# ELECTRONICS DIVISION VLA MEMORANDUM #117

## REPORT ON B.T.L.-NRAO WAVEGUIDE REVIEW MEETING

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On 24-25 October 1973, a group of Bell Telephone Laboratories (BTL) Engineers who are working on the BTL low loss circular waveguide communications system visited Green Bank and met with NRAO Engineers working on the VLA waveguide system.

### ATTENDEES

| BTL | NRAO |
|---|---|
| Tom West | Sander Weinreb |
| Milton Gerdine | Alan Parrish |
| Larry Hinderks | Hein Hvatum |
| Dave Thomson | Jack Campbell |
| John Doane | Read Predmore |
| Dale Young | Peter Napier |
| | George Behrens |
| | Emory Egler |

The purpose of the meeting was to provide a comprehensive review of the planned VLA Waveguide System by an independent group of engineers currently working at a state-of-the-art level on low loss $TE_{01}$ mode waveguide communication systems. The specifications and design of the VLA system and the measurements made by NRAO on waveguide components were presented in detail as follows.

General System Requirements and Specifications: S. Weinreb

In particular, the system loss specifications were given as:

(a) Average waveguide loss: 2 dB/km

(b) Allowable variation in waveguide loss: $\pm 3$ dB over 1 GHz

(c) " " " " " : $\pm 1$ dB over 50 MHz

(d) " " " " " : $\pm .1$ dB over 1 MHz

Waveguide Component Test-set and Results: A. Parrish

Waveguide Internal Diameter and Bend Measurement Set ("mouse") Design: J. Campbell

Coupler Design: R. Predmore

The BTL Engineers identified areas of the proposed system which, from their experience, would present design problems and suggested solutions to some of these problems. A summary of the conclusions of the reviewers and of the main points arising from the discussion are given below.

## Conclusions of the Reviewers:

At the end of the meeting each reviewer was asked to give his overall opinion of the proposed waveguide system design.

T. West: NRAO should be able to lay the waveguide with sufficient straightness so that the loss specifications (b) and (c) above can be met. Special attention should be given to coherent periodic irregularities in the waveguide which could make these two loss specifications difficult to meet.

J. Doane: NRAO should prevent irregularities in the waveguide (eg. changes in internal diameter or radius of curvature) from having mechanical wavelengths less than 3m. As an example of the importance of randomizing the spacing of irregularities, consider a 20 km waveguide run composed of 5m lengths with, at each waveguide joint, a triangular change in internal diameter of 20 micron over 10 cm. Operating at 30 GHz this waveguide system would have variations in loss of 10 dB over .5 MHz bandwidth. If the lengths of the waveguide pieces have lengths that vary randomly about 5m by up to 1 cm max., loss variation will be about .01 dB over .5 MHz bandwidth.

D. Thomson: To ease the severe requirements on variation of waveguide loss with frequency, NRAO should seriously consider digitizing all data at the antennas rather than sending back the 50 MHz bands of data in analog mode.

D. Young: NRAO needs to do a lot of work on the couplers used to connect each antenna into the waveguide system. Detailed computer modeling should be used to estimate the effect of coupler mismatch and mode conversion on system performance.

L. Hinderks: NRAO will have serious problems with the couplers. Experience shows that VSWR problems are usually worse than expected. Digital data transmission is the natural mode for using this type of waveguide.

M. Gerdine: In general the NRAO electrical measurements of the waveguide and components are in good shape. Methods of measuring higher order mode effects by looking at beat patterns as frequency is scanned could miss out very narrow band effects.

## Loss-Frequency Response of the Waveguide

Variations in the radius of curvature or internal diameter of a waveguide run will cause the loss of the waveguide to vary with frequency. The important characteristic of the waveguide in determining the loss is the Power Spectral Density (PSD) of Curvature (units $(1/m)^2$/cycle/m) or the PSD of Diameter (units micron$^2$/cycle/m).

