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WT4 Millimeter Waveguide System:

Field Evaluation Test—Transmission Medium Achievements

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A 14 km length of WT4 *millimeter waveguide, designed to operate from 40 to 110 GHz, was installed in northern New Jersey and tested during the AT&T* WT4 *field evaluation test. The waveguide transmission medium has characteristics and requirements which are quite different from those for existing Bell System facilities, such as coaxial cable or microwave radio. Thus, a significant part of the field evaluation test effort was devoted to the installation and characterization of the waveguide transmission medium. The most significant transmission medium achievements of the field test were: (i) demonstration of the practicality of sheath and waveguide installation with standard construction methods, (ii) low transmission medium losses which allow a repeater spacing in excess of 50 km, (iii) theoretical prediction of electrical losses from mechanical measurements of waveguide curvatures, and (iv) development of an experience and data base from which losses for future waveguide routes were projected. The measured loss of the 14-km-long field evaluation test waveguide line was approximately 1 dB/km or less across the 70 GHz band—the lowest losses for a waveguide system yet reported in the world—which confirms that the installation methods used result in curvatures acceptable for a commercial* WT4 *system.*

I. INTRODUCTION

The WT4 millimeter waveguide transmission system is a long-haul, high-capacity digital transmission system. In order to prove-in the various manufacturing, installation, and maintenance procedures of the

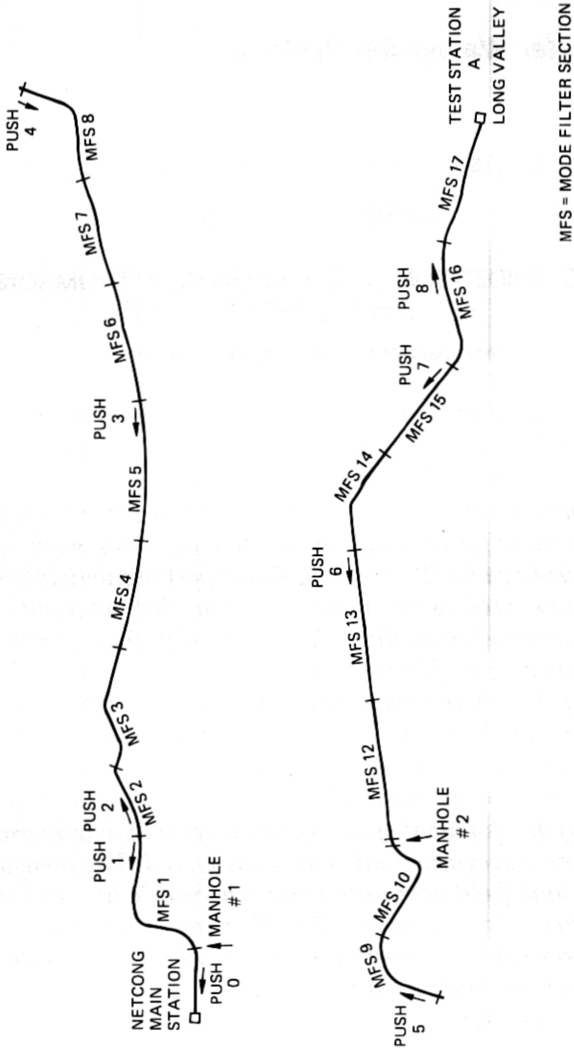

Fig. 1—WT4 field evaluation test between Netcong and Long Valley.

WT4 system, a 14-km length of WT4 millimeter waveguide was installed in Northern New Jersey and tested during the WT4 AT&T field evaluation test. The waveguide is supported on spring supports inside a protective sheath. The waveguide was inserted into the previously installed sheath in several sections, called "pushes." [1] The route, as shown in Fig. 1, began at the Long Lines main station in Netcong and terminated at a temporary facility, Test Station A, in Long Valley, N.J. Two intermediate manholes, which were required to support the transmission medium measurements, were located at approximately 0.4 km and 8.6 km from the Netcong main station. The manholes would not be required for a commercial WT4 system. A variety of route features, typical of those expected for future installations, were encountered along the right-of-way, some of which are listed below:

Push 1, mode filter section 1—steep grade and plan bends.
Push 4, mode filter section 6—Route 206 road crossing.
Pushes 4 and 5, mode filter sections 8 and 9—plan bends and swampy areas.
Push 7, mode filter section 14—severe profile bends in part due to a stream crossing.
Push 8, mode filter section 17—wet area and plan bends.

The installed WT4 transmission medium consists of 60 mm diameter dielectric-lined circular waveguide with one 9-m-long helix waveguide mode filter for approximately every 800 m of dielectric-lined waveguide. Thus the field evaluation test waveguide line consists of 17 mode filter sections each of approximately 800 m in length. The location of each helix waveguide mode filter and each push are shown on Fig. 1.

The field test has proved-in the sheath and waveguide installation procedures for future WT4 commercial applications. The most significant transmission medium result of the field test was the realization of low waveguide losses of approximately 1 dB/km or less across the band, which allow a repeater spacing in excess of 50 km for a commercial WT4 system. The electrically measured transmission medium losses are discussed in Section III. The importance of being able to predict electrical losses from mechanical measurements of the in-place waveguide curvature was recognized early in the WT4 development. The results of the field test mechanical measurements are given in Section IV. Loss calculations and their agreement with electrically measured losses are discussed in Section V. Lastly, the field test has provided data and experience which further our ability to project losses for future waveguide routes. Using field test curvature data and basic statistical models for vertical and horizontal waveguide curvatures, a Monte Carlo computer study was initiated. The initial results from this study for expected losses and loss fluctuations of what is referred to in this paper as nominally "straight" waveguide sections are discussed in Section VI. In nominally "straight" waveguide mode filter sections, the waveguide has random curvatures due to manufacturing deviations and trench bottom roughness. However, there are no curvatures due to plan bends or grade changes in nominally "straight" mode filter sections.

II. TRANSMISSION MEDIUM INSTALLATION

The field evaluation test transmission medium was constructed in two basic steps. First, the protective steel sheath was constructed along the right-of-way and buried, using methods similar to those used in ordinary pipeline laying. Long Lines Northeastern Area craftspersons supervised the sheath construction which was done by a pipeline contractor. The waveguide was then inserted into the sheath in sections, referred to as "pushes," which ranged in length from 0.5 km to 2.5 km. The push points are indicated on Fig. 1 along with the direction of each push. The Long Lines Northeastern Area craftspersons operated the specially designed waveguide insertion equipment. Thus, the sheath and waveguide installation procedures have been demonstrated to be practical for WT4 commercial applications.[2–4] The field test has also proved-in the WT4 transmission medium reliability and maintenance methods.[5]

III. ELECTRICAL RESULTS

Electrical loss measurements were made from the Netcong main station as each push was completed and for the entire 14 km length of the test.[6] Briefly, a shutter in manhole 1 was used as the reference point for the loss measurements of pushes 1–3, 1–4, 1–5, and 1–8 as described in Ref. 6. Manhole 2 was the reference point for loss measurements for pushes 6, 6–7, and 6–8. The accuracy of the loss measurement at 110 GHz for the entire test length, pushes 1–8, is within 2 percent.[6]

Measured losses of individual pushes are desirable in order to compare them with loss calculations and to determine the dependence of individual push losses on the number and severity of route bends and grade changes. Since the loss measurements are made in a field environment, it is necessary to obtain them with minimum relocation of test equipment. The individual push losses can be obtained from the loss measurements on pushes 1–3, 1–4, 1–5, etc., as follows. The losses of separate mode filter sections can be considered independent of one another because of the helix mode filters between sections. Thus, the loss at any one frequency for individual pushes can be obtained from the above measurements by subtraction. That is, the loss for push 4 is given by the difference between the loss measurements of pushes 1–3 and those of pushes 1–4.

