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AN EVALUATION OF THE PERFORMANCE OF THE VLA CIRCULAR WAVEGUIDE SYSTEM

J. W. Archer, E. M. Caloccia[1], R. Serna

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ABSTRACT

A practical and theoretical evaluation of the characteristics of the unique millimeter wavelength, helix-lined, circular waveguide system installed at the Very Large Array Program in New Mexico is presented. The communication system, as installed, exhibits performance characteristics which exceed the original specifications, indicating that carefully planned direct burial of overdimensioned circular waveguide can be a practical and cost-effective installation technique.

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[1] E. M. Caloccia is now with Raytheon, Inc., Bedford, Massachusetts.

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I. INTRODUCTION

The Very Large Array (VLA) is a high sensitivity, multi-frequency Fourier synthesis radio telescope, which provides high resolution brightness maps of cosmic radio sources (Heeschen 1975). The VLA consists of 27 antennas arranged along the arms of a Y configuration. Each arm is between 19 and 21 kilometers in length and may be comprised of nine operational antennas at a given time, located at any of 24 observing stations. A low-loss, wideband reciprocal transmission system is required for communication between any antenna and a central Control Building. The preliminary design of the millimeter wavelength waveguide system adopted for the VLA has been described by Weinreb, Predmore, Ogai and Parrish (1977).

The millimeter wavelength circular waveguide system installed at the VLA is unique in concept and is presently the only operational system of its type in the world. This paper describes the final design of the waveguide network and discusses the problems which arise from the need for the insertion of many nonuniformly spaced, directional power coupling devices in the transmission system. System performance is evaluated by considering the relationship between measured attenuation per unit length as a function of frequency, total installed waveguide length and time since installation. Consideration is also given to the effects of TE_{01} mode reflections, and of coupling from the TE_{01} mode to higher-order circularly symmetric modes, on the waveguide transmission response.

II. BRIEF SYSTEM DESCRIPTION

A single 60-mm diameter helix-lined waveguide carrying the low-loss TE_{01} mode and extending along each arm of the Y is sufficient to communicate all signals to and from the nine antennas on an arm. In order to avoid a large number of cables and the need for electronic equipment at more than one location at each antenna, 20-mm diameter helix-lined waveguide carries the signals from a directional coupler in the 60-mm trunk waveguide to the vertex equipment room of each antenna. The final design transmission system uses sector couplers, described by Archer, Ogai and Caloccia 1979, exclusively for coupling between antenna and trunk waveguides. These couplers exhibit very low main line TE_{01} mode insertion loss, very low main-line TE_{01} to TE_{0n} mode coupling and are easily fabricated for a wide range of coupling values. The complete waveguide system is pressurized with dry nitrogen, at 2 psi gauge, to avoid the increase in attenuation above 50 GHz due to oxygen resonance absorbtion and to reduce the possibility of water leakage into the buried waveguide.

Each antenna is assigned a 1-GHz bandwidth communication channel and eleven channels (2 spares) are allocated in the 27 to 53 GHz range. Within these 1 GHz, single sideband modulated channels, the signals communicated from the Control Building to an antenna are:

i) A pair of local oscillator reference tones separated in frequency by 600 MHz.

ii) Digital command signals for antenna and receiver electronics control, which are amplitude modulated onto the higher frequency reference tone.

The return signals to the Control Building from each antenna are similar in nature to i) and ii) above, but with the addition of four 50-MHz bandwidth analogue IF signals in the frequency range 1.3 to 1.7 GHz, upper sideband, relative to the carrier. The forward and return signals are time multiplexed with a transmission cycle: 1 msec outward, 51 msec return. The configuration for transmission from an antenna to and from the Control Building is shown in Figure 1.

If the minimum signal-to-noise ratio for the IF signals at any communication system modem receiver is specified to be 20 dB, the maximum loss between the Control Building and antenna modems must be no greater than 56 dB, for a typical receiver noise figure of 12 dB and a minimum transmitted power spectral density of -8 dBm/50 MHz. Furthermore, small scale, frequency dependent variations in the phase and amplitude response of the waveguide system can significantly affect the performance of the antenna array, especially when the frequency dependence varies with time. Local oscillator phase relationships at the antennas can be modified and the phase and amplitude relationship between IF passbands can be altered when the variations occur within small frequency intervals. For these reasons,

