NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROJECT

VLA ELECTRONICS MEMORANDUM NO. 150

C. Read Predmore
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A REPORT ON THE VLA WAVEGUIDE

During April 1-3, 1976, I visited the VLA site near Socorro, New Mexico and discussed the VLA waveguide system with E. Caloccia, M. Ogai, F. Wells, and A. R. Thompson. Following those discussions I reviewed and analyzed several areas of interest. They are: 1) the helical coupler design; 2) instrumentation for measurement and analysis of waveguide curvature; 3) design considerations for the remaining system designs; and 4) possible techniques for broading the helical couplers. A fifth section with miscellaneous information and comments has also been included.

I) Helical coupler design

This will be a VLA Technical Report, so only an outline is given here.

1. Introduction
2. Helical coupler paper
3. Coupler performance
4. Mechanical design data
5. Coupler Fabrication
6. Improvements

Appendixes A. 1 Computer Design Program
A. 2 VLA Electronics Memo #128

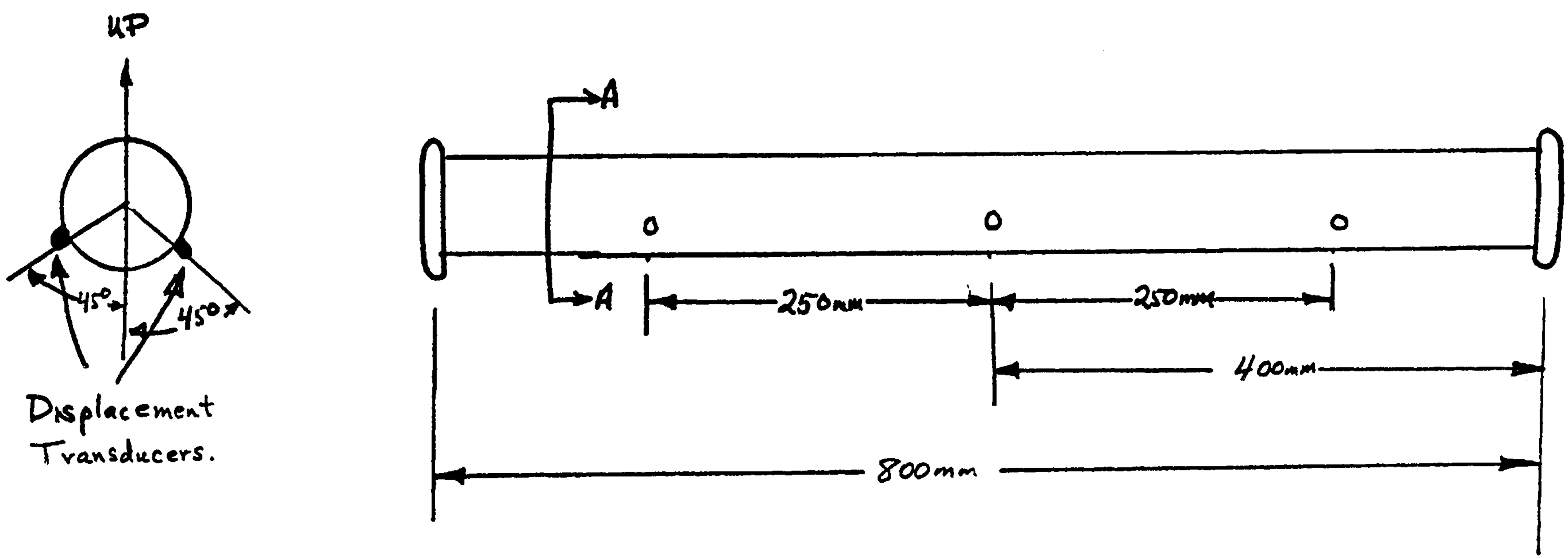
II) Measurements of waveguide curvature

The major cause of increased waveguide loss between manufacture and use in the VLA Waveguide system is the curvature due to the direct burial of the waveguide. Consequently, an accurate measurement of the waveguide curvature, before installation, just after installation and at later times is important.

