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Evaluation of waveguide-to-coaxial-line adaptors at frequencies up to 40 GHz

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ABSTRACT

Four techniques for determining the loss of waveguide-to-coaxial-line adaptors have been evaluated. One method, known as the Adaptor Removal Technique used with Automatic Network Analysers offers a means of measuring the full s-parameters of a single adaptor over a given frequency range, whereas the remaining three techniques all measure the insertion loss of adaptor pairs and rely on calculations to determine the loss of each adaptor.

The results obtained using the four techniques are compared for measurements of adaptors in three waveguide sizes, WG14 to APC7, WG18 to APC7 and WG22 to Type 'K', and conclusions on the accuracy of each technique are given.

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1. INTRODUCTION

From previous research work undertaken by members of the RF and Microwave Guided Wave Standards Branch (formerly EM4 division, RSRE), there is some documentary evidence [1,2,3,4,5] that the most satisfactory means of measuring the characteristics of coaxial to waveguide adaptors is to employ the Adaptor Removal technique as developed for the HP8510 Automatic Network Analyser (ANA) [6]. The above mentioned research work concentrated on Type-N to waveguide adaptors which are employed within the Power Standards section, but owing to the sexed (male and female) nature of the Type-N connector only a limited set of intercomparison measurements were realisable. In this more extensive research project it was decided to evaluate the Adaptor Removal technique against as many different measurement methods as possible with the goal of establishing the most reliable attenuation calibration method for waveguide to coaxial adaptors at frequencies up to 40 GHz.

Sets of waveguide to coaxial adaptors were purchased in three waveguide sizes, WG14, WG18 and WG22, with both the WG14 and WG18 sets of adaptors fitted with APC7 coaxial connectors and the WG22 adaptors fitted with Type-K connectors. The initial phase of the project concentrated on measuring the characteristics of the WG14 and WG18 adaptors fitted with sexless APC7 coaxial connectors, this allowed the characteristics of each individual adaptor to be evaluated. Once an estimation of the accuracy of each measurement technique had been established with these adaptors, a similar evaluation was then conducted with the adaptors fitted with sexed Type-K coaxial connectors to extend the scope of the work to cover measurement frequencies up to 40 GHz.

The measurement techniques chosen for the evaluation of the waveguide to coaxial adaptors were :-

(i) Power Ratio attenuation measurement technique, using waveguide systems within the Attenuation Standards section.

(ii) Adaptor Removal technique for ANA measurement of non-insertable devices.

(iii) ANA measurement of insertable coaxial devices.

(iv) ANA measurement of insertable waveguide devices.

Method (ii) is the only one of the above techniques in which a single waveguide to coaxial adaptor can be characterised directly, all the remainder require the measurement of a pair of waveguide to coaxial adaptors. For sexless coaxial adaptors it is possible to calculate the attenuation contribution of each using the de-embedding calculations shown in Appendix A.

2. MEASUREMENT TECHNIQUES AND ASSOCIATED UNCERTAINTIES

2.1 POWER RATIO

The power ratio measurement technique is a well established attenuation measurement method used within the Attenuation Section for the measurement of the insertion loss of low attenuation devices. The method is based on the measurement of the power level of a signal at two specific monitor points

(see Figure 1). These two power level readings, P_{in} and P_{out}, are taken on either side of the measurement plane; firstly a pair of 'datum' power levels are measured without the device under test (DUT) in the system and secondly, a pair of 'atten' power levels are measured with the DUT inserted. The attenuation of the DUT is easily calculated from :

$$Attenuation = 10.\log\left(\frac{P_{out}datum}{P_{in}datum}\right) - 10.\log\left(\frac{P_{out}atten}{P_{in}atten}\right)$$

This technique relies on the DUT being an insertable device, i.e. having input and output ports of the same type, hence the power ratio technique is limited to the measurement of the attenuation of pairs of waveguide to coaxial adaptors. The attenuation of each individual adaptor is then calculated as described in Appendix A.

The measurement uncertainties encountered in the power ratio measurement technique can be divided into random measurement uncertainty and mismatch uncertainty. Random uncertainty is dependent on the repeatability of the waveguide matings as the DUT is inserted and removed from the measurement system, and is also dependent on the stability of the measurement system. The magnitude of the random uncertain can be reduced by having good mating surfaces at the measurement plane and by using precision dowels to facilitate accurate waveguide alignment. The mismatch uncertainty is dependent on the source and load match of the measurement system and the s-parameters of the DUT itself, and is reduced by the careful choice of components immediately prior to and after the measurement plane.