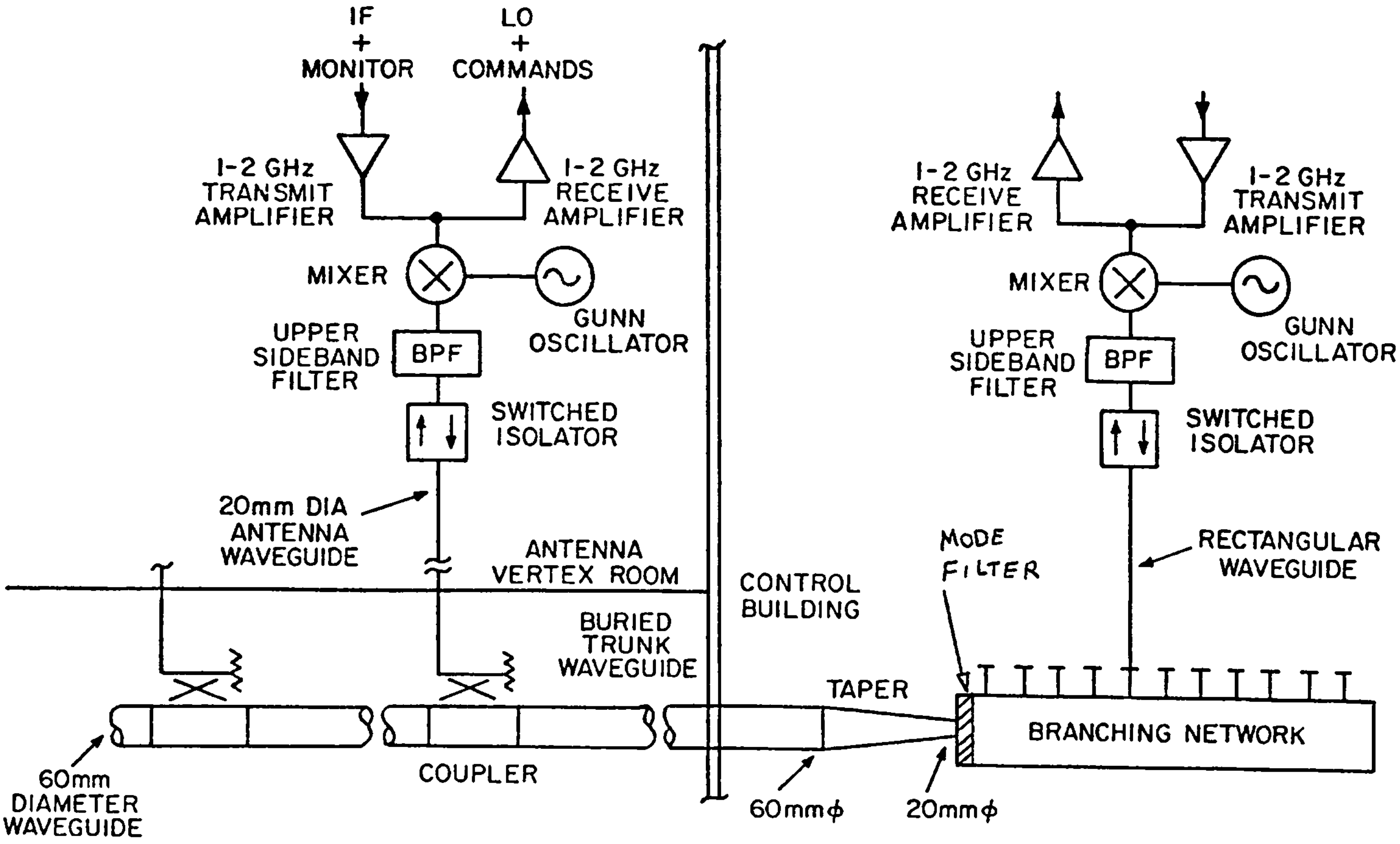

Figure 1: VLA waveguide communication system configuration.

the maximum rms deviation in the magnitude of the TE_{01} mode transfer function, between any antenna and the Control Building, is specified as 1% of the mean power transmission response within any 10-MHz band. In the same band, the corresponding allowable rms deviation of the phase response from linearity is 0.3° (Archer 1978).

III. MAIN LINE TRANSMISSION LOSS EVALUATION

The 60-mm diameter circular waveguide in the VLA transmission system is presently installed using the direct burial technique described below. The helix-lined waveguide (manufactured by Sumitomo Electric Co.), after application of a special corrosion resistant protective coating, is buried at a minimum depth of one meter on a 30-cm thick smoothed bed of compacted sand. The assembled waveguide, comprising sections 4.95 meters (±50-mm randomization) in length, fixed together with precision alignment coupling sleeves (joint offset less than 80 microns rms, joint tilt less than .001 radian rms), is laid and pretensioned on the compacted base to line and grade so that the initial radius of curvature is greater than 1000 meters in both horizontal and vertical planes. Sand fill is then added to a depth of 4 cm and bedded down to provide a side compacted support for the waveguide. This is followed by a 30-cm layer of compacted sand shading, 30 cm of compacted sand backfill and finally earth backfill to ground level.

An earlier, less successful technique, mentioned in the subsequent performance analysis, used a compacted base layer followed by a 30-cm thick compacted backfill, without pretensioning or careful side compaction after waveguide installation. The use of pretensioning, side compaction and 3-level compacted sand backfilling significantly improves waveguide performance stability as a function of time.

An early waveguide evaluation technique involved the use of an electro-mechanical device pulled through the waveguide to measure the waveguide straightness after backfilling. The use of this device has been discontinued due to the proven high risk of causing mechanical damage to the fragile wire-wrap of the interior waveguide surface. All performance evaluations are currently carried out by direct measurement of the millimeter wavelength TE_{01} mode attenuation of each newly installed waveguide section, using an RF pulse reflection method (Weinreb et al. 1977).

The curves of Figures 2 and 3 indicate the variation in the measured waveguide attenuation per unit length as a function of frequency, as total length from the Y center increases. Figure 2 represents results of measurements, without couplers installed, on the southwest arm of the array, where a total length of 17.72 km of circular waveguide has been installed. Figure 3 shows similar measured attenuation curves for the southeast arm, where the total installed waveguide length is 14.17 km. Since the sections nearer the center of the Y were the first to be installed, it is evident that revisions of the installation techniques with time have brought about an improvement in waveguide performance.