II.1 Mouse

The "mouse", which was implemented at NRAO by Jack Cambell, is approximately 80 cm long with orthogonal pairs of sensors in the center and ±25 cm from the center as sketched in Figure 2.0. The displacement

FIGURE 2.0 MOUSE



transducers are electronically summed, scaled and subtracted within the bosy of the mouse to provide an output of the deviation from straightness with a typical sensitivity of 14 V/millimeter. The radius of curvature is the inverse of the measured deviation δ,

$$R(\text{meters}) = \frac{\ell^2}{8\delta} = 31.3/\delta \text{ (mm)}$$

where ℓ = 50cm is the distance between the first and third pair of transducers. To measure an radius of 2000m (twice the 1000m spec.) a deviation of 16 microns or a voltage of 0.22 V is required.

The electronic displacement transducers have a 100Hz bandwidth and the mouse is pulled through the waveguide at a rate of 0.1m/sec. Thus the number of data points generated in measuring the curvature of 1km of waveguide in two planes is

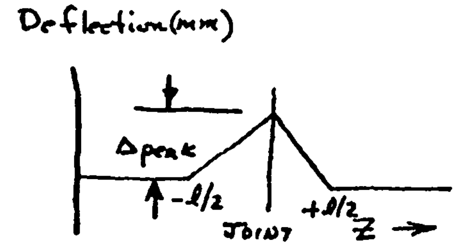
$$N = 2 \text{ X } 2 \text{ 100Hz } \frac{1000\text{m}}{0.1\text{m/sec}} = 4 \text{ X } 10^6 \text{ data points /km.}$$

The measurement of the entire VLA waveguide system generates 252 $\text{X}10^6$ data points. However this high data rate is needed only to measure the joint offset and tilt. To characterize the offset and tilt in two planes for the 12,600 waveguide couplings in the VLA only 50,400 numbers are required. Because of the response function of the mouse described in II.2, only four points per meter are required to characterise the waveguide curvature in each plane, or a total of 4 X 63,000 = 252,000 points. This may be further consolidated by using 1000 points to produce one power spectra of the curvature, and an rms curvature for each 500m length of the waveguide. This power spectra and rms curvature will be used to study any changes in the waveguide curvature in a compact and useful form.

II.2 Mouse Response

1) Joint tilt.

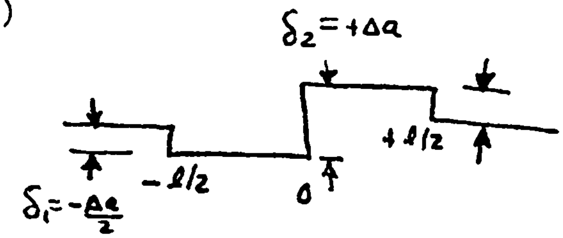
$$\theta(\text{radians}) = \frac{4\,\Delta_{peak}(\text{mm})}{\ell},$$



where ℓ = 500mm is the distance between the first and third sensors.

2) Joint Offset (or diameter change)

$$\Delta a = -\frac{\delta_1 + \delta_2 - \delta_3}{2}$$



Response to an upward offset or diameter decrease ($AD=2\Delta a$).

The average is used to minimize noise.

3) Sinusoidal variation in waveguide position,

$$y(z) = A_0 \sin(2\pi z/\lambda_m)$$

where Z(m) is the displacement along the waveguide axis, A(mm) is the amplitude of the sinusoidal variation, and λ_m(m) the mechanical wavelength of the variation. The mouse response is

$$\delta(\text{mm}) = 2A_0 \sin^2(\pi\ell/\lambda_m)\sin(2\pi z/\lambda_m)$$

the amplitude of this response is

$$A(\lambda_m) = 2A_0 \sin^2(\pi\ell/\lambda_m) = 2A_0 \sin^2(\pi f_m \cdot \ell),$$

where $f_m = 1/\lambda_m$ is the mechanical frequency in cycles/meter. A(fm) is plotted in Figure 2.2 for ℓ = 0.50m.