The loss is obtained by convolving the PSD function with a "mode function" $A(f_m)$ defined as

$$A(f_m) = \frac{1}{\Delta\alpha} \frac{CC^2}{1 + \frac{(\Delta\beta - f_m^2)}{\Delta\alpha}}$$

where $f_m$ = mechanical frequency, $\Delta\alpha$ = differential attenuation constant between the $TE_{01}$ mode and the higher order mode under consideration, CC = coupling coefficient between the two modes and $\Delta\beta$ = differential phase constant between the two modes.

The BTL waveguide system consists of dielectric lined waveguide runs 40 km long. At 110 GHz BTL expects $\pm 1$ dB variations in loss at 2 cycles per GHz. This is due to bends in the waveguide causing coupling to $TE_{12}$ and $TM_{11}$ modes. They may use mode filters (helix waveguide) to reduce this ripple. NRAO should not experience this problem because of their lower operating frequency. On a finer frequency scale, BTL expects as much as $\pm$ 5 dB variation in loss over 1 MHz bandwidth, but again NRAO's lower frequency should protect against this.

Randomization of Waveguide Lengths

BTL randomizes the lengths of their waveguide pieces. It seems essential to do this as loss resulting from periodic irregularities in a waveguide run of length L increase as $L^2$. Lengths need be randomized by only a very small amount (1 cm in 5m) because the length increments are cumulative.

NRAO Waveguide Measurements

The error in the NRAO waveguide measurements is less than 0.01 dB due to noise and less than 0.025 dB due to systematic errors. The measurements show the expected inverse 3/2 power decrease in heating loss with frequency.

Pressure Windows

BTL are not using windows to give pressure isolation of adjacent parts of their system because they have welded flanges and their waveguide is laid inside a protective sheath. The use of a sliding window or rotating valve which could be placed in position only when a pressure seal is needed (eg. when a coupler is being removed) was suggested. BTL have used a window comprised of a 6 inch piece of styrofoam inserted in the waveguide. This window had a return loss of 30 dB - Seymour Shapiro at BTL has worked on this window.

Milar windows are not recommended by BTL. If a window bows under pressure it will generate $TE_{02}$. A milar window set at 45° in the waveguide has an elliptical cross-section and will generate $TE_{21}$ and $TM_{21}$ modes.

To examine the effect of waveguide contamination BTL filled 1600 ft. of waveguide with mud and water and then cleaned the pipe with high pressure water. The loss increased by 5% and returned to normal after a few months.

BTL does not expect to have a continuous flow of gas through their waveguide but expects to purge it at regular intervals. Great care must be taken to detect leaks of nitrogen into a manhole. A manhole could completely fill with nitrogen causing the asphyxiation of anyone entering it.

Tapers

NRAO is having difficulty preventing $TE_{02}$ mode generation in waveguide from exceeding the maximum allowable level of -35 dB. Using tapers designed by Wang of BTL, BTL has obtained 35 dB return loss but have found it difficult to do much better than this. One cause of the NRAO problem may be an incorrect choice of diameter for the copper - helix junction at the ends of a taper - the dimensions should be chosen so that the effective electrical diameters of the two types of waveguide are the same. Jim Carlin at BTL has looked into this problem.

Waveguide Run Up Antenna

Both the flexible waveguide and mitre bends seem to have too much loss or spurious mode generation at present for the run up the antenna structure through the bearings to the vertex room. Suggested solutions to this problem were: bend small diameter rigid waveguide into the required bends being careful that the cross section remains circular - this can be done by constraining the waveguide between rigid plates during the bending; send the signals down the antenna on coax and have the millimeter mixer at the base of the antenna; use a radiated link from vertex room to ground.

Installation Procedure

BTL do not see any advantage in using sleepers in the bottom of the trench to support the waveguide. It is possible that the backfill would not adequately fill in between the sleepers leaving the waveguide sitting on point supports. BTL prefer to lay the guide directly onto the bottom of a trench lined with sand that has been smoothed by dragging a long sledge along it. If sleepers are used their spacings must be randomized.