Below about 35 GHz, the attenuation response changes little with increasing total waveguide length. In this region of the frequency domain the loss is dominated by the heat loss in the copper wires forming the helix lining of the interior waveguide surface. However, for higher frequencies, the effects of power loss due to coupling between the TE_{01} mode and higher-order nonsymmetric modes, which are strongly attenuated due to the mode filtering action of the helix-lined waveguide, become progressively more evident. These effects contribute an excess loss, which, when added to the expected ohmic loss, results in the behavior exhibited by the measured attenuation curves. In particular, the predominant effect is that of mode coupling due to small deviations from straightness of the waveguide line. The most significant coupled modes in this case are the TE_{1n} modes.

The shift in the minimum of the curves and the reduction in the attenuation per unit length as total waveguide length increases results from a significant improvement in mean waveguide straightness. Figures 2 and 3 also show the theoretical TE_{01} mode attenuation response due to ohmic losses for perfectly straight, pure copper waveguide of 60-mm diameter. A constant difference between this curve and the measured attenuation curve of 0.3 dB/km may be observed for frequencies below about 35 GHz. The offset results from an excess attenuation due to the increased azimuthal surface

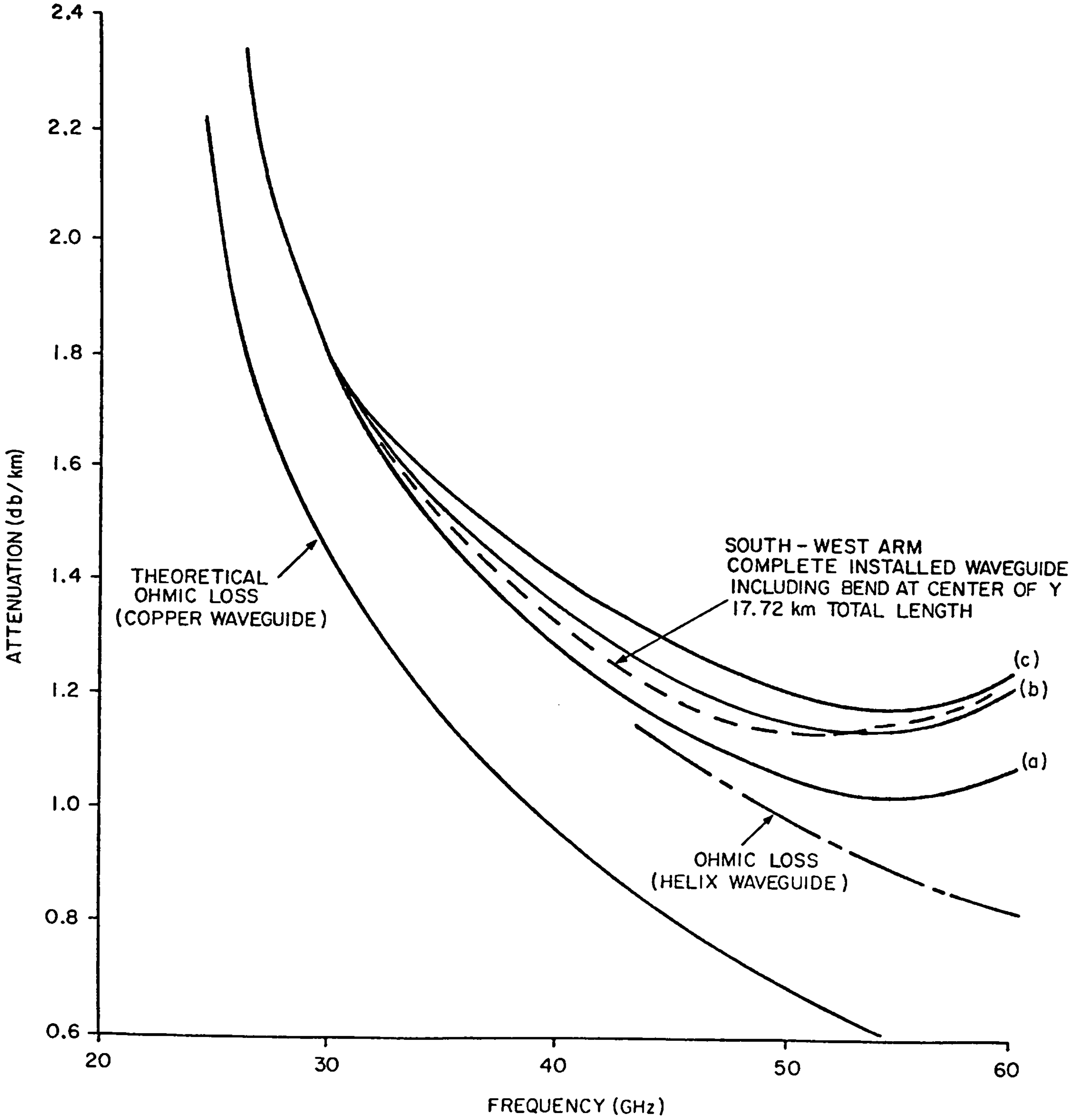

Figure 2: Measured attenuation per unit length as a function of transmission frequency for the Southwest arm of the array (pressurized with dry nitrogen).
Curve a) 16.47 km from Y center - mean radius of curvature 1150 meters
Curve b) 9.78 km from Y center - mean radius of curvature 1050 meters
Curve c) 2.48 km from Y center - mean radius of curvature 1000 meters