II.3) Instrumentation

I recommend recording all of the mouse measurements on a portable instrumentation tape recorder. An example of a tape recorder is the Hewlett-Packard 3960A recorder: The options and estimated cost are:

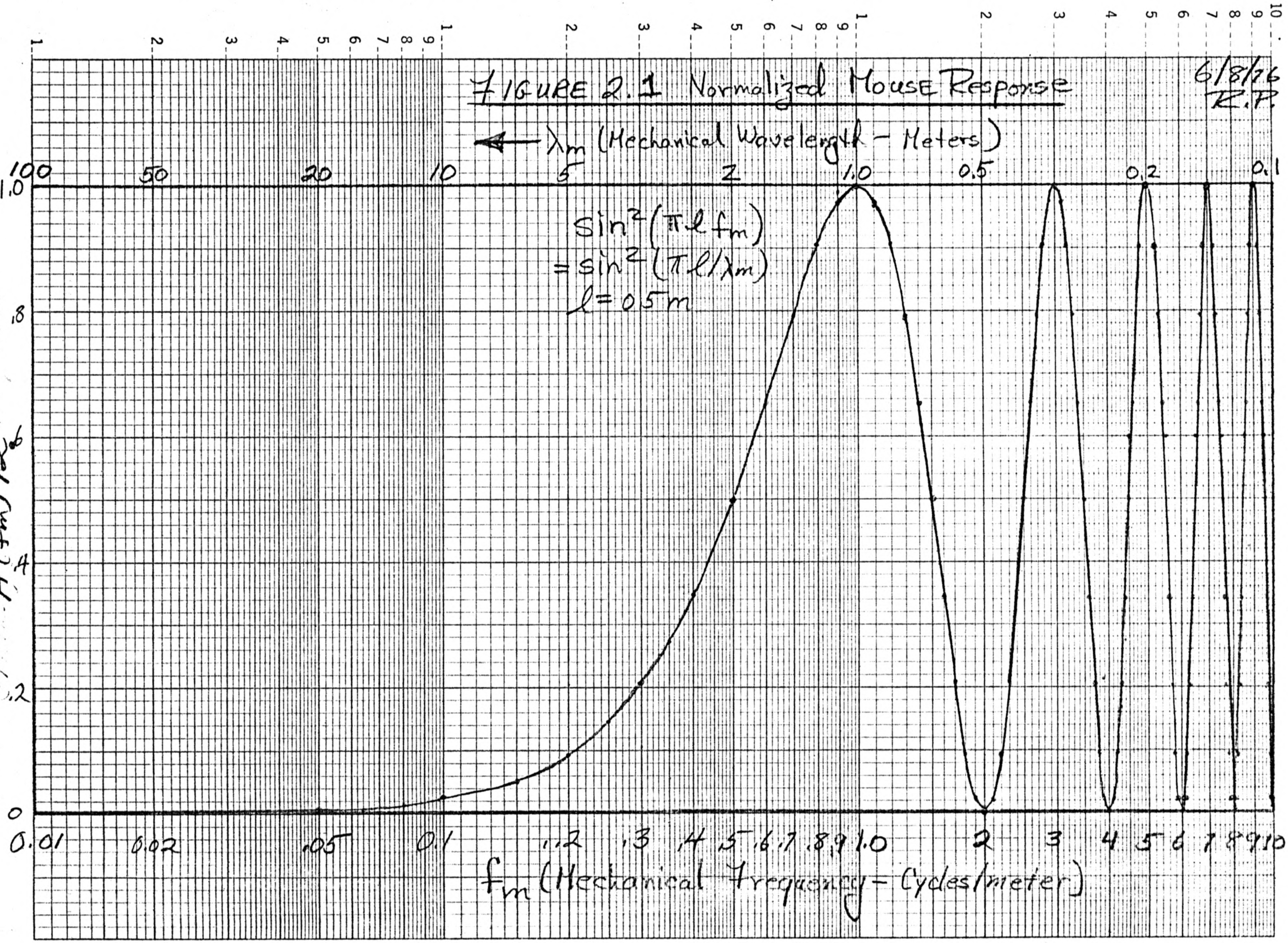


FIGURE 2.1 Normalized Mouse Response
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R.P.
← λ_m (Mechanical Wavelength – Meters)
100 50 20 10 5 2 1.0 0.5 0.2 0.1
$\sin^2(\pi l f_m)$
$= \sin^2(\pi l/\lambda_m)$
$l = 0.5m$
$A(f_m)/2$
1.0 .8 .6 .4 .2 0
0.01 0.02 .05 0.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 2 3 4 5 6 7 8 9 10
f_m (Mechanical Frequency – Cycles/meter)