The error associated with the measured loss at 110 GHz for individual pushes is higher than the 2 percent loss measurement error quoted for

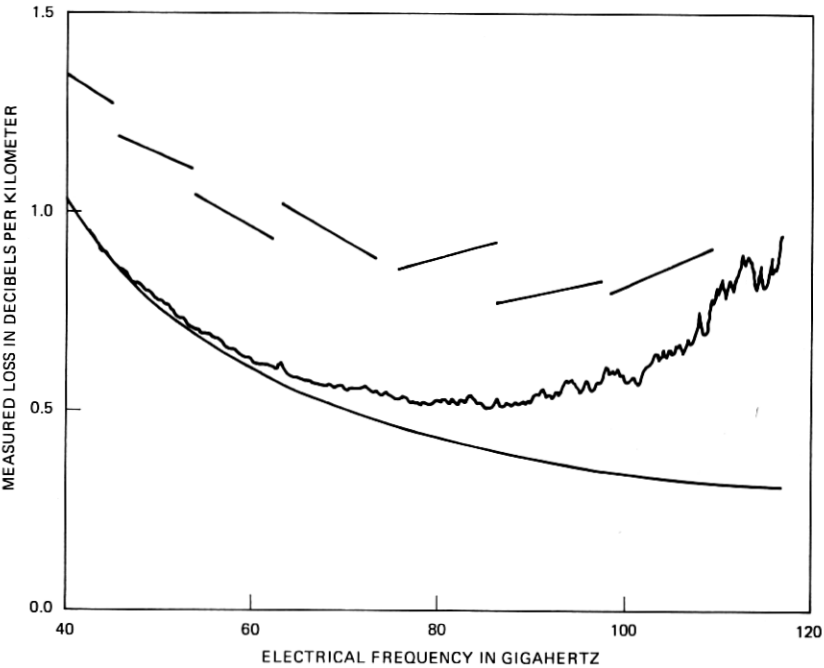

Fig. 2—WT4 field test measured loss; 50-km loss ceilings.

the entire test length, pushes 1–8. The two primary contributors to the error are the loss measurement test set error, as discussed in Ref. 6, and the error incurred by the subtraction process described above. The error in the measured losses at 110 GHz for pushes 5, 6, and 7 is estimated to be about 10–15 percent. This figure is based on both the test set errors and a comparison between the push 6 measured losses with the reference short circuit in manhole 1 and manhole 2.

The measured loss for pushes 1–8, which is approximately 13.6 km long, was approximately 1 dB/km or less across the 70 GHz band from 40–110 GHz. This overall field test loss measurement is shown in Fig. 2 along with the estimated transmission medium heat loss. The medium loss ceilings, also shown in Fig. 2 for a 50-km repeater spacing, depend on the channelizing network loss and on the available gain for the repeater as discussed in Refs. 7 and 8. Several notable observations can be made from this figure. First, the transmission medium losses allow a repeater spacing of 50 km or more across the entire 40–110 GHz band. The losses of approximately 1 dB/km or less across the 70 GHz band are the lowest losses for a waveguide system yet reported in the world.[9,10] These low system losses are the result of concentrated efforts to manufacture, with economical processes, very high quality waveguide, reduce the curvatures which result from installation, and minimize the number

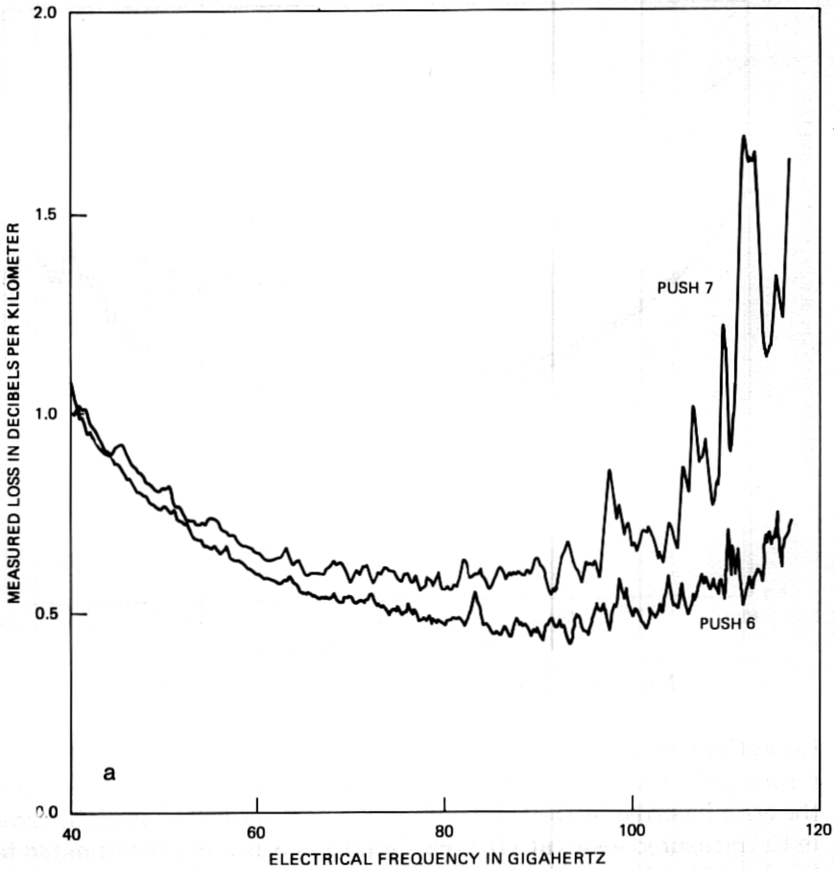

Fig. 3—Measured loss for (a) push 6 and push 7, (b) push 6 and push 5.

of helix mode filters needed for spurious mode suppression.[1,11] The high quality of the manufactured waveguide is particularly reflected in the fact that there is essentially *no* mode conversion loss at the low end of the band. In fact, for all loss measurements made, the transmission medium loss at the low end of the band consisted predominately of heat loss as discussed further in Section V. Thus, the transmission medium loss at the low end of the band is predictable.

The characteristics of the transmission medium loss at the high end of the band are different. At 110 GHz, there is extensive mode conversion loss both in dielectric-lined waveguide and in helix mode filters. At high frequencies, the helix waveguide has much higher loss than the dielectric-lined waveguide and, therefore, contributes significantly to the total loss at 110 GHz. Mode conversion losses at the high end of the band are sensitive to trench bottom roughness and route bends with the second