2.2 ANA ADAPTOR REMOVAL TECHNIQUE

The Adaptor Removal measurement technique, available on the Automatic Network Analyser, allows the full s-parameters of a non-insertable device to be 'measured' directly. This technique, as the name implies, mathematically removes the characteristics of a transforming adaptor used during the calibration of the ANA and measures the s-parameters of the device inserted in its place (see Figures 2a, 2b & 2c). The calibration sequence used was as follows :-

(i) Assemble the interconnecting transitions and cables from the ANA so that the measurement ports are compatible for mating with the DUT (in this particular case it was arranged so that port 1 was in coaxial line and port 2 in waveguide).

Choose a temporary adaptor which has a similar physical structure to the DUT and of a known electrical length, enter the characteristics of this adaptor into the waveguide CAL KIT (as described in Appendix B). Connect this temporary adaptor to port 2 of the ANA thus allowing port 1 and port 2 to be connected.

With the temporary adaptor attached to port 2, perform a full 2-Port calibration using the appropriate coaxial line calibration kit. When this calibration is complete store the resultant calibration data in CAL SET 1.

(iv) Remove the temporary adaptor from port 2 and connect it to port 1. Perform a second 2-Port

calibration with the appropriate waveguide calibration kit and store the resultant calibration data in CAL SET 2.

(v) CAL SET 1 and CAL SET 2 are combined through the MODIFY CAL SET menu (as described in Appendix B) to produce a third calibration set, CAL SET 3. The temporary adaptor is now removed leaving a fully calibrated measurement system capable of measuring coaxial to waveguide adaptors.

The Adaptor Removal technique was used to measure the full s-parameters of each coaxial to waveguide adaptor and from these values the attenuation of each adaptor was calculated from the vectorial addition of the forward and reverse transmission coefficients, i.e. $10\log(S_{21}xS_{12})$.

The uncertainties associated with the Adaptor Removal technique have not been quantified and an estimate can only be based on the uncertainty of the two individual 2-Port calibrations. The only figures quoted for ANA calibration uncertainties [5] are :

(i) Waveguide calibration using TRL calibration technique - 0.005 in magnitude and 1° in phase.
(ii) Type-N coaxial calibration using sliding load - 0.015 in magnitude and 2° in phase.

These uncertainties combine to give an overall estimated uncertainty of 0.02 in magnitude and 3° in phase. This figure is equivalent to an attenuation uncertainty of 0.175dB.

2.3 ANA MEASUREMENT OF AN INSERTABLE COAXIAL DEVICE

Connecting two waveguide to coaxial adaptors together by their waveguide ports creates an insertable coaxial device which can be measured directly by an ANA (see Figure 3). This measurement requires a singe 2-Port calibration of the ANA using the appropriate coaxial calibration kit. The attenuation of the adaptor pair can then be calculated from $10\log(S_{21}xS_{12})$.

The uncertainties associated with an ANA measurement of this kind have not been quantified and an estimate can only be based on figures for Type-N coaxial calibrations as mentioned in Section 2.2. These figures lead to an equivalent attenuation uncertainty of 0.131dB.

2.4 ANA MEASUREMENT OF AN INSERTABLE WAVEGUIDE DEVICE

Connecting two waveguide to coaxial adaptors together by their coaxial ports creates an insertable waveguide device which can be measured directly by an ANA (see Figure 4). This measurement requires a singe 2-Port calibration of the ANA using the appropriate waveguide calibration kit. The attenuation of the adaptor pair can then be calculated from $10\log(S_{21}xS_{12})$.

The uncertainties associated with an ANA measurement of this kind have not been quantified and an estimate can only be based on figures for TRL waveguide calibrations as mentioned in Section 2.2. These figures lead to an equivalent attenuation uncertainty of 0.044dB.

3. RESULTS

3.1 WG14 TO APC7 ADAPTORS

Measurements were made using three WG14 to APC7 adaptors, adaptor A, adaptor B and adaptor C at frequencies of 6.0, 7.0, 8.0 and 8.2 GHz using the four measurement techniques described in Section 2.

Power Ratio Measurements

The forward and reverse attenuations of each adaptor pair (A&B, B&C, C&A) were measured by repeated insertion and removal from the measurement system. The resultant mean attenuation value and a standard deviation figure for each individual pair of adaptors are shown in Table 1 along with mismatch uncertainties derived from the s-parameters for the measurement system and the DUT.

The calculated mean attenuation of each individual adaptor and the overall measurement uncertainty at each frequency are shown in Table 2. A plot of the mean attenuation values, Figure 5, shows that all three adaptors have similar insertion loss characteristics.