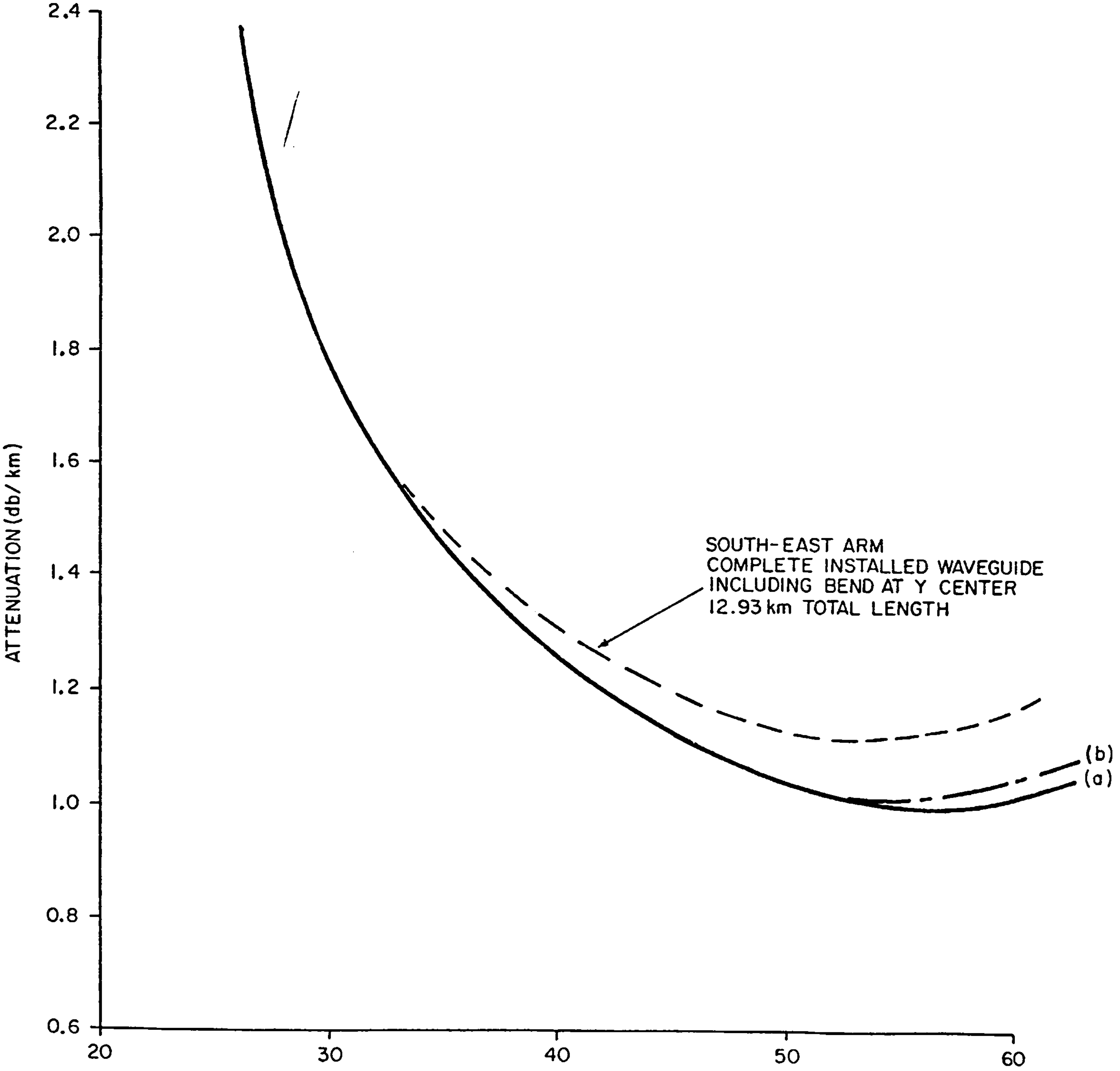

Figure 3: Measured attenuation per unit length as a function of transmission frequency for the Southeast arm of the array (pressurized with dry nitrogen).
Curve a) 11.64 km from Y center - mean radius of curvature 1190 meters
Curve b) 3.28 km from Y center - mean radius of curvature 1180 meters

impedance of the helix lining of the interior waveguide surface relative to that of pure copper waveguide. Using this result, it is possible to determine the actual ohmic loss contribution at frequencies above 35 GHz [assuming ohmic losses are inversely proportional to $(\text{frequency})^{3/2}$] and, thus, that part of the loss contributed by higher order mode coupling may be estimated. Applying the results of Rowe and Warters (1962), the mean radius of curvature for each waveguide run has been estimated from the derived mode coupling power loss, for assumed inverse fourth power horizontal and vertical curvature power spectra, and is listed in Figures 2 and 3. It is clear that for the total length of VLA waveguide presently installed, the mean radius of curvature attained exceeds 1000 meters. The rms curvature for a section of the waveguide run (c) in Figure 2 was measured mechanically and good agreement between the curvature values derived from the attenuation curve was found, verifying the present method of analyzing the mean waveguide straightness.

Variation of waveguide attenuation as a function of time has also been investigated. Four sections of waveguide were studied, one of which was installed using the early version of the burial technique and three others which were buried using the improved installation procedure.

As can be seen from Figure 4, which relates measured attenuation per unit length to time since installation at a frequency of 50 GHz, the most rapid deterioration in performance, if any, occurs shortly after burial. Thereafter, the attenuation characteristics have been found to remain very stable as a function of time. In the case where the old version burial technique was employed, a quite marked initial degradation in loss was observed, prompting a revision of the techniques used for waveguide installation. The results presented in Figure 4 show that a significant improvement has been obtained in loss stability after implementation of the revised approach to waveguide installation.