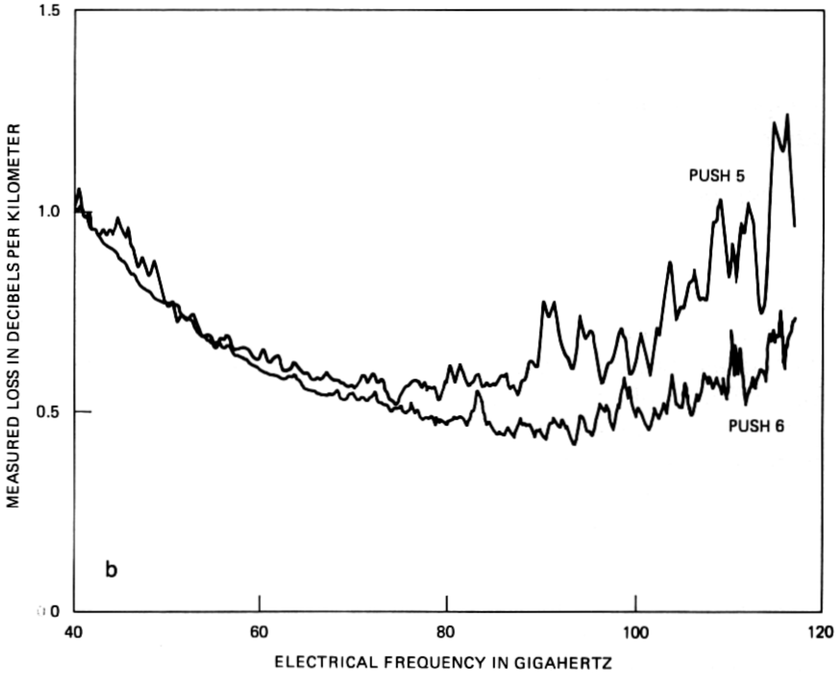

Fig. 3 (*continued*)

order TM_{21} losses being especially sensitive.[12] Consequently, the transmission medium loss at 110 GHz varied considerably from push to push depending on the amount of trench roughness and the type of route bends present. Since second-order TM_{21} mode conversion losses had not been anticipated prior to the field test, the overall loss margin at 110 GHz was smaller than that at 40 GHz. Notice also that this overall loss margin at 110 GHz could be quite different for another route, depending on the number and type of route bends present. Mode conversion losses are discussed further in Section V.

The sensitivity of second-order mode conversion losses to route bends is clearly illustrated in Fig. 3a, which compares the measured losses for pushes 6 and 7. The measured loss for push 6, with only trench bottom roughness and no plan or profile bends, is very low (about 0.6 dB/km at 110 GHz). On the other hand, push 7 had one plan bend and two severe profile bends. The high push 7 loss (over 1 dB/km at the high end of the band) reflects the large second-order mode conversion losses caused by the severe profile curvatures.[12] Figure 3b compares the loss measurements for pushes 5 and 6. Push 5 had several plan bends and also has significant second-order mode conversion losses.

Over the two-year period since the field test was installed, many measurements of loss have been made both on the entire line and on shorter sections. Comparison of these measurements confirms the stability of the transmission medium losses as a function of time. The losses measured at 40 GHz vary by less than 0.01 dB/km after correcting for temperature variations. At 110 GHz, the variation is less than 0.02 dB/km.

IV. MECHANICAL RESULTS

Mechanical measurements of the installed field test waveguide geometry were also obtained and losses calculated from them. Power spectral densities were calculated from the measured vertical and horizontal curvatures, as a function of length along the waveguide axis.[13] The power spectral density (PSD) of the curvature in the horizontal or vertical plane of a given length of waveguide is the magnitude squared of the Fourier transform of the horizontal or vertical curvature divided by the total length of the waveguide. Each component of mode conversion loss listed below is directly related to either the mean-squared curvature or to the mechanical PSD of curvature or of functions of horizontal and vertical curvatures as given below:

(*i*) Helix loss: mean-squared horizontal and vertical curvature.[14]
(*ii*) TM_{11}, TE_{12} loss: S_{C_h} = PSD of horizontal curvature, $C_h(z)$, and S_{C_v} = PSD of vertical curvature, $C_v(z)$.[15]
(*iii*) TM_{21} loss: $S_{C_h^2-C_v^2}$ = PSD of the function $C_h^2(z) - C_v^2(z)$ and $S_{C_hC_v}$ = PSD of the function $C_h(z)C_v(z)$.[12]

The individual loss components are discussed in greater detail in Section V. The power spectral densities (S_{C_h}, S_{C_v}, $S_{C_h^2-C_v^2}$, $S_{C_hC_v}$) were computed for each mode filter section in the field test and then averaged to obtain average power spectral densities for the entire test length. Figures 4 to 7 show the average power spectral densities, S_{C_v}, S_{C_h}, $S_{C_h^2-C_v^2}$ and $S_{C_hC_v}$, of the installed waveguide for the 14-km-long test. The mechanical frequency ranges which determine the most significant losses in the WT4 band are indicated on each figure. These ranges, for the appropriate spectra, are

0.33 c/m (110 GHz) to 0.51 c/m (51 GHz) for TM_{11}
0.50 c/m (110 GHz) to 1.5 c/m (40 GHz) for TE_{12}
0.04 c/m (110 GHz) to 0.80 c/m (40 GHz) for TM_{21}

The average vertical spectrum in Fig. 4 is relatively flat out to about 0.1 c/m where it drops off rapidly. This low-frequency vertical curvature (below 0.1 c/m) is due primarily to trench bottom roughness and the cutoff is due to the mechanical filter of the waveguide support system.[1] Vertical curvatures at higher mechanical frequencies are associated with manufacturing curvatures in the waveguide and distortions at couplings.[11] The low, 10^{-8} $1/m^2/c/m$ level of the vertical spectrum above

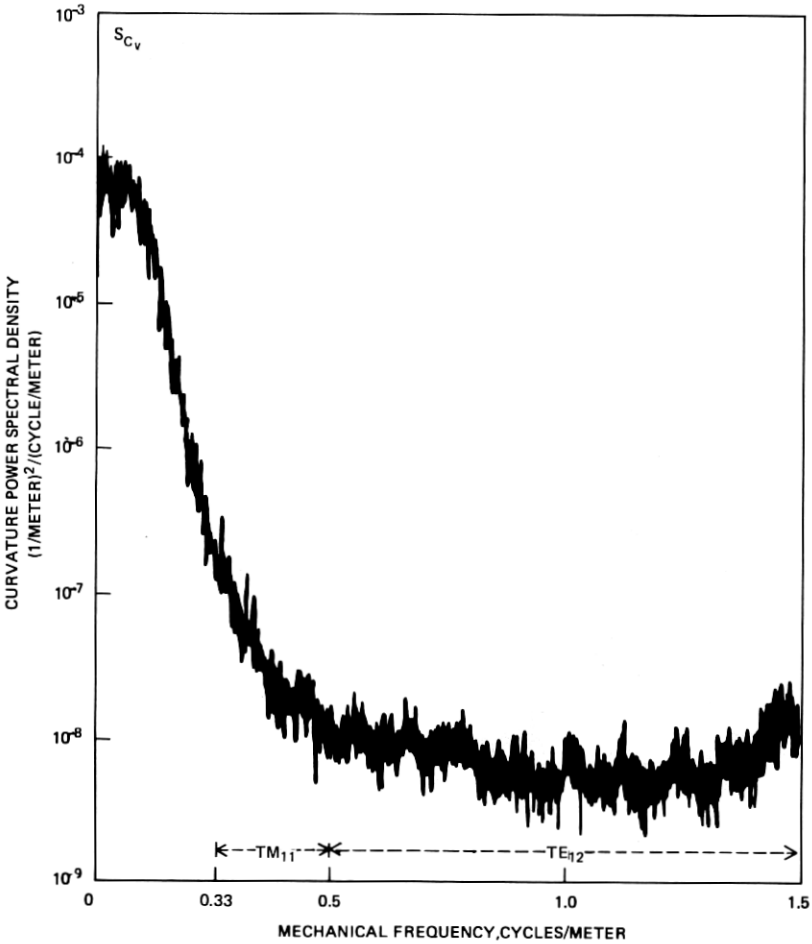

Fig. 4—Average field test vertical curvature spectrum.

