ 98,N
        READ 100, LEN
        READ 100, A
        READ 100, B
        READ 100,X
        READ 100,TH
        DO 99 I=1,N
     99 READ 100,D(I)
        ALPHA = .014576
        K = .862
    100 FORMAT (F6.4)
     98 FORMAT (I2)
        DO 200 I = 1,501
        F(I) = I
        F(I) = 85.E9+10.E7*(F(I)-1.)
        CALL FILTER(F(I),FWD(I),REV(I))
    200 F(I) = F(I)/1.E9
        CALL SIMPLOT(F,FWD,501,0,'FREQ  GHZ','FWD DB',5,0)
        CALL SIMPLOT(F,REV,501,0,'FREQ  GHZ','REV  DB',5,0)
        CALL ENDPLOT
        END
```

```
C*DECK,FILT
            SUBROUTINE FILTER(F,FWD,REV)
      C
      C
      C     COMPUTES FOWARD (MIXER) AND REVERSE (ANTENNA) COUPLED POWER FOR
      C     RESONANT RING INJECTION FILTER VS FREQUENCY.
      C     F = FREQUENCY IN GHZ
      C     FWD = FOWARD COUPLED POWER (DB)
      C     REV = REVERSE COUPLED POWER (DB)
      C
      C     ***NOTE - COMMON STATEMENT MUST APPEAR IN CALLING ROUTINE
      C
      C
      C
      C
            COMMON A,B,D,X,TH,LEN,N,ALPHA,K
            DIMENSION D(20)
            DIMENSION T(2,2),R(2,2),TRM(2,2),TRIP(2,2),BFM(4,4),L(4),M(4)
            REAL LEN,LAM,LAMG,K
            COMPLEX RO,T12,T,R,TRM,TRIP,BFM,R11,R12,R21,R22,  L,M,R5,R6
            COMPLEX KR,KH,DET
            CALL CPLR(F,RO,T12,KR,KH)
            LAM = 1.18E10/F
            LAMG = LAM/SQRT(1.-LAM**2/4./A**2)
            BETA = 6.283185/LAMG
            T(1,1) = CEXP(K*CMPLX(ALPHA,BETA))
            T(2,2) = 1./T(1,1)
            T(1,2) = 0.
            T(2,1) = T(1,2)
            R(1,1) = 1./T12
            R(1,2) = -RO/T12
            R(2,1) = RO/T12
            R(2,2) = (T12*T12-RO*RO)/T12
            CALL CMPY(R,T,TRM,2,2,2)
            CALL CMPY(T,TRM,TRIP,2,2,2)
            R11 = TRIP(1,2)
            R12 = TRIP(1,1)
            R21 = TRIP(2,2)
            R22 = TRIP(2,1)
            DO 101 I1= 1,4
            DO 101 J = 1,4
        101 BFM(I1,J)= (0.,0.)
            BFM(3,2) = (-1.,0.)
            BFM(4,1) = (-1.,0.)
            BFM(1,3) = RO/R12+R22*T12/R12
            BFM(1,4) = T12*(R21-R22*R11/R12)-RO*R11/R12-(1.,0.)
            BFM(2,3) = RO*R22/R12+T12/R12-(1.,0.)
            BFM(2,4) = RO*(R21-R22*R11/R12)-T12*R11/R12
            BFM(3,3) = KR*R22/R12-KH/R12
            BFM(3,4) = KR*(R21-R22*R11/R12)-KH*R11/R12
            BFM(4,3) = KH*R22/R12+KR/R12
            BFM(4,4) = KH*(R21-R22*R11/R12)-R11*KR/R12
            CALL CMINV(BFM,4,DET,L,M)
            L(1) = -KR
```