3660A Transport Assembly: (15/16, 15/4, 15 ips standard)	$3,700
Option A03: Three channel FM Record/Reproduce	1,350
Option 023: Voice Channel	215
Option 028: Rack Mount	25
Option 029: Transit Case	425
Total	$5,715

The FM channel at 15/16 ips has a bandwidth of 312 Hz which is greater than the 100Hz bandwidth of the displacement transducers. The faster speeds can be used on playback to decrease the data analysis time. The output of the mouse can go directly onto the recorder. Recordings can be made of the mouse calibration procedure and the zero curvature levels for later use in the data analysis.

Chart recordings can be made in parallel with the FM recording as a check on the measurement and for preliminary analysis.

II.4) Data Analysis

The purpose of the mouse measurement and data analysis is to provide information on:

1) Joint tilt and offset.

2) Waveguide curvature.

These quantities will be measured soon after the waveguide installation and at later times to check since the increase in waveguide loss varies as

$$\Delta\alpha(dB/km) \approx 10\left[\frac{f(GHz)}{R(m)}\right]^2 + B\cdot\theta^2 f^2,$$

where R is the rms curvature and θ the rms tilt. The offset is not as important as the other two effects.

As shown in Figure 2.2, the analysis of the joint tilt and offset can be done by playing back the measurement at 15 ips, passing the X and Y (horizontal and vertical) output through 1600Hz low pass filters, differentiating the curvature data to look for peaks and steps in the curvature slope. As was shown in section II.2, the offset causes an up-down-up step function and the tilt a triangular function so the derivative is a set of up-down-up delta functions and an up-down-up step function respectively. The derivative can then be analyzed by peak detector circuits to give the offset and by high-low comparaters to give the tilt. Alternately, as shown in Figure 2.2b, all of the data near a joint could be digitized in a 12-Bit ADC at 3200Hz rate for further analysis on a computer such as the Mod Comp or the DEC 10. Only 10% of the data is at joints so this is not an undo amount of data for analysis.

The curvature can be analyzed at a much lower rate since only mechanical frequencies of less than 2 cycles /m are properly sampled by the mouse. Two methods of data analysis are outlined in Figure 2.3. Figure 2.3a shows an analog scheme for averaging the curvature squared for a given length of waveguide. The mechanical frequency is cutoff at 1.5 cycles/m, the mouse velocity ($\approx$0.1 m/sec) during the measurement is $\mathcal{V}_m$, and the factor of 16 is the ratio of the playback to record speeds on the tape recorder. Because of the low data rate ($\approx$2.4Hz) it is quite feasible to do a digital analysis even on a slow machine such as the H/P 9830. A 12-Bit analog to digital conversion can be done at a 4.8Hz rate, which can be put onto digital cassette tapes. This could be analyzed for rms curvature and an autocorrelation with 64 lags can be accumulated and then Fourier transformed to give a curvature power spectra as a function of mechanical frequency, from 0 to 1.5 cycles/m in .02 cycles/m steps.