0.5 c/m confirms the high quality of the manufacturing and couplings of the waveguide. A vertical spectrum level of 10^{-8} 1/m^2/c/m at 0.5 c/m corresponds to a loss of only 0.022 dB/km at 110 GHz due to TE_{12} mode conversion.

The shapes and levels of the spectra are directly related to route features. Profile curves have short arc lengths (less than 30 m) which tend to increase the level of the entire vertical spectrum. However, the waveguide support system filters out most of the increased curvature above 0.1 c/m. To illustrate, Fig. 8 compares the vertical spectra from mode filter section 12 and mode filter section 14. Mode filter section 12 is in push 6, which is "straight," while mode filter section 14 is in push 7, which had severe profile curves. Notice a difference in the vertical

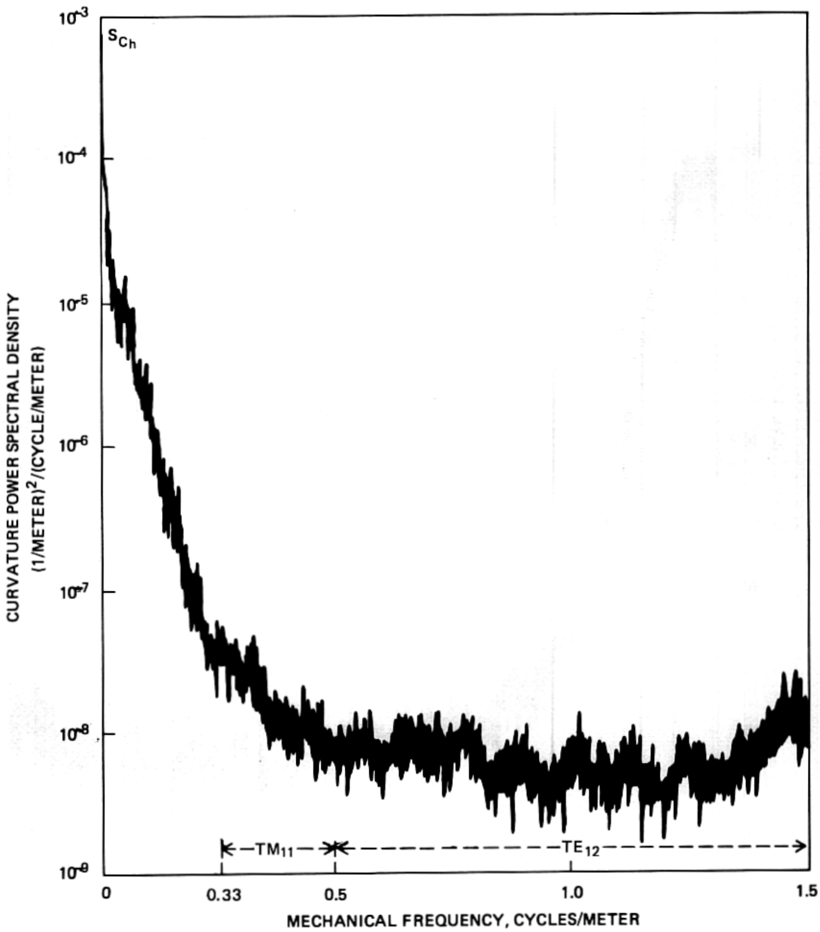

Fig. 5—Average field test horizontal curvature spectrum.

spectra of at least one-half a decade at mechanical frequencies below 0.1 c/m. The difference between these spectra is clearly demonstrated by their respective rms curvatures. Mode filter section 12 has a rms curvature corresponding to a 326 m radius of curvature, whereas the rms curvature for mode filter section 14 corresponds to a 170 m radius of curvature.

Horizontal power spectral densities are affected by plan bends. Unlike profile bends, plan bends usually have long arc lengths (100–200 m) with gradually tapered curvatures into and out of the bends. Therefore, in the horizontal spectrum, a plan bend appears as a narrow peak, much like a delta function, with most of the energy below 0.02 c/m. Figure 9 compares the horizontal spectra for push 5, which had several plan bends,

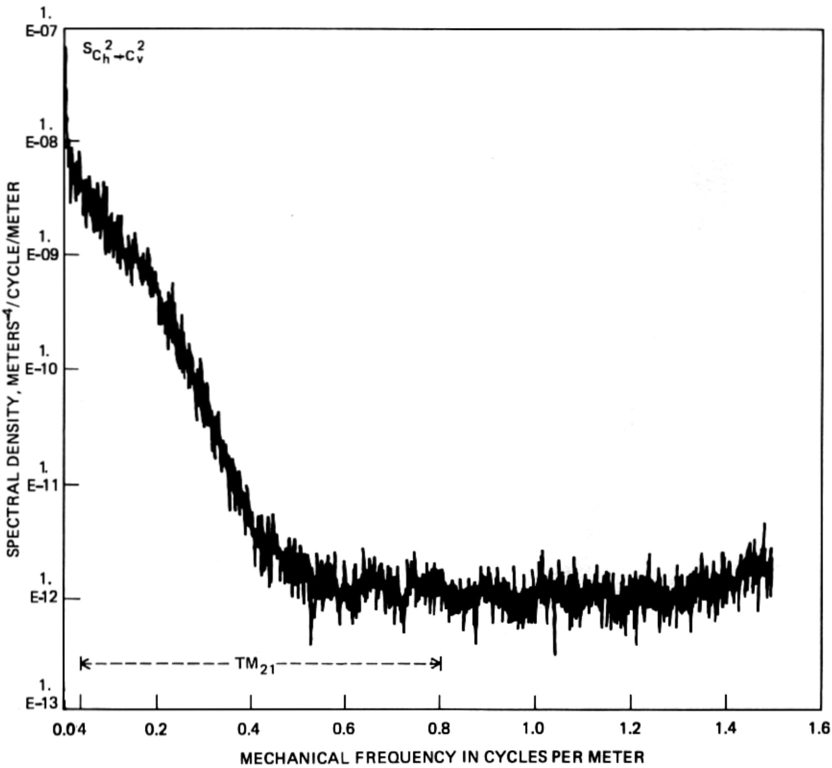

Fig. 6—Average field test $C_h^2 - C_v^2$ spectrum.

with that for push 6 with no plan bends. Notice the high peak (about 5×10^{-3} 1/m^2/c/m at about 0.002 c/m in the push 5 horizontal spectrum.

V. LOSS CALCULATIONS

The WT4 transmission medium losses for the test route have been calculated from mechanical measurements of the in-place waveguide curvatures. Comparison of loss calculations and measured losses for the entire test length and most individual pushes has yielded good agreement. The transmission medium loss calculations include the following loss components:

(*i*) Heat loss
(*ii*) Additional attenuation due to helix mode filters
(*iii*) First-order mode conversion losses (TM_{11} and TE_{12} modes)
(*iv*) Second-order mode conversion losses (TM_{21} mode).