IV. ANTENNA WAVEGUIDE EVALUATION

During the course of the VLA Program a number of different

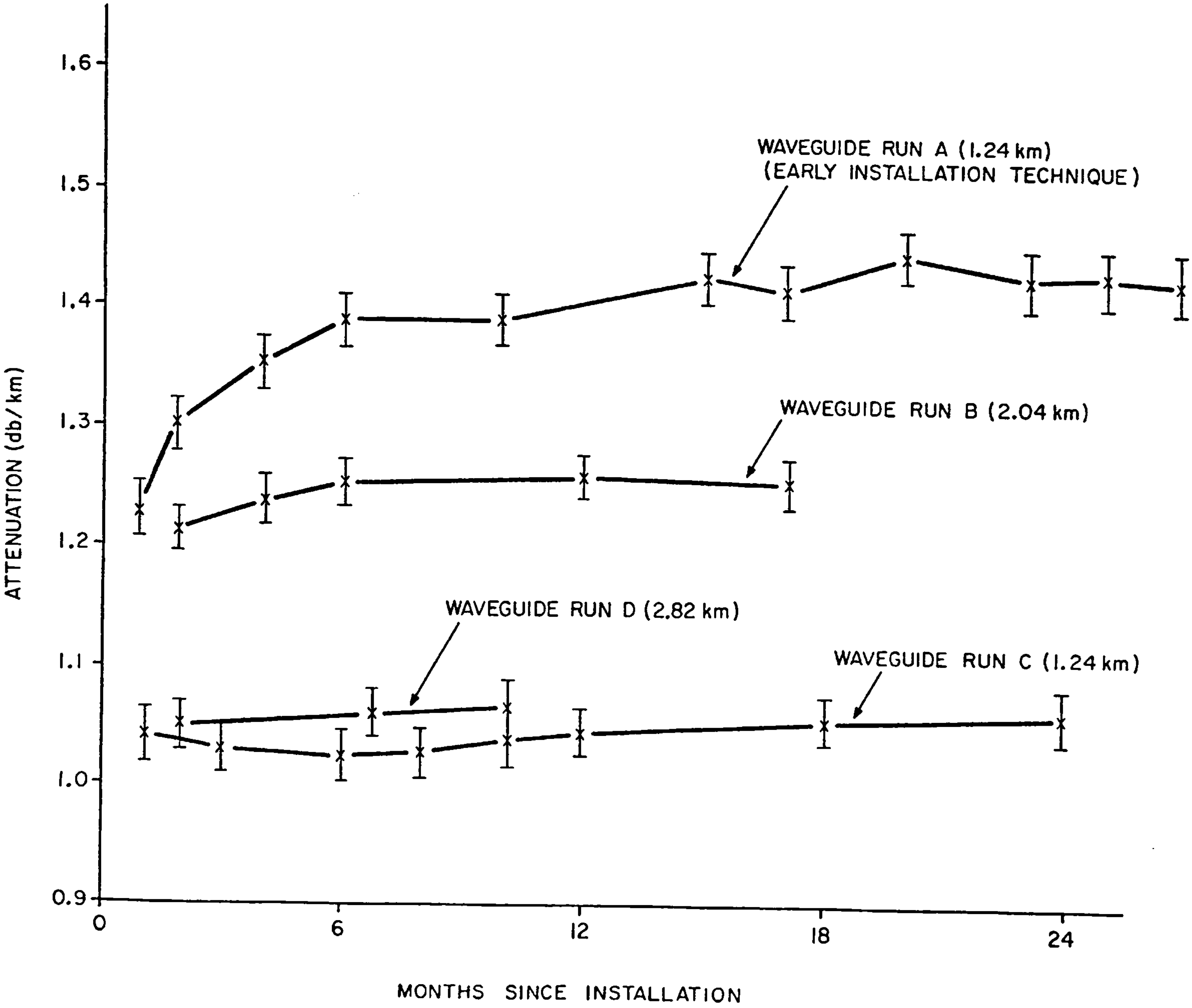

Figure 4: Waveguide loss per unit length for different runs measured at 50 GHz as a function of time since installation.

20-mm diameter helix-lined waveguide configurations have been evaluated. The waveguide run on each antenna is comprised of two rotatable joints, rigid and flexible waveguide sections joined together to form a continuous transmission system approximately 30 meters in length. Figure 5 shows the total antenna waveguide loss as a function of frequency for three different configurations.

The earliest system [curve (a)] proved unsatisfactory due to the presence of a sharp resonance in the response near 30 GHz. The resonance was shown to result from the characteristics of the flexible waveguide (Furukawa Ltd.) used in these early runs. Curve (b) shows the attenuation response which resulted from replacing these flexible sections with units from a different manufacturer (Fujikura Ltd.). The final configuration VLA antenna, however, using an improved flexible waveguide section from the same manufacturer, exhibits the much improved response shown in curve (c). In all cases, the total change in attenuation as the antenna is moved in elevation from zenith to horizon or through 360° in azimuth is less than 0.3 dB.

V. A TRANSMISSION SYSTEM LOSS BUDGET

From the above results it is possible to determine whether the VLA waveguide communication system is capable of meeting the 56 dB maximum modem-to-modem loss specification. Figure 6 shows the worst case attainable waveguide system loss budget, with couplers installed at every station on the southwest arm, at frequency of 50 GHz. To derive this curve, a maximum sector coupler main line insertion loss of 0.2 dB has been assumed (Archer et al. 1979). Furthermore, rectangular waveguide losses and branching network losses have been lumped together and set at a total of 7 dB. Worst case antenna waveguide loss has been assumed to be 3 dB.