Adaptor Removal Technique

The mean attenuation value and standard deviation for each adaptor, as measured by three separate Adaptor Removal calibrations, are given in Table 3. The estimated ANA uncertainty associated with attenuation values obtained using the Adaptor Removal Technique is 0.175dB (the uncertainty as calculated in Section 2.2).

A plot of the mean attenuation of each adaptor, Figure 6, shows that all three adaptors have similar insertion loss characteristics.

3.1.3 ANA Measurement of an Insertable Coaxial Device

The calculated attenuation values for each adaptor are given in Table 4. The estimated ANA uncertainty associated with attenuation values obtained using this method is 0.131dB (the uncertainty as calculated in Section 2.3). Figure 7, shows a plot of the insertion loss of each adaptor.

3.1.4 ANA Measurement of an Insertable Waveguide Device

The calculated attenuation values for each adaptor are given in Table 5. The estimated ANA uncertainty associated with attenuation values obtained using this method is 0.044dB (the uncertainty as calculated in Section 2.4). A plot of the insertion loss of each adaptor, Figure 8, shows that all three adaptors have similar insertion loss characteristics, but differences between the three curves are more evident at the top of the frequency band.

WG18 TO APC7 ADAPTORS

Measurements were made using three WG18 to APC7 adaptors, adaptor A, adaptor B and adaptor C. Power ratio measurements were made at spot frequencies of 12.4, 13, 14, 15, 16, 17, and 18GHz, and the ANA measurements were made at 0.1 GHz steps from 12.4 GHz to 18 GHz.

3.2.1 Power Ratio Measurements

The forward and reverse attenuation of each adaptor pair (A&B, B&C, C&A) was measured by repeated insertion and removal from the measurement system. The resultant mean attenuation value and a standard deviation figure for each individual pair of adaptors are shown in Table 6 along with mismatch uncertainties derived from the s-parameters for the measurement system and the DUT.

The calculated mean attenuation of each individual adaptor and the overall measurement uncertainty at each frequency are shown in Table 7. A plot of the mean attenuation values, Figure 9, shows that all three adaptors have similar insertion loss characteristics with the insertion loss slowly increasing as the measurement frequency increases.

3.2.2 Adaptor Removal Technique

A plot of the mean attenuation of each adaptor, as measured by three separate Adaptor Removal calibrations, is shown in Figure 10. This plot highlights an oscillatory component in all three insertion loss curves which is increasing in magnitude as the measurement frequency increases. To obtain 'realistic' insertion loss values at the spot frequencies specified for the Power Ratio measurements it was necessary to interpolate a smooth response curve using the measured values and to read off the insertion loss values at the required frequencies. The mean attenuation value and standard deviation for each adaptor are given in Table 8. The estimated ANA uncertainty associated with attenuation values obtained using the Adaptor Removal Technique is 0.175dB (the uncertainty as calculated in Section 2.2).

ANA Measurement of an Insertable Coaxial Device

The calculated mean attenuation values for each adaptor are plotted in Figure 11, with the mean attenuation and standard deviation for the reduced frequency set shown in Table 9. The estimated ANA uncertainty associated with attenuation values obtained using this method is 0.131dB (the uncertainty as calculated in Section 2.3).

ANA Measurement of an Insertable Waveguide Device

The calculated mean attenuation values for each adaptor are plotted in Figure 12, with the mean attenuation and standard deviation for the reduced frequency set shown in Table 10. The estimated ANA uncertainty associated with attenuation values obtained using this method is 0.044dB (the uncertainty as calculated in Section 2.4).

3.3 WG22 TO K ADAPTORS

Due to the sexed nature of the Type-K connector the evaluation of the characteristics of a single WG22 to K adaptor is only possible using one of the four adopted measurement techniques - the Adaptor Removal technique. Hence to evaluate the results obtained by the four techniques it was necessary to combine the results of a pair of adaptors, one male and one female, measured using the Adaptor Removal technique and compare this value against the results obtained for the same pair of adaptors measured using the other three techniques. For these comparisons three WG22 to K male adaptors (M1, M2 & M3) and three WG22 to K female adaptors (F1, F2 & F3) were used, which provide nine unique adaptor pairs.

Power ratio measurements were made at spot frequencies of 26.5 GHz then at 1 GHz steps from 27 GHz to 40 GHz, and the ANA measurements were made at 26.5 GHz and at 0.2 GHz steps from 26.6 GHz to 40 GHz.

3.3.1 Power Ratio Measurements

The attenuation of each adaptor pair (FxMy) was measured by repeated insertion and removal from the measurement system. The resultant mean attenuation value and standard deviation figure for each pair of adaptors, along with the estimated mismatch uncertainty are shown in Tables 11a, 11b and 11c. Figures 13a, 13b and 13c show the insertion loss values for the various adaptor pair combinations, with each female adaptor being combined with each one of the set of three male adaptors.