Figure 2.2 Joint Analysis

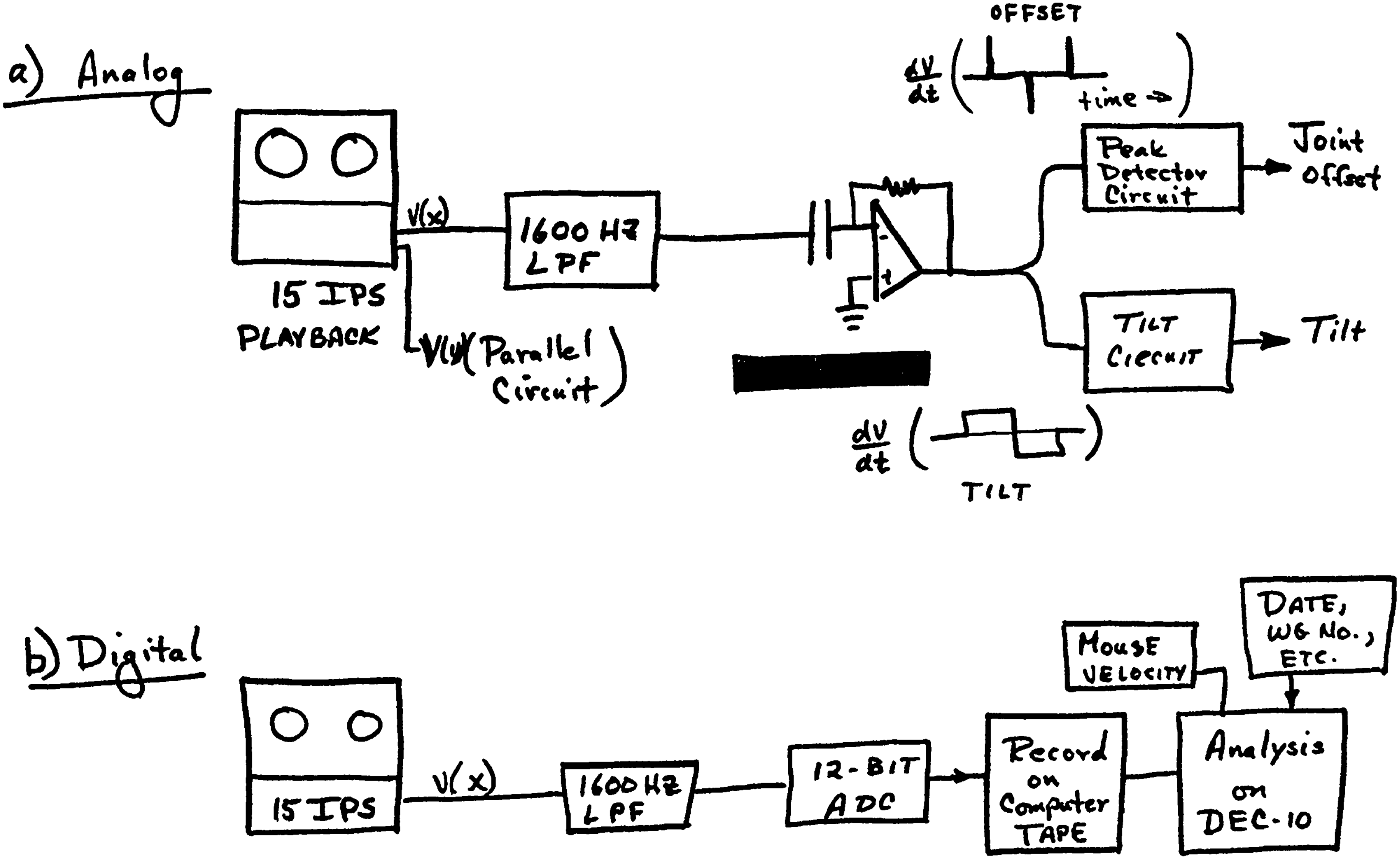
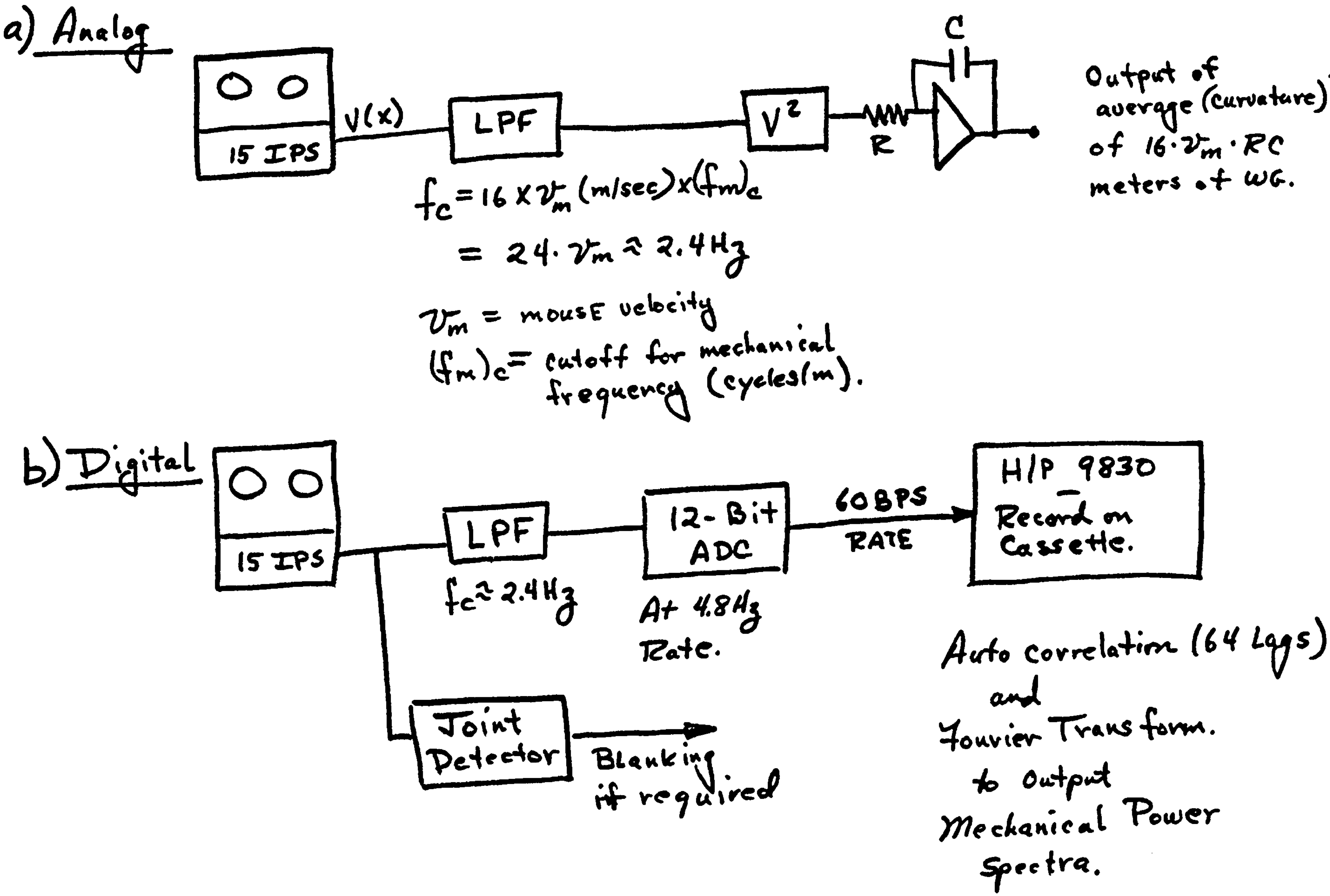