It can be seen that, at 50 GHz, there exists a 17.6 dB loss margin, modem-to-modem, over the full 21 km of waveguide. A similar analysis at 30 GHz shows that, at the lower frequency, this margin is substantially reduced to approximately 5 dB. It is clear that excellent waveguide system performance is attainable for opera-

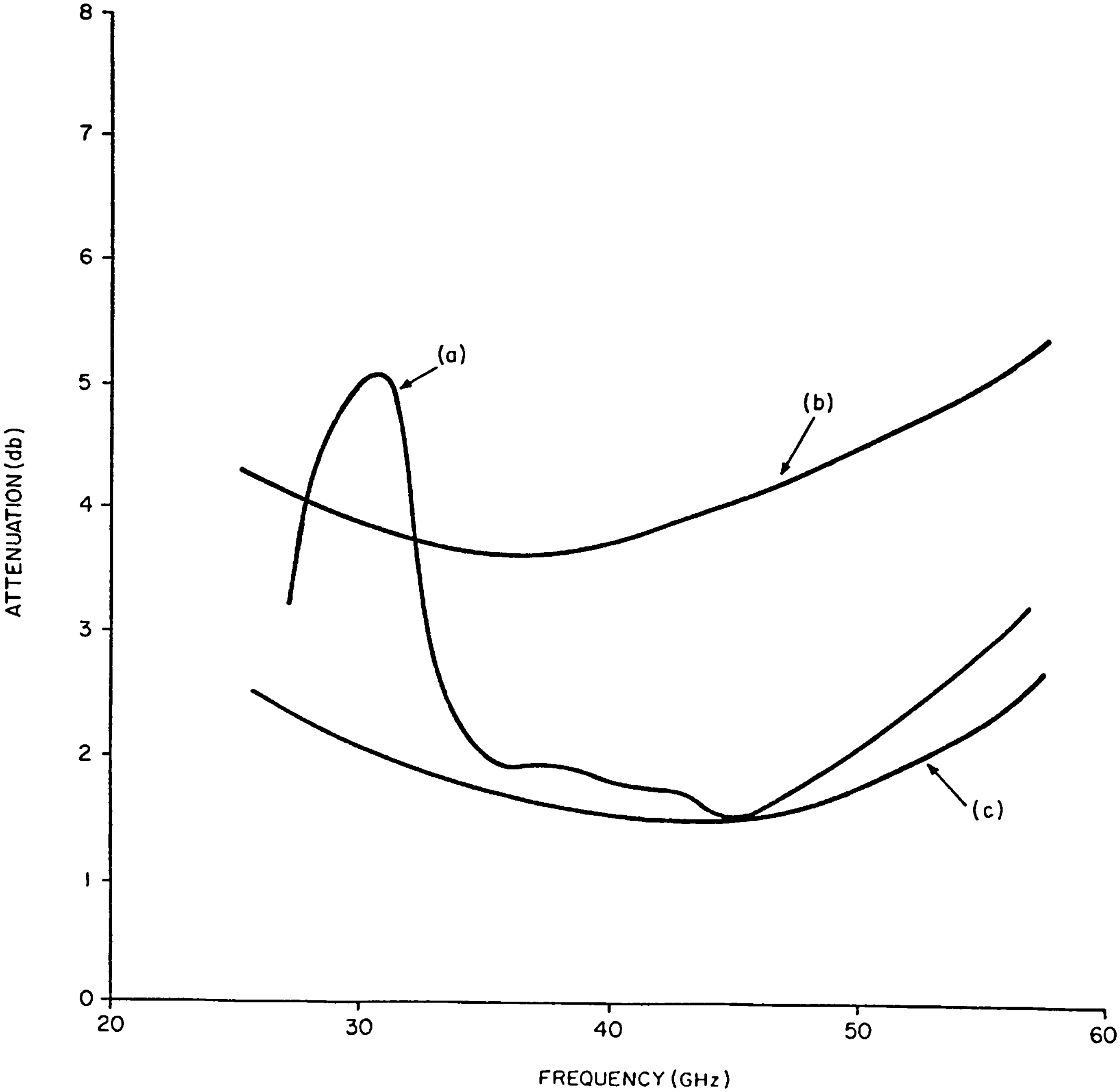

Figure 5: Typical measured attenuation versus frequency response for the antenna waveguide.