Mode conversion losses to other modes have been calculated from ge-

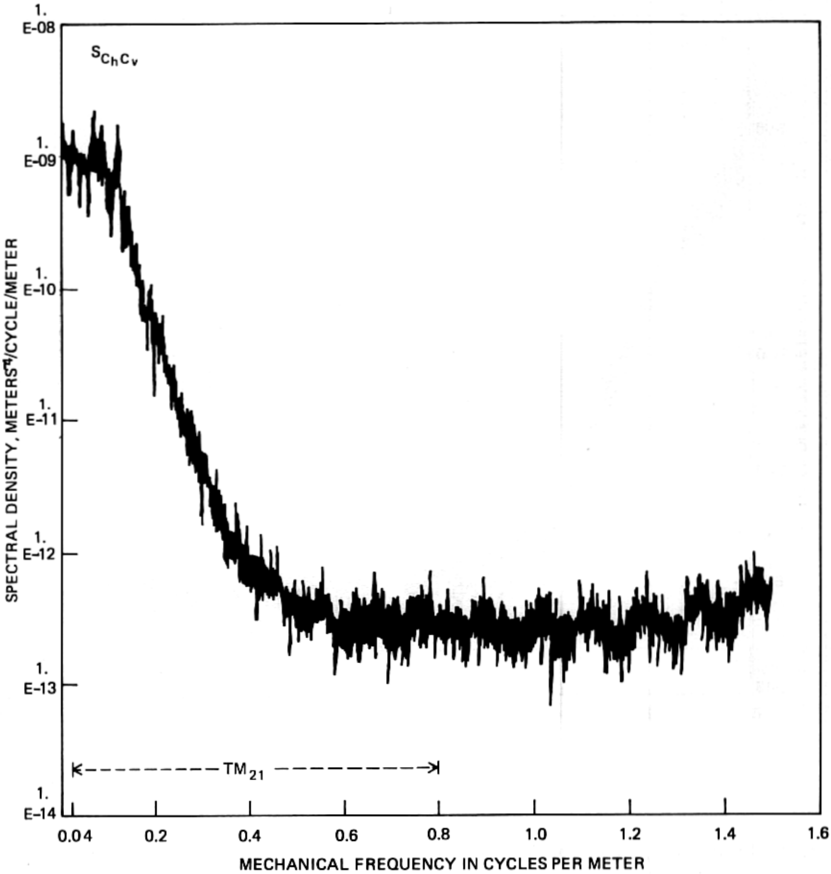

Fig. 7—Average field test C_hC_v product spectrum.

ometry data of manufactured waveguide and found to contribute less than about 3 percent of the total loss and are therefore omitted from the loss calculations. Each loss component is discussed below and is shown on the estimated field test loss curves on Fig. 10.

The transmission medium heat loss is estimated by the formula

$$\alpha + \alpha \times 0.20(f/100)^{1.5}$$

where α is the theoretical ohmic loss, f is the electrical frequency in GHz, and the second term represents additional loss due to copper roughness or surface imperfections. The transmission medium heat loss estimate agrees with laboratory measurements at both the low and high ends of the band. The heat loss estimate of .32 dB/km at 110 GHz may be high by, at worst, 10 percent due to mode conversion losses which may have been included in the laboratory measurements. The heat loss estimate

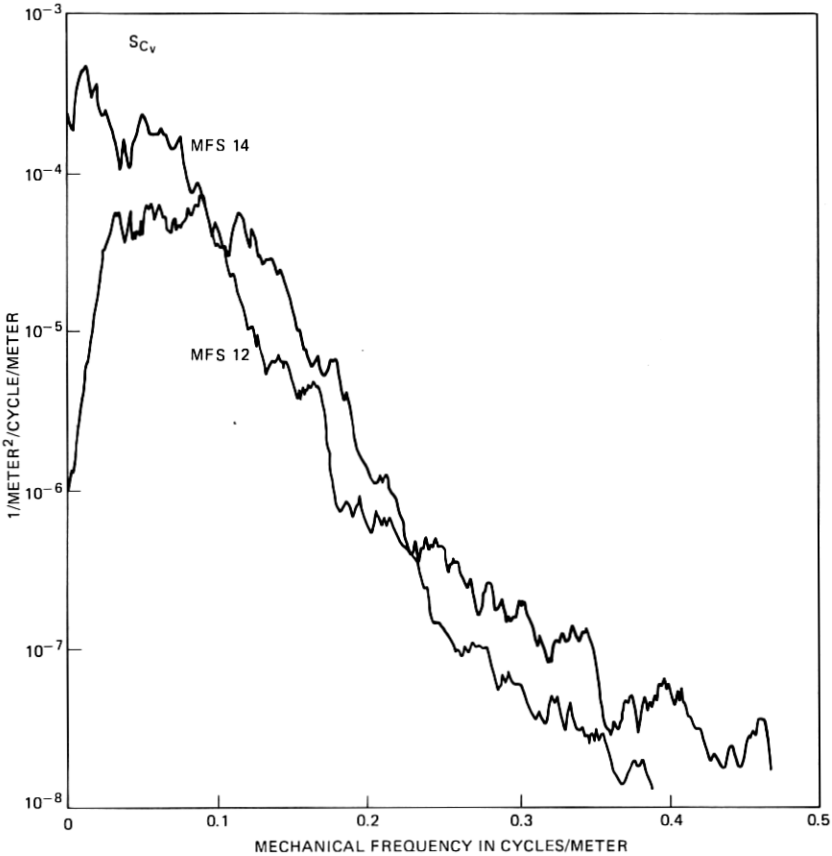

Fig. 8—Vertical curvature spectra.

of 1.03 dB/km at 40 GHz has been confirmed by the field test loss measurements and, notably, is significantly lower than had been anticipated at the beginning of the WT4 development. The measured heat loss at 40 GHz is only 6 percent above the theoretical limit for copper and is confirmation of the high-quality copper plating process.

A direct loss estimate for each helix mode filter in the test from its measured curvature is difficult since the mode filter is only 9 meters long and because the curvatures at its ends are nonzero. Therefore, known methods of calculating loss in helix waveguide are not applicable, necessitating the use of an approximate estimate of the mode filter losses. The helix mode filter loss estimates include loss due to both manufacturing curvatures and curvatures associated with placing.

The helix manufacturing loss was estimated from loss calculations, using the results of Young,[16] and measurements of a string of six precisely

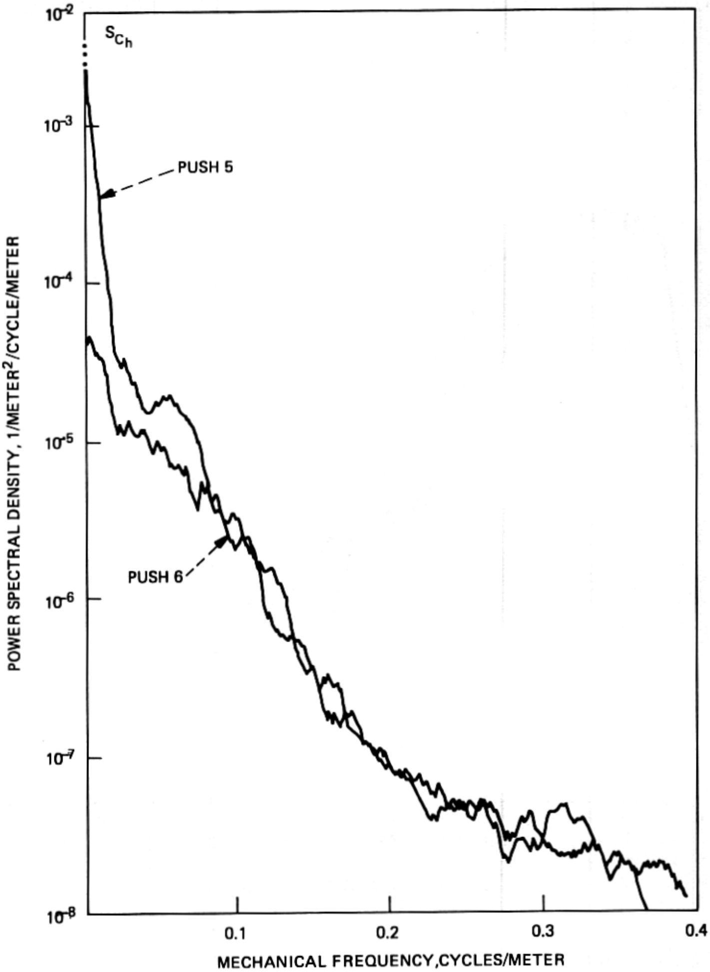

Fig. 9—Horizontal curvature spectra.

aligned, 4.5-meter-long helices which are representative of the test helices. The resulting average helix manufacturing loss was 3.6 dB/km at 110 GHz. Further measurements of field test helices has indicated a possible range of manufacturing loss from 2 dB/km to 10 dB/km at 110 GHz. The source of the large variation in the manufacturing loss for helix waveguide has been identified and will be corrected for the commercial WT4 system.