FIGURE 2.3 Curvature Analysis



III) Waveguide System

The major decisions in the waveguide system design have been made and are summerized in the paper by S. Weinreb, R. Predmore, M. Ogai and A. Parrish, and VLA Electronics Memo 120. However, the couplers for the outer 10 stations of the VLA are still being designed and the question of TE°_{02} mode filters for the use with the 60mm helical couplers and beam splitter couplers has not been settled. The enclosed Table 3.1 summerizes the performance of a 60mm beam splitter coupler as measured in Greenbank in October 1973. This coupler had not been compensated for TE°_{02} mode conversion.

Since a TE°_{01} to TE°_{02} conversion and subsequent TE°_{02} to TE°_{01} mode reconversion is required to cause an undersired ripple in the transmission system, the effect can be limited to an acceptable level by decreasing the mode conversion and/or the mode reconversion, and by increasing the spurious mode loss with a mode filter.

For a signal coupled into the waveguide system with a 60mm helical coupler the $TE^{\square}_{10}$ to TE°_{02} coupling is only 10dB less than the $TE^{\square}_{10}$ to TE°_{01} coupling. This mode discrimination is fixed with the present design but may be improved with broad banding techniques. To decrease the 0.1 to 0.5dB ripple presently measured in the VLA waveguide system, I recommend measuring the TE°_{01}-TE°_{02} mode conversion of the tapers being used so that the effect of the coupler and the taper can be separated and the best tapers used in the system. This taper measurement should also be performed on subsequent tapers when they are first received. If the new tapers on order from Fujikura do not have at least a -35dB mode conversion, two Bell Labs designs are available in the files at the VLA site for fabrication into helix lined tapers or electroformed tapers.