3.3.2 Adaptor Removal Technique

Due to a lack of an independent WG22 to K adaptor required as a transforming adaptor during the Adaptor Removal calibration process, each DUT adaptor was used in turn to be the calibration adaptor mathematically removed during the Adaptor Removal calibration process. This process produced three calibrations for measuring the WG22 to K male adaptors and three calibrations for measuring the WG22 to K female adaptors. The labelling convention used to identify each DUT measurement was Mx_y where x is the adaptor number being measured and y represents the adaptor used during the Adaptor Removal calibration process, e.g. M2_1 identifies that adaptor M2 was measured using M1 as the calibration adaptor.

The results obtained using the three WG22 to K male calibrations are shown in Figures 14a, 14b and 14c, from which it is clear that all three male adaptors have similar insertion loss characteristics no matter which adaptor was used during the Adaptor Removal calibration process. The mean insertion loss and standard deviation for each male adaptor over the reduced frequency set, are shown in Table 12. The estimated ANA uncertainty associated with attenuation values obtained using the Adaptor Removal Technique is 0.175dB (the uncertainty as calculated in Section 2.2).

The results obtained using the three WG22 to K female calibrations are shown in Figures 15a, 15b and 15c, and show that female adaptor F2 has a marked increase in insertion loss between 37 GHz and 40 GHz, and that adaptor F3 has a slightly higher insertion loss than adaptor F1 across the whole of the frequency range. It is also clear that the measured insertion loss of each adaptor is dependent

on the adaptor used during the Adaptor Removal calibration process. This is highlighted in Figure 16, where the insertion loss of adaptor F1, as measured by the separate Adaptor Removal calibrations, is shown.

In order to provide a means of comparing the insertion loss of the various adaptor pairs, as measured by the four techniques, the results for each female adaptor were combined with the results for each of the three male adaptors. These combined values are shown in Figures 17a, 17b and 17c.

ANA Measurement of an Insertable Coaxial Device

The characteristics of each adaptor pair (FxMy) were measured three times using separate ANA calibrations in Type-K, the resultant mean attenuation values are plotted in Figures 18a, 18b and 18c. These plots show that the three female adaptors produce distinctively different insertion loss characteristics when combined with a particular male adaptor, but there is little difference in the insertion loss curves produced when a particular female adaptor is combined with each of the three male adaptors.

The mean attenuation, standard deviation and estimated ANA uncertainty values for the reduced frequency set are shown in Tables 13a, 13b and 13c.

ANA Measurement of an Insertable Waveguide Device

The characteristics of each adaptor pair (FxMy) were measured three times by separate ANA calibrations in WG22, the resultant mean attenuation values are plotted in Figures 19a, 19b and 19c. These plots show that each adaptor pair produces a very smooth insertion loss response, this is in marked contrast to the responses produced using the previous two calibration techniques. These results also confirm the insertion loss differences between the female adaptors and the relatively minor differences in the insertion losses of the three male adaptors.

The mean attenuation, standard deviation and estimated ANA uncertainty values for the reduced frequency set are shown in Tables 14a, 14b and 14c.

4. DISCUSSION OF RESULTS

4.1 WG14 RESULTS

The three waveguide to coaxial adaptors have(een measured by four different techniques and the results obtained for each adaptor are compared in Figures 20a, 20b and 20c. The measured attenuation values are extremely consistent for all the measurement methods employed, indicating that the Adaptor Removal Technique gives an accurate method of measuring waveguide to coaxial adaptors at frequencies up to 8.2GHz.

4.2 WG18 RESULTS

The three WG18 to APC7 adaptors have been measured by four different techniques with the results for each adaptor compared in Figures 21a, 21b, and 21c. From these plots it is clear that all four measurement techniques give consistent results at frequencies up to 15 GHz, however above this frequency there are noticeable variations in the measured attenuation values. In an attempt to explain these inconsistencies the results obtained by the three ANA techniques are examined more closely.

The attenuation values obtained by the insertable waveguide technique, Figure 12, show the smoothest response curves across the whole of the frequency band, but there is an obvious anomaly for adaptor B at frequencies in the region of 16 GHz and to a lesser extent adaptor C in the same part of its response curve. The observed increase in insertion loss in this region could be due to interactions at the coaxial ports of the joined adaptors, but on examination of the s-parameters of all three adaptors there appears to be no obvious variation in the coaxial match of any of the adaptors in the frequency range of interest. A second explanation, is the presence of evanescent modes in both the coaxial path and the two waveguide sections. If evanescent modes are present in the coaxial section then these same modes would be present in the Power Ratio measurements but this was not the case, hence evanescent modes within the waveguide sections is the likely cause of the response anomaly.