Helix placing losses were estimated from the mean-squared curvatures measured for each mode filter.[14] The estimated helix placing losses varied from 2 to 20 dB/km at 110 GHz for the test mode filters. The total helix mode filter loss was then estimated by the sum of the average helix

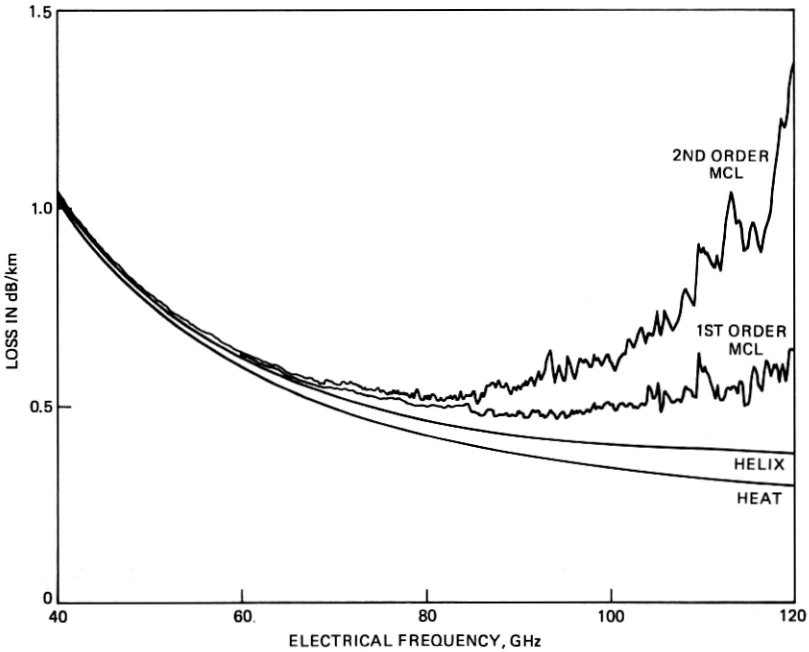

Fig. 10—WT4 field evaluation test estimated loss.

manufacturing loss (3.6 dB/km at 110 GHz) and the helix placing loss derived from the measured mean-squared curvature for each mode filter. Therefore, the total helix losses represent our best estimate of the mode filter losses but may be in error by as much as 50 percent for any one mode filter. A large part of this 50 percent error is due to the fixed 3.6 dB/km estimate of helix manufacturing loss at 110 GHz for each mode filter. However, the predicted helix loss for the entire field test is better and is estimated to have an error of 20 percent or less.

First-order mode conversion losses are directly proportional to the vertical and horizontal power spectral densities, which are calculated from mechanical measurements.[13,15] Modes in circular waveguide can be generated in two polarizations depending on the plane of curvature, as discussed by Carlin and Moorthy.[12] The symbols $\uparrow$ and $\rightarrow$ represent the horizontal and vertical polarizations, respectively. The largest proportion of the first-order losses is usually due to the $TM_{11}\rightarrow$ (generated by vertical curvature) mode. The error in the first-order loss calculations is estimated at less than 10 percent, based on comparisons of these first order loss calculations and direct numerical solutions of the coupled-line equations. Second-order $TM_{21}\uparrow$ and $TM_{21}\rightarrow$ losses are approximated by expressions which are proportional to the power spectral densities of $C_h^2(z) - C_v^2(z)$ and $C_h(z) \cdot C_v(z)$.[12] Some TM_{21} second-order loss results

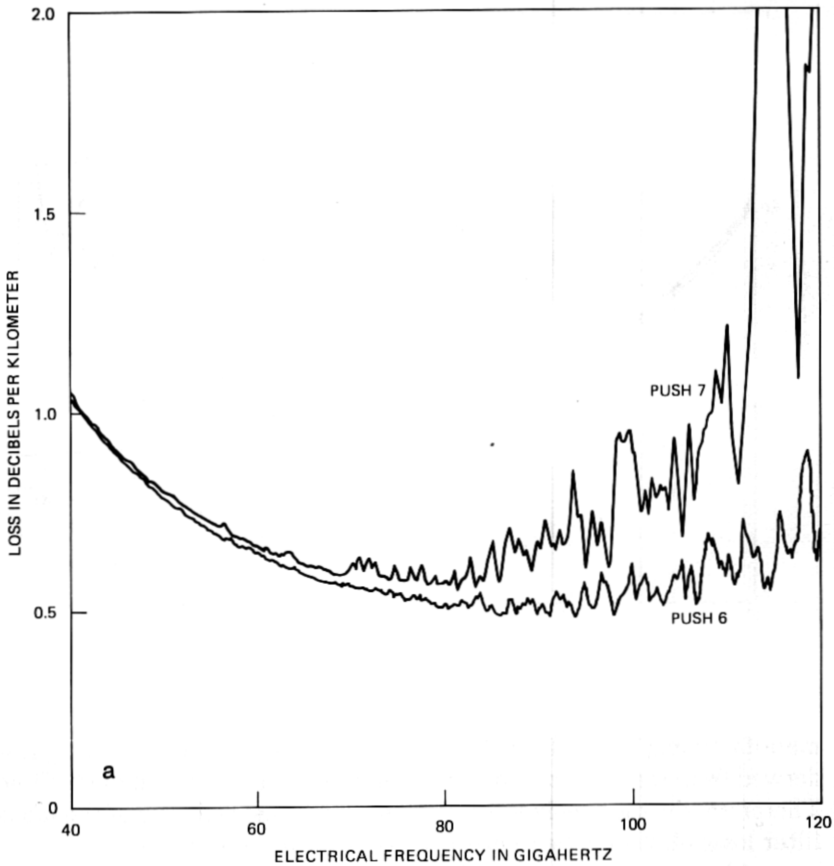

Fig. 11—Netcong curvature loss for (a) push 6 and push 7, (b) push 6 and push 5.

from trench bottom curvatures, but plan or profile bends increase the TM_{21} losses dramatically, as was seen in Fig. 3. These second-order TM_{21} loss calculations are estimated to be accurate to about 20–25 percent except at very high loss peaks as in push 7 at 113 GHz. Comparisons of second-order mode conversion loss calculations to exact solutions are discussed by Carlin and Moorthy.[12]