TABLE 3.1

60 mm Beam Splitter Hybrid (no dielectric).

Frequency Band	Average Insertion Loss (dB)	TE_{02} Mode Conv. (dB)	TE_{03} Mode Conv. (dB)	Return loss (dB)
26 – 33 GHz	.75 – .50 dB	≤ –16 dB	≤ –20 dB	
33 – 40 GHz	.650 – .40	≤ –21 dB	≤ –18 dB	≤ –35
40 – 46 GHz	0.40 – 0.35	≤ –22 dB	≤ –21 dB	≤ –36
46 – 52 GHz,	0.30 – 0.35	≤ –23 dB	≤ –21 dB	≤ –41

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$L_d = 20\log_{10}\left(1 - .279\,(\lambda/a)^{3/2}\right)$

$= 20\log_{10}\left[.51\cdot(\lambda/a)^{3/2}\right]$

f	Insertion loss	TE_{02} mode Gen.
25	–.63	~~–11.8~~ –17.8
26	–.60	~~–11.3~~ –18.3
30	–.48	~~–10.0~~ –20.2
35	–.38	–22.2
40	–.31	–23.9
45	–.26	–25.5
50	–.22	–26.8
52	–.21	–27.3
55	–.19	–28.1
60	–.17	–29.2

Reed Predmore
NRAO

To evaluate the over performance I recommend a model of the waveguide system and the mode generation and conversion elements such as couplers and tapers be made. The model follows the analysis of Rowe and Warters (BSTJ, Vol. 41, PP. 1031-1170, 1962). Figure 3.1 shows a model of TE^{o}_{01} and TE^{o}_{02} transmission lines coupled by N mode converters. The effective mode conversion-reconversion strength for each pair of converters is

$$C_{JK} = C_J C_K \, 10^{-[L_{JK}/20]}$$

where C_J, C_K are voltage coupling coefficients. The peak to peak ripple for this system is

$$R_{pp}(dB) = 20 \log_{10} \frac{1+\rho}{1-\rho} \approx 20 \log_{10}(1+2\rho) \approx 17.4\rho,$$

where $$\rho = \sum_{J=1}^{N-1} \sum_{K=J+1}^{N} C_{JK} .$$

The rms ripple is

$$R_{rms}(dB) = 20 \log_{10}(1+\rho/\sqrt{2}) \approx 6.14\rho .$$

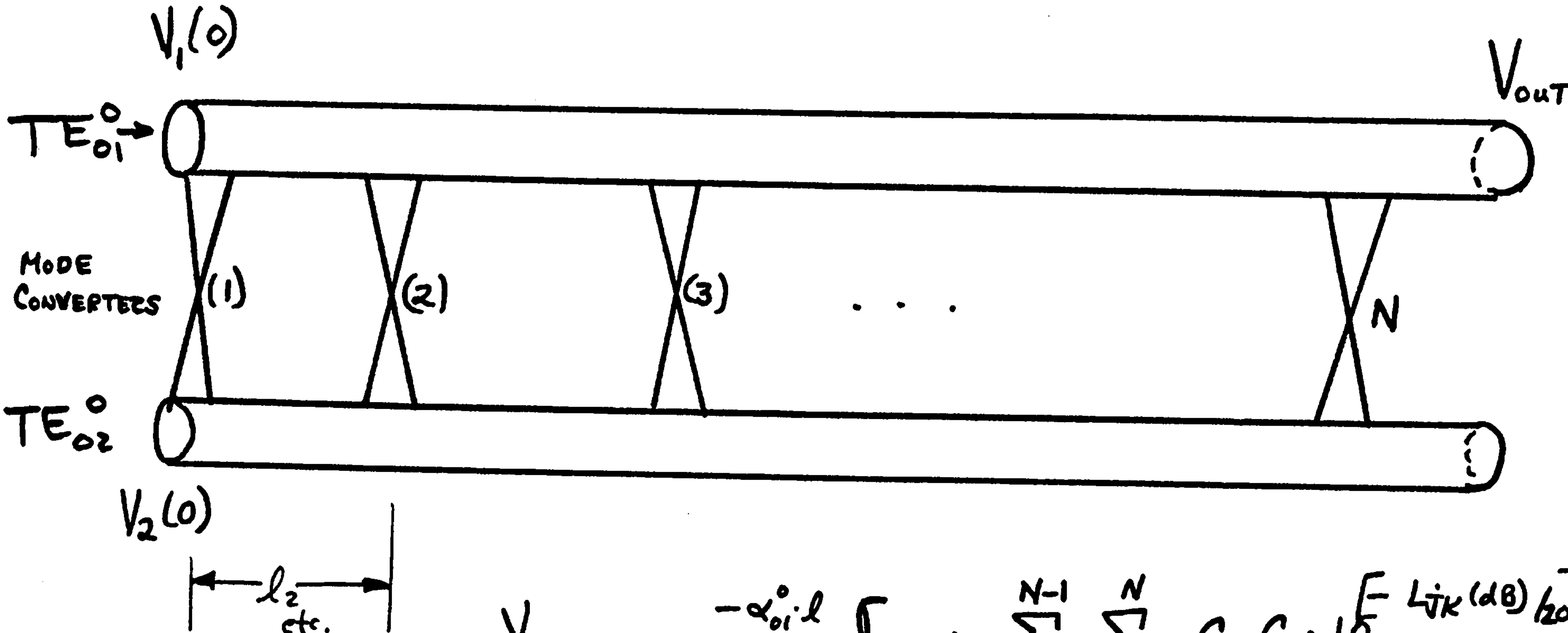
The same model can be used for TE^{o}_{01} mode reflections caused by windows and beas splitter and sector couplers by letting