The response curves obtained from the insertable coaxial device technique, Figure 11, show the same overall characteristics as those mentioned above but there are more discontinuities in the detailed shape of each curve. This is most noticeable at measurement frequencies close to 16 GHz. In this region there are signs that a strong resonance effect is distorting the measured response of all three adaptors, but unlike the results obtained using the insertable waveguide technique, the distortion creates a drop in the insertion loss response curves at 16 GHz as opposed to an increase in the measured insertion loss as mentioned above. As this drop in insertion loss is present in all three response curves, this is probably due to a calibration effect being imposed on the waveguide evanescent modes explained above.

The attenuation values obtained using the Adaptor Removal technique, Figure 10, show that all three response curves suffer from a strong oscillatory component at frequencies in excess of 15 GHz. This could have been caused by the long coaxial cables needed for the Adaptor Removal technique measurements and/or the mathematical manipulations undertaken in the formation of the ANA 2-port calibration. In either case the accuracy of the Adaptor Removal technique is more limited at the higher frequencies of WG18.

From the overall WG18 to APC7 results it is clear that all four measurement techniques are suitable at frequencies up to 15 GHz with the proviso that evanescent modes can be eliminated. But, as the measurement frequency increases, the accuracy of the ANA techniques is limited by factors such as interconnecting cable quality, initial calibration accuracy and the amount of physical movement of the measurement ports. Given all these associated problems, the agreement between the results obtained by the Power Ratio technique and the Adaptor Removal technique is good, with the difference between the two techniques only being appreciable at the higher measurement frequencies (difference in adaptor C measurements of 0.037 dB at 18 GHz).

4.3 WG22 RESULTS

From all four measurement techniques it is clear that the three WG22 to K male adaptors have similar insertion loss response characteristics, with adaptor M2 having a consistently higher insertion loss than both M1 and M3. The insertion loss characteristics of the female adaptors is more difficult to quantify. All four techniques show F1 as having the lowest loss with F3 having a loss approximately 0.06dB higher than F1, however the characteristics of F2 are far from consistent.

The Power Ratio measurements of adaptor pairs which included adaptor F2 (ie F2M1, F2M2 and F2M3) were much less consistent than measurements on the other combinations of adaptor pairs. This is shown by the large increase in the standard deviation figures of Table 11b. For frequencies above 30 GHz the repeatability of the Power Ratio measurements became poor, indicating that the adaptor F2 is very sensitive to waveguide alignment. This points to bad tuning of the adaptor.

The results obtained using the Insertable Coaxial Device technique show the same overall trend as the Power Ratio measurements, with adaptor F2 introducing increased loss between 33 GHz and 35 GHz. There is a corresponding increase in the standard deviation figures over this region indicating that mating repeatability of adaptor F2 is poor, this could be attributed to poor coaxial mating repeatability with the measurement port of the ANA or to poor waveguide mating repeatability with the male adaptor of the adaptor pair. Both these conclusions point to poor tuning of adaptor F2.

The full set of Insertable Coaxial Device measurements also highlight the 'spiky' responses obtained using coaxial calibrations at these frequencies, this is almost certainly due to the quality of the two port calibration (and the quality of the calibration items).

Using the Insertable Waveguide technique the difference in insertion loss between adaptors F1 and F3 is confirmed, and the peculiarities associated with adaptor F2 are increased. These set of measurements indicate that there is an increase in loss between 31 GHz and 33 GHz as well as an increase in loss between 37 GHz and 39 GHz. In both of these regions there is a corresponding increase in the standard deviation value indicating poor tuning of adaptor F2.

The measurements made using the Insertable Waveguide technique show characteristics which are smooth across the band without the discontinuities shown by the previous set of ANA measurements, this highlights the superior quality of TRL calibrations at high frequencies.

The Adaptor Removal measurements indicate that all three WG22 to K male adaptors have similar characteristics, but major discrepancies appeared when the female adaptors were measured. As shown in Figure 15a, adaptor F2 appears to suffer from a marked increase in insertion loss at around 38 GHz, this increase is much more pronounced than increases measured using the other three measurement techniques, confirming F2 as being a poor, unreliable adaptor. This finding is consistent with the all other measurements of adaptor F2.