Figure 10 gives the upward cumulative loss break-down calculation for the 14 km long test with each curve labeled according to the components listed above. Notice that the steeply rising second-order TM_{21} losses comprise about ⅔ of the total mode conversion loss at the high end of the band. This loss calculation agrees well with the electrically measured test losses shown in Fig. 2. The error between estimated and measured losses for the entire test length increases from about 0.02 dB/km at 85 GHz to about 0.09 dB/km at 117 GHz. The rate of increase

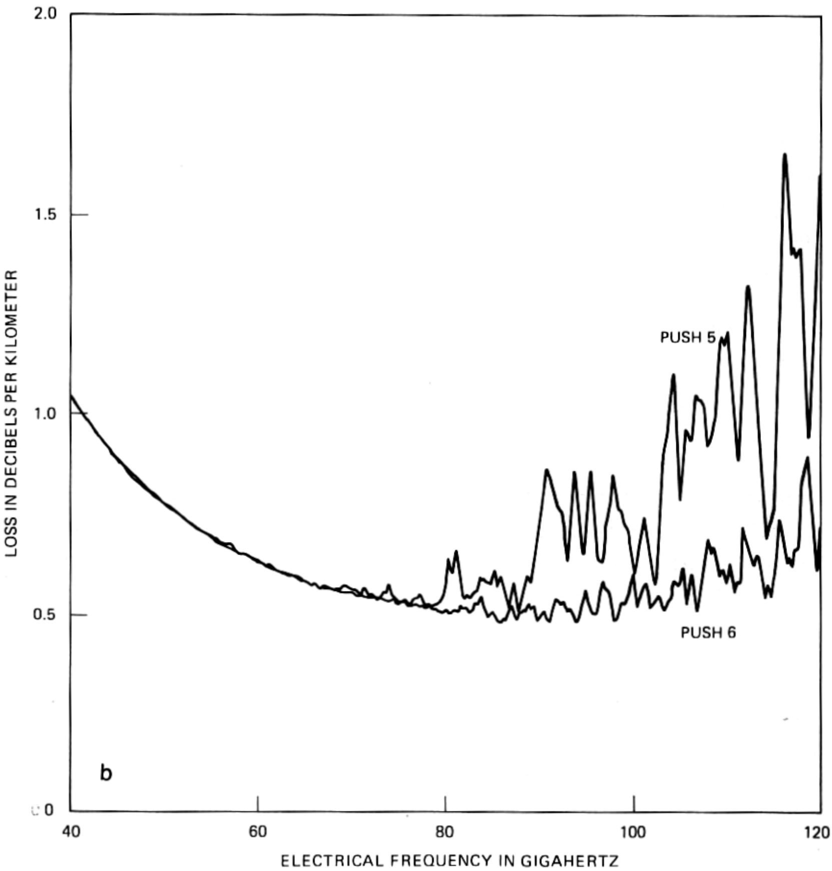

Fig. 11 (*continued*)

for this error is roughly proportional to the fifth power of frequency, indicating that the majority of the error is in the perturbation loss calculations rather than in the helix loss estimate.

Figure 11a compares the estimated losses for pushes 6 and 7. Push 6 has no plan or profile bends but push 7 has two severe profile bends and therefore has significant second-order mode conversion loss. The push 7 loss estimate compares favorably to the measured losses in Fig. 3 except at peaks at the high end of the band and especially at the very high loss peak at 113 GHz. The error between peaks in the estimated and measured losses for push 7 is probably due to the overestimation of the TM_{21} loss.[12] The shape of the push 6 loss estimate agrees with that of the measured losses but is higher than the measurement by about 0.03 dB/km at 60 GHz to about 0.05 dB/km at 110 GHz. This difference may be due to an overestimate of the helix loss or to the errors associated with the measured losses for a single push as discussed in Section III. Figure 11b compares the loss calculations for pushes 5 and 6. The shape of the estimated loss for push 5, which has several plan bends, agrees well, over most of the band, with the measured loss shown in Figure 3b. Again the estimated loss is higher than the measured loss at loss peaks for push 5, which is probably due to an overestimation of the TM_{21} losses. In general, the rest of the pushes showed similar agreement between calculated and measured losses, as does the overall loss estimate for the entire test length.

VI. STATISTICS OF SPECTRA AND LOSSES

The field test transmission medium curvature measurements have also established a data base for projecting waveguide losses of future WT4 routes. Field test mechanical curvature measurements of in-place waveguide, combined with basic statistical models of curvature, were employed to perform a Monte Carlo computer simulation of waveguide losses. The statistical models used and details of the study are discussed below. The results of the study were estimates of expected losses and loss fluctuations from the TM_{11}, TE_{12}, and TM_{21} modes in dielectric-lined waveguide for a nominally "straight" mode filter section.

For a nominally "straight" waveguide right of way, the curvatures in the horizontal and vertical planes are stationary Gaussian random processes.[13] Thus, their vertical and horizontal curvature spectra, at each mechanical frequency, are each distributed as Chi-Squared random variables with two degrees of freedom. Since first-order mode conversion losses are directly proportional to the vertical and horizontal spectra, the Chi-Squared model for these spectra yields estimates of their loss fluctuations. However, the second-order mode conversion losses are approximately proportional to $S_{C_h^2-C_v^2}$ and $S_{C_hC_v}$. The distributions of the spectra of $C_h^2(z) - C_v^2(z)$ and $C_h(z)C_v(z)$ do not readily lend themselves to analysis since neither $C_h^2(z) - C_v^2(z)$ nor $C_h(z)C_v(z)$ can be assumed to be Gaussian random variables. To estimate the magnitude of loss fluctuations for second-order mode conversion losses, a Monte Carlo computer study was performed. The horizontal and vertical spectra from seven nominally "straight" mode filter sections of the test were separately averaged to obtain an average S_{C_h} and an average S_{C_v} for "straight" mode filter sections. From these averaged spectra and a pseudorandom number generator, sets of vertical and horizontal curvatures were obtained.

The results of this study of nominally "straight" mode filter sections, were that the $S_{C_h^2-C_v^2}$ and $S_{C_hC_v}$ were each approximately distributed as a Chi-Squared random variable with two degrees of freedom. A typical quantile-quantile plot of the quantiles of the 140 samples of $S_{C_h^2-C_v^2}$ vs. the Chi-Squared-2 quantiles is shown in Fig. 12.[17] This particular QQ

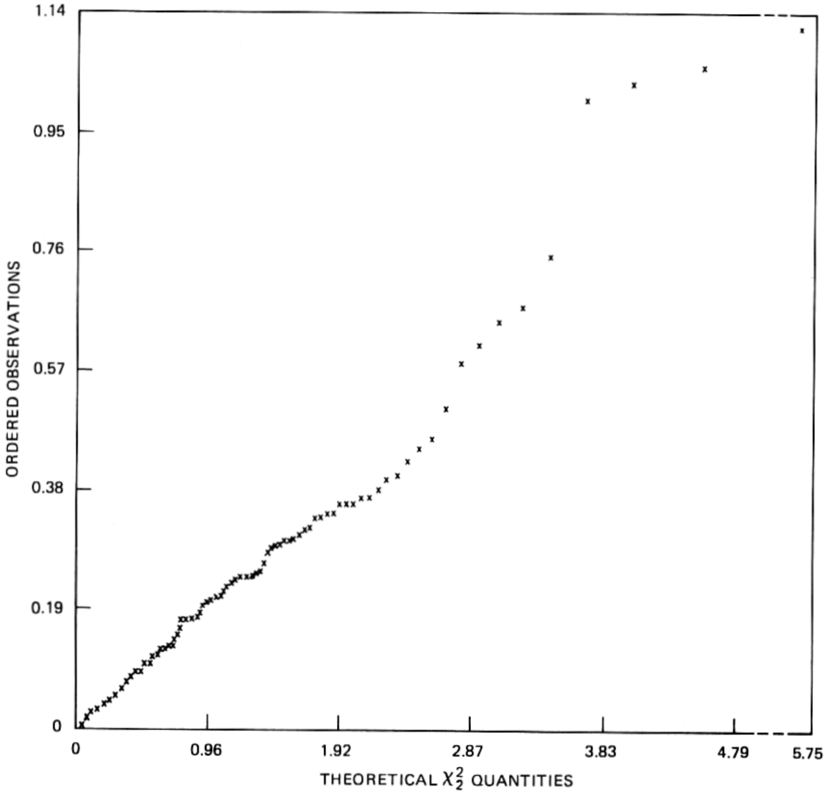

Fig. 12—QQ plot of TM_{21} losses at 110.22 GHz vs. χ_2^2 quantiles.

plot shows the distribution of the $S_{C_h^2-C_v^2}$'s at 0.04 c/m mechanical frequency, which corresponds to 110.22 GHz for the TM_{21} mode.