BTL laid 1500 ft of waveguide with this direct burial method during the fall 10 years ago. This waveguide was buried at 4 feet depth by a 6-man construction team at an average of 400 ft. per week through dry rock, swamp and pasture. The waveguide was 51 mm diameter operating at 90 GHz (this corresponds to 65 GHz for the VLA). The initial burial caused the waveguide loss to increase .3 dB/mile. During the winter there was no change in loss but in the spring there was a further increase in loss of .3 dB/mile

For their present waveguide system, BTL will have waveguide runs 21 miles long and will lay the protective sheath in 1-1/2 mile sections. The waveguide will be pushed into the sheath on rollers for 1-1/2 miles.

Waveguide Couplings

BTL uses welded flange joints to couple their pieces of waveguide together. They use a hydraulically operated press to align and hold the 4 inch diameter flanges together with a force of 5000 lb. during the welding operation. The welder is a custom mode tungsten arc welder made by Doerfer Co. in Iowa. The radial alignment accuracy of the system is 2 mil RMS.

BTL experienced problems with early Japanese threaded couplings; they were inadequately machined and a coupling with a tapered pipe thread was found to compress significantly the internal diameter of the waveguide. The possiblity, as suggested by Bechtel Corp., that the NRAO threaded couplings may not be strong enough for the thermal stresses that will be encountered, can easily be determined by testing some of the couplings in a Mechanical Laboratory. Ray Tuminaro at the Chester Labs of BTL has done a lot of mechanical testing of BTL waveguide.

Mouse Design

NRAO must be careful in choosing a cable to pull the mouse through the waveguide. A cable with a set in it will cause the mouse to twist. L. Hinderks has samples of cable that were especially made for the BTL mouse. Wheels or sliding surfaces on the mouse should not be made of soft materials (eg. nylon) because these pick up any dirt in the waveguide and become abrasive.

Couplers and Mode Filters

Because they always want to drop all channels at once at their repeaters, BTL do not have problems with couplers similar to those experiencedby NRAO. NRAO will have to develop couplers suitable for their own particular requirements. Considerable effort should be put into developing a 60 mm waveguide coupler. Direct coupling from 60 mm waveguide into rectangular waveguide appears feasible; a paper by Davies in the IEE shows how the holes in such a coupler can be staggered for broadbanding. The effect of holes in the walls of $TE_{01}$ waveguide is to cause forward scatter in higher order modes; a paper by Glazer and Hughs of BTL investigates this effect. The BTL expert on couplers is Dr. Wang.

BTL have theoretical designs but no working models for $TE_{on}$ mode filters (n greater than 1). A paper by a Japanese engineer (from Sumitomo?) describes a mode filter made of waveguide with a non circular cross-section which converts $TE_{on}$ modes into modes with longitudinal wall currents that are attenuated by the helix waveguide. Typically the loss of such a filter for $TE_{01}$ mode is 1 dB and for $TE_{on}$ $(n>1)$ modes it is 30 dB.

Matched Loads for Circular Waveguide

For 60 mm waveguide an open ended piece of waveguide is a very good termination. For small diameter circular waveguide the load cone must be about 5 wavelengths long, extremely sharp and precisely located in the center of the waveguide. BTL have made loads with 35-40 dB return loss using magnetite loaded Epoxy supplied by the Custom Load Co. in Massachusetts.

Leak Detection

To locate leaks in their waveguide system BTL fill their waveguide with helium and use a probe on the surface of the ground to detect the helium leak. Successful tests have been made at Chester using a probe detector that is a standard unit made by the Mine Safety Appliance Co. This unit needs to be modified by putting in a center reading meter (D. Thomson knows about this). NRAO must mark the positions of the waveguide couplings on the ground surface during installation.

## Digital Transmission in Circular Waveguide

The BTL waveguide communications system has a 274 M baud/sec data rate over channels spaced 500 MHz apart (4 bit sampling is used). A signal to noise ratio of 35 dB is used, total loss over a 25 mile run, including coupling losses at each end, is 40 dB.

## Lightning Protection

A book by Sunde - Earth Conduction Effects - published by Dover, gives useful information on lightning protection.