The use of a poor adaptor, F2, during the Adaptor Removal technique did highlight a problem not observed during previous Adaptor Removal measurements. This problem is graphically illustrated by Figure 16, which shows the insertion loss of adaptor F1 as measured by three separate Adaptor Removal calibrations. This shows that when adaptor F1 was measured using an F2 calibration, some

of the characteristics of the F2 adaptor are superimposed on the measured response of adaptor F1. Due to the peculiarities of adaptor F2 any calibration made using this adaptor must be regarded as being of dubious quality and thus measurements made using such a calibration could easily be dismissed, however from Figure 16 it is also clear that the characteristics of adaptor F1 are also affected by the F3 calibration. As adaptor F3 appears to be a perfectly good adaptor these measurements cannot be disregarded and it is clear that the Adaptor Removal technique does not make a full removal of the calibrating adaptors characteristics, this must be addressed.

When the Adaptor Removal characteristics for each adaptor are combined, to make adaptor pairs, the response curves produced are spiky, this is probably due to the use of a full 2 port coaxial calibration during the Adaptor Removal technique. The errors introduced into a single Adaptor Removal calibration could then be doubled when the characteristics for two adaptors are added.

The insertion loss response curves for adaptor pairs F1M1, F2M1 and F3M1 as measured by the four different techniques are shown in Figures 22a, 22b and 22c. The differences in the response curves are small except for Adaptor Removal measurements which include adaptor F2.

5. CONCLUSIONS AND RECOMMENDATIONS

5 POWER RATIO TECHNIQUES

It has been shown that the insertion loss of pairs of waveguide to coaxial adaptors can be measured using the Power Ratio technique at frequencies of up to 40 GHz. For sexless adaptors (APC7 coaxial ports), it was also shown that the characteristics of each adaptor in an adaptor pair could be determined if three adaptors of the same connector type were available. It was also shown that three adaptors purchased from the same manufacturer had slightly different insertion loss characteristics thus making a simple divide by 2 technique to obtain the insertion loss of individual adaptors subject to error.

The measurement uncertainties associated with Power Ratio measurements are well defined and tend to be dominated by mismatch uncertainty, these uncertainties can be reduced for single frequency calibrations where waveguide tuners are used to reduce the source and load VSWR coefficients. The repeatability of the measurements made using the Power Ratio technique were good, with random variations generally better than 0.02 dB.

The Power Ratio technique has been used at frequencies up to 105 GHz at NPL Malvern, and thus the measurements of adaptor pairs in waveguide sizes to WG27 are feasible using this technique.

5.2 ADAPTOR REMOVAL TECHNIQUE

The accuracy of the Adaptor Removal Technique has proven suspect in two respects. Firstly, the technique employed during the calibration phase had to be refined to reduce calibration errors, and more significantly, the results obtained from 'good' Adaptor Removal calibrations were found to be inconsistent in an unpredictable way during the WG22 to K adaptor measurements.

For reliable Adaptor Removal measurements it is crucial that a good ANA calibration is made. It was found that the most reliable way to make an Adaptor Removal calibration was to calibrate the waveguide port (port 2) first, completing this calibration with measurement of the transmission parameters, then commencing the coaxial calibration (port 1) by measuring the transmission parameters. This procedure minimises the number of reconnections required during the two calibrations, thus reducing the effects of connector repeatability.

On completion of the two 2-Port calibrations the through loss of the system is measured using both the stored calibration sets (waveguide and coaxial) to check the accuracy of the calibrations. If the loss of the through connection is very small and the agreement between the two calibrations is good, continue on to the Adaptor Removal stage of the calibration. In cases where the two 2-Port calibrations are poor, the Adaptor Removal calibration produced often exhibits sharp 'resonant' peaks and troughs in the response curve of the temporary adaptor. These are often large enough to indicate 'gain' through the adaptor at certain frequencies on the response curve.

The repeatability of measurements made using the Adaptor Removal technique were dependent on the quality of the calibration. The random variation with good calibrations was generally better than 0.02 dB.

The inconsistencies observed during the WG22 to K adaptor measurements highlighted the fact that not all the characteristics of the calibration adaptor (the temporary adaptor used during the Adaptor Removal calibration process) were removed during the calibration process. This leads to the characteristics of the calibration adaptor being superimposed on the characteristics of the adaptor under test to produce erroneous measurements.

To reduce the errors associated with the Adaptor Removal technique it is necessary to choose the calibration adaptor carefully. It should be chosen to have the lowest possible insertion loss, together with as flat a response as possible, so that the effects of its characteristics on the adaptor being measured are minimised.

5.3 INSERTABLE COAXIAL DEVICE TECHNIQUE

Measurement of the insertion loss of adaptors made using the Insertable Coaxial Device technique have to a large extent agreed with the results obtained using the other three techniques. The major problem associated with this technique is systematic calibration errors which manifest themselves as spiky response curves, this is probably caused by imperfections in the full 2-Port calibration technique.