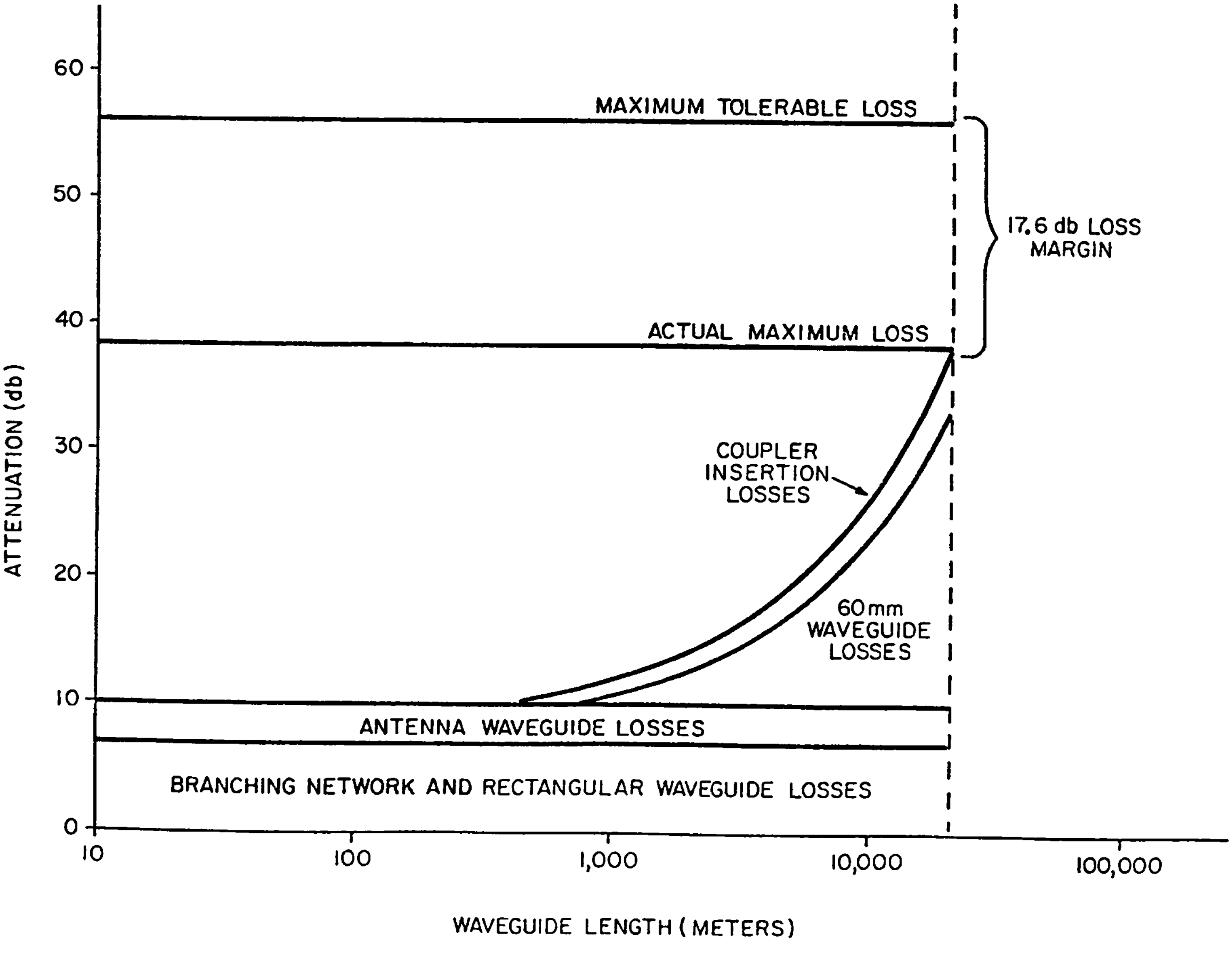

Figure 6: Worst case system loss budget at 50 GHz with couplers installed at every station (Southwest arm).

tion in any channel with center frequency greater than about 40 GHz. Furthermore, the system is usable over the full 21 km for all channels above 30 GHz, but with reduced margin for departure from nominal modem performance at the lower frequencies.

As an example, consider the use of channel 9 (center frequency 47.1 GHz) for an antenna located at the penultimate station on the southwest arm (17.72 km total 60-mm diameter waveguide length). The total system attenuation is 35.73 dB at this frequency, including branching network and antenna waveguide losses, implying that the minimum required coupling for the coupler at this station at channel 9 is 20.26 dB. Significantly, this suggests that high performance sector couplers with relatively loose coupling, low main line insertion loss and low main line TE_{0n} mode generation can be used at every station in the array, considerably simplifying the design of antenna station manholes, antenna foundation waveguide installation and implementation of the nitrogen gas pressurization system.

VI. TRANSMISSION DISTORTION DUE TO SPURIOUS SIGNALS

Frequency dependent phase and amplitude variations in the helix-lined waveguide system transfer function may be attributed to two mechanisms:

i) Mode conversion-reconversion between the TE_{01} mode and higher order TE_{0n} modes at separated points in the waveguide network.

ii) TE_{01} mode reflections at discrete discontinuities.

A complete understanding of the effects of these nonuniformities on the performance of the VLA waveguide system requires the consideration of interactions between a large number of discrete mode conversion and TE_{01} mode reflection sources in the network. A statistical analysis of these mechanisms for the case of the VLA has been carried out by Archer (1978), resulting in expressions for the root mean square variation in waveguide attenuation as the transmission frequency is varied.

It has been found (Archer 1978) that the predominant source of transmission distortion in the VLA waveguide system is TE_{01} to TE_{0n}

mode coupling and that reflective interactions do not contribute significantly to transfer function nonuniformities. Specifically, the sector coupler main waveguide to coupled waveguide coupling response exhibits significant TE_{01} to TE_{02} modal interactions of nominal magnitude -13 dB, with frequency dependent variations of ±3 dB about this value (Archer et al. 1979). Furthermore, the branching network possesses a TE_{01} to TE_{02} mode coupling response of nominal magnitude -25 dB over most of the waveguide band.