In addition to ascertaining the approximate distributions of the second-order mode conversion losses, estimates of the total expected losses and loss fluctuations were obtained. The results of the Monte Carlo study for nominally "straight" mode filter sections indicate that almost all the mode conversion loss in dielectric-lined waveguide is due to the $TM_{11}\rightarrow$ mode (generated by vertical curvature) and the $TM_{21}\uparrow$ mode which is generated by the curvature function $C_h^2 - C_v^2$. The estimated expected values of these losses at 110 GHz are about 0.2 dB/km for $TM_{11}\rightarrow$ and 0.16 dB/km for $TM_{21}\uparrow$. The other modes ($TE_{12}\uparrow$, $TE_{12}\rightarrow$, $TM_{11}\uparrow$, and $TM_{21}\rightarrow$) yield a combined mode conversion loss of about 0.05 dB/km at 110 GHz. The expected losses for each mode from 100–110 GHz are shown on Fig. 13. As shown in Fig. 13, there is a $TM_{11}\rightarrow$ loss peak of about 0.1 dB/km at 110 GHz. This loss peak is due to a peak in the vertical spectrum at 0.33 c/m and is also evident in the measured losses discussed in Section III. The peak occurs in the vertical spectra of most mode filter sections and is believed to be a harmonic of either the tube length or the sheath length. The loss peak at 106 GHz is also due to a harmonic of the tube or sheath length.

Loss fluctuations are also important parameters for future WT4 systems. The distribution of loss for a 50-km-long repeater span has more than 100 degrees of freedom since it consists of more than 60 independent mode filter sections each with at least two degrees of freedom. Therefore, a 3σ repeater span loss is, approximately, at the 99.9 percent confidence level where σ is the standard deviation of loss at any one frequency. Also shown on Fig. 13 is the "3σ" loss based on the loss fluctuations of the Monte Carlo study and a 50-km repeater span consisting of sixty-two 800-m-long, nominally "straight" mode filter sections. This "3σ" loss includes empirical fluctuations from both polarizations of the TM_{11}, TE_{12}, and TM_{21} modes in dielectric-lined waveguide and is about 0.53 dB/km at 110 GHz. Any practical route would contain both plan bends and grade changes along with their associated increases in loss and loss fluctuations. Therefore, Monte Carlo studies for mode filter sections containing plan and profile bends are currently in progress.

Preliminary results for mode filter sections containing a single 90 degree, 81 m radius-of-curvature plan bend indicate an added loss of 0.23 dB at 110 GHz for the plan bend. The Monte Carlo results also showed that the added loss for the plan bend is a rapidly increasing function of frequency which increases about as frequency to the seventh power. The distribution of the total mode conversion loss in a mode filter section with a plan bend differs from that of a nominally "straight" mode filter section in that the loss is now primarily due to three polarizations: $TM_{11}\rightarrow$ and both polarizations of the TM_{21} mode. In nominally "straight" mode filter sections, the loss is primarily due to only two polarizations, $TM_{11}\rightarrow$ and $TM_{21}\uparrow$. However, the loss in each particular polarization is still approximately distributed as a Chi-Squared random variable with two degrees of freedom, as were the individual polarization losses in nominally "straight" mode filter sections.

VII. SUMMARY

The field evaluation test results discussed in this paper have led to an increased understanding of the characteristics and requirements of the transmission medium for a commercial WT4 system. The WT4 field evaluation test has:

(*i*) Demonstrated the practicality of sheath and waveguide installation procedures.

(*ii*) Achieved a transmission medium loss which allows a repeater spacing in excess of 50 km.

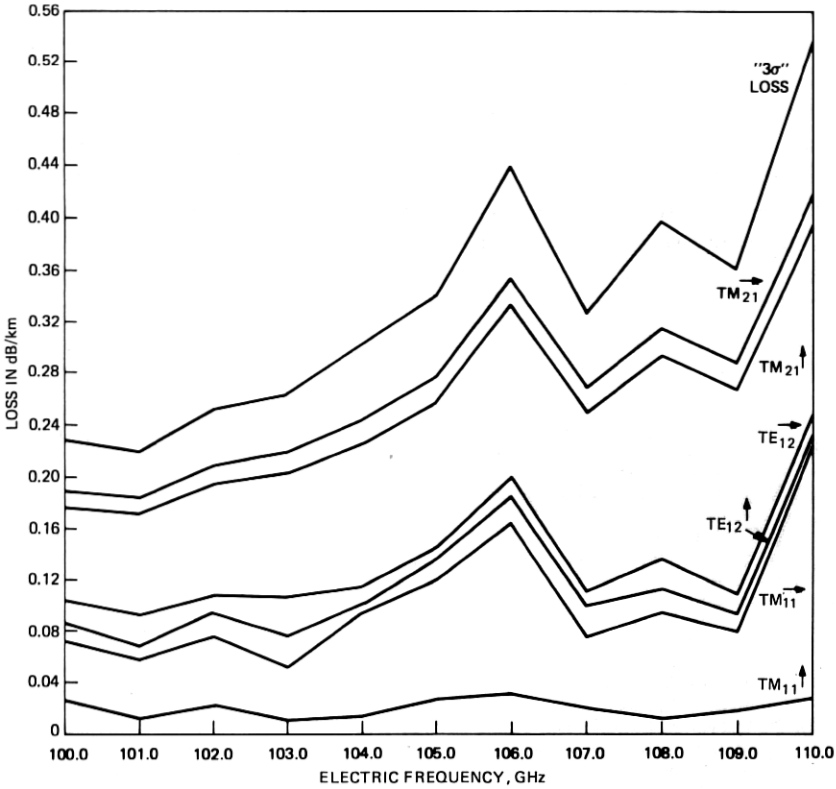

Fig. 13—Expected loss and "3σ" loss for nominally "straight" mode filter sections.

(*iii*) Successfully predicted electrical losses from mechanical measurements of in-place waveguide curvatures.

(*iv*) Established an experience and data base from which to project transmission medium losses for future waveguide routes.

Monte Carlo studies for mode filter sections with no route bends have established a statistical model for waveguide losses in these nominally "straight" sections. The higher losses and loss fluctuations associated with route bends affect repeater spacings, and are therefore also being evaluated using Monte Carlo techniques. A statistical model for waveguide losses has been established for mode filter sections with a single plan bend. Additional Monte Carlo studies are underway to determine expected losses and loss fluctuations for waveguide routes which have both plan and profile bends.

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