The repeatability of measurements made using the Insertable Coaxial Device technique were good, with random variations generally better than 0.02 dB.

5.4 INSERTABLE WAVEGUIDE DEVICE TECHNIQUE

The smooth response curves produced when measurements were made using this technique indicate

that the TRL calibrations used for calibrating the ANA produce much fewer systematic calibration errors. The results obtained using this technique again showed good agreement with results obtained using the three other techniques apart from obvious discrepancies during the WG18 measurements. This error was probably caused by evanescent modes in the adaptors under test.

The repeatability of measurements made using the Insertable Waveguide Device technique were good, with random variations generally better than 0.02 dB.

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3.	EM4 Research Note No.44	An investigation into the loss through our existing HP type-N to waveguide adaptors.
4.	EM4 Research Note No.53	Measurement of the SESC type-N adaptors using an HP8510B ANA.
5	EM4 Research Note No.56	Comparing methods for characterising type-N to waveguide adaptors and the uncertainties involved in each method.
6.	HP Product Note 8510-13	Measurement of Noninsertable Devices - A new technique for measuring components using the HP8510B Network Analyser.

APPENDIX A

Due to the device insertability requirements of three of the attenuation measurement techniques employed it is necessary to measure the attenuation of a pair of adaptors and to calculate the attenuation contribution of each. In the simplest form this requires three sexless devices to be measured in pairs. This produces three sets of equations which can be solved as shown below :-

The three adaptors A, B, & C are measured in pairs and give :

$$A + B = val\_1$$

$$B + C = val\_2$$

$$C + A = val\_3$$

These three equation are solved to give :

$$A = (val\_1 + val\_3 - val\_2)/2$$

$$B = (val\_2 + val\_1 - val\_3)/2$$

$$C = (val\_3 + val\_2 - val\_1)/2$$

The uncertainty value associated with the calculated attenuation of each adaptor can be assessed as follows :-

$$A+U_a + B+U_b = val\_1+U$$

$$B+U_b + C+U_c = val\_2+U_2$$

$$C+U_c + A+U_a = val\_3+U_3$$

These equations give values of A,B and C as above and leave the uncertainty of each measurement as :-

$$U_a = U_b = U_c = \tfrac{1}{2}\sqrt{(U_1^2 + U_2^2 + U_2^2)}$$

APPENDIX B -ADAPTOR REMOVAL TECHNIQUE

1 Specifying Temporary Adaptor

(i) Measurement of Electrical Length of temporary adaptor

Firstly making a short circuit 'response' calibration of the coaxial port of the measurement set up (* NOTE - specify 'coaxial delay' and Zo = 50 Ω from the ANA menus). Now connect the temporary adaptor to the coaxial port and terminate the waveguide port of the adaptor with a short circuit. Alter the delay type to WAVEGUIDE delay, and alter the display to observe the phase response of S11. Determine the electrical delay of the adaptor by increasing the internal electrical delay to obtain a flat phase response. The amount of electrical delay required to achieve phase flatness is equal to twice the electrical delay of the adaptor.

(ii) Modification of Cal Kit

Enter the characteristics of the temporary adaptor into the coaxial calibration kit by following this sequence of key presses :- **CAL, MORE, MODIFY <cal kit label>, DEFINE STANDARD, 20 x1** {ENTER}, **DELAY/THRU**. The electrical delay of the adaptor is entered by **SPECIFY OFFSET, OFFSET DELAY**, now enter the electrical delay of the adaptor, **WAVEGUIDE, MINIMUM FREQUENCY**, enter the cut-off frequency of waveguide size and press **STD OFFSET DONE**. The characteristics of the adaptor are now stored in calibration standard 20. To label this new calibration standard select **LABEL STANDARD**, enter a title using the title menu then press **TITLE DONE, STD DONE (DEFINED)**. The type of standard entered now needs to be specified by pressing **SPECIFY CLASS, MORE, MORE, SPECIFY ADAPTOR, 20 x1** {ENTER}, **CLASS DONE**. Finally the class label needs to be entered, **LABEL CLASS, MORE, MORE, ADAPTOR**, enter title using title menu, **TITLE DONE, LABEL DONE,**, enter an appropriate title for the modified calibration kit using title menu **LABEL KIT, TITLE DONE, KIT DONE (MODIFIED)**.