The curves of Figure 7 show measured and predicted rms power transmission response variation in a 10-MHz bandwidth as a function of waveguide length measured from the branching network. Clearly, for stations within about 3 km from the center of the Y the rms deviation exceeds the specified 1% maximum. Temporal variations in the electrical length of the waveguide path can cause significant phase and amplitude deviations at a given fixed frequency if nonuniformities of this magnitude exist in the response. A simple reflective TE_{02} mode filter (Archer 1979) inserted in the waveguide line adjacent to the branching network (see Figure 1) has been used to reduce the rms variation in the response to an acceptable level, as shown in Figure 7. The effects of trapped mode resonances on the fundamental TE_{01} mode response due to the reflective nature of the filter are predicted, and have been found experimentally, to be undetectable when the device is installed as shown in Figure 1. This is because the measured TE_{02} mode return loss at the branching network circular waveguide port is confirmed by measurement to be greater than 20 dB.

VII. CONCLUSIONS

This paper has outlined a theoretical and practical evaluation of the performance of the VLA helix-lined millimeter wavelength circular waveguide system. It has been shown that the performance achieved with the presently installed waveguide exceeds the requirements of the original specification with regard to loss per unit length as a function of frequency, attenuation stability as a function of time and uniformity of the amplitude and phase frequency responses. Recently

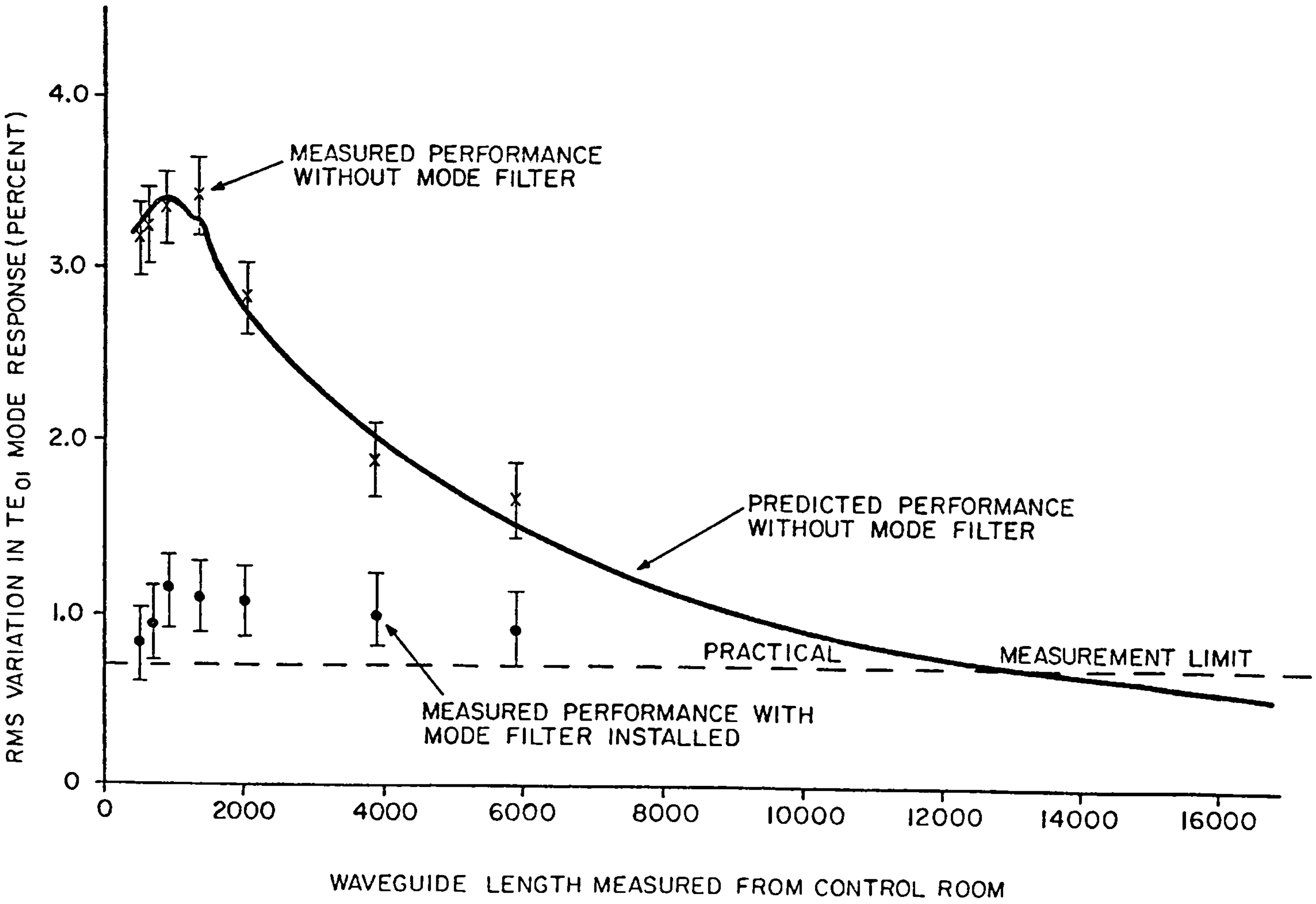

Figure 7: The effect of mode coupling on the TE$_{01}$ mode amplitude response in any 10-MHz bandwidth of a 1-GHz channel centered at 35 GHz on the Southwest arm (couplers installed at every station).

completed measurements on a further 15 kilometers of waveguide installed on the north and southeast arms of the array show similar performance to that reported here.

In the present case, the direct burial technique has proven to be a most cost-effective means of installing a high performance low-loss waveguide transmission medium. Although the San Augustin basin is relatively geologically stable, the soil conditions over the extent of the array vary markedly from wet clay, with a high water table, to dry sandy earth. Therefore, it is felt that the method used for waveguide burial has played a major role in the achievement of stable, low-loss performance.

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