```
      L(2) = -KH
      L(3) = -T12
      L(4) = -RO
      CALL CMPY(BFM,L,M,4,4,1)
      M(3) = M(3)/T(1,1)
      M(4) = M(4)/T(1,1)
      R5 = M(4)*KH+M(3)*KR
      R6 = M(4)*KR+M(3)*KH
      REV = 10.*ALOG10(CABS(R5)**2)
      FWD = 10.*ALOG10(CABS(R6)**2)
      RETURN
      END
```

```
      C*DECK,CCOSH
      C
      C
      C      COMPLEX HYPERBOLIC COSINE
      C      X = COMPLEX ARGUMENT
      C      ***NOTE - CCOSH MUST APPEAR IN COMPLEX STATEMENT IN CALLING PRGM
      C
      C
      C
      C
0001         COMPLEX  FUNCTION CCOSH(X)
0002         COMPLEX X,A,B
0003         A = CEXP(X)
0004         B=1./A
0005         CCOSH =(A+B)/(2.,0.)
0006         RETURN
0007         END
```

```
      C*DECK,CPLR
0001        SUBROUTINE CPLR(F,RO,T12,KR,KH)
      C
      C
      C     F = FREQUENCY OF COUPLER EVALUATION
      C     RO = REFLECTION COEFFICIENT AT ANY PORT OF COUPLER (OTHER PORTS
      C     TERMINATED IN THE CHARACTERISTIC IMPEDANCE OF THE LINE)
      C     T12 = THROUGH ARM TRANSFER COEFFICIENT
      C     KR = REVERSE COUPLING COEFFICIENT
      C     KH = FOWARD COUPLING COEFFICIENT
      C     NOTE - RO, T12, KR, KH ARE COMPLEX
      C     A = WAVEGUIDE WIDTH
      C     B = WAVEGUIDE HEIGHT
      C     D = DIAMETER OF COUPLING HOLE
      C     X = DISTANCE FROM EDGE OF GUIDE TO CENTER OF COUPLING HOLE
      C     TH = THICKNESS OF WALL CONTAINING COUPLING HOLE
      C     LEN = DISTANCE BETWEEN COUPLING HOLES
      C     N = NUMBER OF COUPLING HOLES PER COUPLER
      C     ALPHA = ATTENUATION CONSTANT OF WAVEGUIDE (NEPERS)
      C
      C
      C
      C
0002        COMMON A,B,D,X,TH,LEN,N,ALPHA,A2
0003        COMPLEX T12,RO,KR,KH,ML,GAMMA,CSINH,CCOSH
0004        COMPLEX M1,M2,M3,MT,GAMMAO,GAMMAE,TO,TE,M,ME,MO
0005        DIMENSION D(20),M1(2,2),M2(2,2),M(2,2),MT(2,2)
0006        DIMENSION  ME(2,2),MO(2,2),BZ(20),XX(20),BY(20),ML(2,2)
0007        REAL LAM,LAMG,LEN,K1,K2
0008        LAM = 1.18E10/F
0009        LAMG = LAM/(SQRT(1.-LAM**2/4./A**2))
0010        DO 102 K = 1,N
0011        FOE = 1.18E10/1.305/D(K)
0012        FOH = 1.18E10/1.705/D(K)
0013        A2 = (.065*D(K)+TH)/TH
0014        K1 = TAN(3.14159*F/2./FOH)/3.14159/F*2.*FOH
           1*EXP(-6.28319*TH*A2/1.705/D(K)*SQRT(1.-F**2/FOH**2))
0015        K2 = TAN(3.14159*F/2./FOE)/3.14159/F*2.*FOE
           1*EXP(-6.28319*TH*A2/1.305/D(K)*SQRT(1.-F**2/FOE**2))
0016        BY(K)=12.56637*LAMG*D(K)**3*(SIN(3.14159*X/A))**2/A/B/LAM**2/12.
0017        XX(K)=12.56637*D(K)**3*(SIN(3.14159*X/A))**2/A/B/LAMG/6.
0018        BZ(K)=-3.14159*LAMG*D(K)**3*(COS(3.14159*X/A))**2/A**3/B/6.
0019        BY(K) = BY(K)*K2
0020        XX(K) = XX(K)*K1
0021    102 BZ(K) = BZ(K)*K1
0022        M1(1,1) = (1.,0.)
0023        M1(1,2) = (0.,0.)
0024        M1(2,1) = (0.,0.)
0025        M1(2,2) = (1.,0.)
0026        M2(1,1) = (1.,0.)
0027        M2(1,2) = (0.,0.)
0028        M2(2,1) = (0.,0.)
0029        M2(2,2) = (1.,0.)
0030        GAMMA = CMPLX(ALPHA,6.283185/LAMG)
```