$$\phi_{JK} = 2\,\beta^{o}_{01}\,(l_K - l_J)$$

and $$L_{JK} = 2\,\alpha^{o}_{01}\,(l_K - l_J)$$

This analysis applies to only one channel and should be extended to all the channels. This model can be used to select the placement and TE^{o}_{02} loss of any mode filters.

[redacted] F[redacted]URE [redacted]3.1[redacted] W[redacted]E[redacted]BE [redacted]ST[redacted] M[redacted]EL



$$\frac{V_{OUT}}{V_1(0)} = \underbrace{10^{-\alpha^{o}_{01}\cdot \ell}}_{\text{Waveguide Loss}} \left\{ \left[1 + \sum_{J=1}^{N-1} \sum_{K=J+1}^{N} C_J C_K \cdot 10^{\left[-L_{JK}(dB)/20\right]} \times \cos(\phi_{JK}) \right] \right\}$$

$$\phi_{JK} = \left[(\beta^{o}_{01} - \beta^{o}_{02}) \cdot (\ell_K - \ell_J) \right]$$

$$L_{JK} = \left[(\alpha^{o}_{01} - \alpha_{02}) \cdot (\ell_K - \ell_J) \right] + \text{Mode Filter Losses.}$$

IV) Broadbanding Helical Coupler

In the time available I have been able to find some references for broadbanding couplers, but have not been able to investigate the additional bandwidth that could be achieved with the helical coupler. This investigation can be continued if desired.

The references are:

1) A. G. Fox, "Wave coupling by Warped Normal Modes", IEEE-Trans. MTT, pp. 2-6, December 1955.

2) A. G. Fox, Bell Sys. Tech. J., July 1955.

3) C. Staeger, "Computer Aided Design of Broadband Matching and Coupling Structures", European Microwave Conference, pp. 378-381, 1973 or 1974. (Copy is enclosed)

V) General Information

1) Pressurization- Consider the oxidation of the copper and consequent increase in loss when deciding whether to pressurize the waveguide system with dry nitrogen or dry air. I recommend dry nitrogen even though it involves some additional safety procedures when working in confined areas.

2) A copy of a bibliography of waveguide papers is enclosed.

3) Technical information is enclosed on several new products which are useful for the VLA waveguide system.

   3.1) Technicraft flexible millimeter waveguide- Useful between the rectangular output port of a helical or other coupler and the rectangular to 20mm circular waveguide adapter.

   3.2) Watkins-Johnson 33-50GHz BWO-USA source of higher frequency sweepers for the WG Test Set.

   3.3) Flange Programmable Waveguide Attenuator- Useful when measuring the absolute attenuation of up to 20Km of waveguide with the waveguide test set.

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