```
0031          ML(1,1) = CCOSH(GAMMA*LEN/2.)
0032          ML(1,2) = CSINH( GAMMA*LEN/2.)
0033          ML(2,1) = ML(1,2)
0034          ML(2,2) = ML(1,1)
0035          DO 103 K = 1,N
0036          ME(1,1) = (1.,0.)
0037          ME(1,2) = CMPLX(0.,2.*XX(K))
0038          ME(2,1) = (0.,0.)
0039          ME(2,2) = (1.,0.)
0040          MO(1,1) = (1.,0.)
0041          MO(1,2) = (0.,0.)
0042          MO(2,1) = CMPLX(0.,2.*(BZ(K)+BY(K)))
0043          MO(2,2) = (1.,0.)
0044          CALL CMPY(ML,ME,M,2,2,2)
0045          CALL CMPY(M,ML,ME,2,2,2)
0046          CALL CMPY(ML,MO,MT,2,2,2)
0047          CALL CMPY(MT,ML,MO,2,2,2)
0048          CALL CMPY(M1,ME,M,2,2,2)
0049          CALL CMPY(M2,MO,MT,2,2,2)
0050          DO 104 I1 = 1,2
0051          DO 105 I2 = 1,2
0052          M1(I1,I2) = M(I1,I2)
0053      105 M2(I1,I2) = MT(I1,I2)
0054      104 CONTINUE
0055      103 CONTINUE
0056          DO 106 I1 = 1,2
0057          DO 107 I2 = 1,2
0058          ME(I1,I2) = M(I1,I2)
0059      107 MO(I1,I2) = MT(I1,I2)
0060      106 CONTINUE
0061          GAMMAO = (MO(1,1)-MO(2,2)+MO(1,2)-MO(2,1))
             1/(MO(1,1)+MO(1,2)+MO(2,1)+MO(2,2))
0062          GAMMAE = (ME(1,1)-ME(2,2)+ME(1,2)-ME(2,1))
             1/(ME(1,1)+ME(1,2)+ME(2,1)+ME(2,2))
0063          TO = (2.,0.)/(MO(1,1)+MO(1,2)+MO(2,1)+MO(2,2))
0064          TE = (2.,0.)/(ME(1,1)+ME(1,2)+ME(2,1)+ME(2,2))
0065          KH = (TE-TO)/(2.,0.)
0066          KR = (GAMMAE-GAMMAO)/(2.,0.)
0067          RO = (GAMMAE+GAMMAO)/(2.,0.)
0068          T12 = (TO+TE)/(2.,0.)
0069          RETURN
0070          END
```

```
FORTRAN IV      V01C-03A   MON 18-APR-77 12:54:45                PAGE 001
      C*DECK,CMPY
0001           SUBROUTINE CMPY(A,B,C,I,J,K)
      C         MULTIPLIES COMPLEX MATRICES   A*B = C
      C         I = NUMBER OF ROWS IN A
      C         J = NUMBER OF COLUMNS IN A
      C         K = NUMBER OF COLUMNS IN B
0002           COMPLEX A,B,C
0003           DIMENSION A(I,J),B(J,K),C(I,K)
0004           DO 101 L=1,I
0005           DO 100 M = 1,K
0006       100 C(L,M) = (0.,0.)
0007       101 CONTINUE
0008           DO 104 L = 1,I
0009           DO 103 M = 1,K
0010           DO 102 N = 1,J
0011       102 C(L,M) = C(L,M)+A(L,N)*B(N,M)
0012       103 CONTINUE
0013       104 CONTINUE
0014           RETURN
0015           END
```

```
C*DECK,CMINV
      SUBROUTINE CMINV(A,N,D,L,M)
C
C
C     INVERTS A COMPLEX MATRIX
C     A = N X N COMPLEX MATRIX TO BE INVERTED.  MATRIX A IS WRITTEN
C     OVER WITH THE INVERSE OF A.
C     N = ORDER OF MATRIX A
C     D = DETERMINANT OF MATRIX A (RETURNED.  MAY BE TESTED FOR
C     SINGULARITY.)
C     L = WORK MATRIX OF LENGTH N
C     M = WORK MATRIX OF LENGTH N
C     ***ALL QUANTITIES EXCEPT N ARE COMPLEX, N IS INTEGER***
C
C
C
C
      DIMENSION A(1),L(1),M(1)
      COMPLEX  A,BIGA,HOLD,D
      D = (1.,0.)
      NK = -N
      DO 80 K = 1,N
      NK = NK + N
      L(K) = K
      M(K) = K
      KK = NK + K
      BIGA = A(KK)
      DO 20 J = K,N
      IZ = N*(J-1)
      DO 20 I = K,N
      IJ = IZ + I
   10 IF(CABS(BIGA)-CABS(A(IJ))) 15,20,20
   15 BIGA = A(IJ)
      L(K) = I
      M(K) = J
   20 CONTINUE
      J = L(K)
      IF(J-K) 35,35,25
   25 KI = K-N
      DO 30 I = 1,N
      KI = KI+N
      HOLD =-A(KI)
      JI = KI-K+J
      A(KI) = A(JI)
   30 A(JI) = HOLD
   35 I = M(K)
      IF(I-K) 45,45,38
   38 JP = N*(I-1)
      DO 40 J = 1,N
      JK = NK + J
      JI = JP + J
      HOLD = -A(JK)
      A(JK) = A(JI)
   40 A(JI) = HOLD
```

```
   45 IF(CABS(BIGA)) 48,46,48
   46 D = (0.,0.)
      RETURN
   48 DO 55 I = 1,N
      IF(I-K)50,55,50
   50 IK = NK + I
      A(IK) = A(IK)/(-BIGA)
   55 CONTINUE
      DO 65 I = 1,N
      IK = NK + I
      HOLD = A(IK)
      IJ = I-N
      DO 65 J = 1,N
      IJ = IJ + N
      IF (I-K) 60,65,60
   60 IF(J-K) 62,65,62
   62 KJ = IJ-I+K
      A(IJ) = HOLD*A(KJ)+A(IJ)
   65 CONTINUE
      KJ = K-N
      DO 75 J = 1,N
      KJ = KJ+N
      IF(J-K) 70,75,70
   70 A(KJ)=A(KJ)/BIGA
   75 CONTINUE
      D = D*BIGA
      A(KK) = (1.,0.)/BIGA
   80 CONTINUE
      K = N
  100 K = K-1
      IF (K) 150,150,105
  105 I = L(K)
      IF(I-K) 120,120,108
  108 JQ = N*(K-1)
      JR = N*(I-1)
      DO 110 J = 1,N
      JK = JQ+J
      HOLD = A(JK)
      JI = JR+J
      A(JK) = -A(JI)
  110 A(JI) = HOLD
  120 J = M(K)
      IF(J-K) 100,100,125
  125 KI = K-N
      DO 130 I = 1,N
      KI = KI + N
      HOLD = A(KI)
      JI = KI-K+J
      A(KI) = -A(JI)
  130 A(JI) = HOLD
      GO TO 100
  150 RETURN
      END
```