2 Modification of Cal Set

When the two independent calibrations have been completed, the two Cal Sets produces are combined using the key presses : **CAL, MORE, MODIFY CAL SET, ADAPTER REMOVAL**. Now press the CAL SET for port 1 (**CAL SET 1**), and specify the CAL SET for port 2 (**CAL SET 2**). Now select the cal kit which contains the definition of the temporary adaptor and finally press **MODIFY & SAVE** followed by the CAL SET location for storage of the modified ANA calibration coefficients (**CAL SET 3**).

3. Verification of the new Calibration

To verify that the electrical length of the temporary adaptor has been specified correctly examine the through phase response of the adaptor. This response should accurately represent the delay through adaptor, with no unexpected phase variations showing up on the trace.

Measurement Frequency (GHz)	Adaptor Pair under test	Mean Attenuation (dB)	Standard Deviation (dB)	Mismatch Uncertainty (dB)
6.0	A & B	0.0874	0.0087	0.0029
6.0	B & C	0.0952	0.0119	0.0019
6.0	C & A	0.0777	0.0037	0.0033
7.0	A & B	0.0969	0.0117	0.0012
7.0	B & C	0.0959	0.0163	0.0010
7.0	C & A	0.0906	0.0107	0.0010
8.0	A & B	0.1033	0.0128	0.0019
8.0	B & C	0.1072	0.0108	0.0016
8.0	C & A	0.0996	0.0134	0.0010
8.2	A & B	0.1287	0.0117	0.0054
8.2	B & C	0.1231	0.0114	0.0047
8.2	C & A	0.1173	0.0156	0.0038

TABLE 1. Power Ratio measurements of adaptor pairs

Measurement Frequency (GHz)	Mean Attenuation Adaptor A (dB)	Mean Attenuation Adaptor B (dB)	Mean Attenuation Adaptor C (dB)	Uncertainty at Measured Frequency (dB)
6.0	0.0350	0.0525	0.0428	0.0067
7.0	0.0458	0.0511	0.0448	0.0075
8.0	0.0479	0.0555	0.0518	0.0073
8.2	0.0615	0.0673	0.0559	0.0093

TABLE 2. Mean Attenuation of each adaptor measured using Power Ratio Technique

Measurement Frequency (GHz)	Results for Adaptor	Mean Attenuation (dB)	Standard Deviation (dB)	Estimated ANA Uncertainty (dB)
6.0	A	0.0573	0.0140	0.175
7.0	A	0.0674	0.0035	0.175
8.0	A	0.0555	0.0051	0.175
8.2	A	0.0635	0.0035	0.175
6.0	B	0.0491	0.0056	0.175
7.0	B	0.0530	0.0014	0.175
8.0	B	0.0459	0.0045	0.175
8.2	B	0.0531	0.0043	0.175
6.0	C	0.0437	0.0052	0.175
7.0	C	0.0533	0.0015	0.175
8.0	C	0.0484	0.0029	0.175
8.2	C	0.0518	0.0010	0.175

TABLE 3. Adaptor Removal measurents of WG14 to APC7 adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor A (dB)	Mean Attenuation Adaptor B (dB)	Mean Attenuation Adaptor C (dB)	Estimated ANA Uncertainty (dB)
6.0	0.0424	0.0417	0.0400	0.131
7.0	0.0391	0.0419	0.0453	0.131
8.0	0.0413	0.0473	0.0482	0.131
8.2	0.0522	0.0617	0.0515	0.131

TABLE 4. WG14 to APC7 adaptors measured using Insertable Coaxial Device Technique

Measurement Frequency (GHz)	Mean Attenuation Adaptor A (dB)	Mean Attenuation Adaptor B (dB)	Mean Attenuation Adaptor C (dB)	Estimated ANA Uncertainty (dB)
6.0	0.0439	0.0491	0.0522	0.044
7.0	0.0488	0.0437	0.0475	0.044
8.0	0.0560	0.0387	0.0497	0.044
8.2	0.0644	0.0408	0.0490	0.044

TABLE 5. WG14 to APC7 adaptors measured using Insertable Waveguide Device Technique

Measurement Frequency (GHz)	Adaptor Pair under test	Mean Attenuation (dB)	Standard Deviation (dB)	Mismatch Uncertainty (dB)
12.4	A & B	0.1415	0.0011	0.0048
12.4	B & C	0.1722	0.0017	0.0067
12.4	C & A	0.1608	0.0028	0.0068
13.0	A & B	0.1398	0.0016	0.0045
13.0	B & C	0.1582	0.0024	0.0042
13.0	C & A	0.1457	0.0019	0.0037
14.0	A & B	0.1496	0.0017	0.0020
14.0	B & C	0.1743	0.0021	0.0017
14.0	C & A	0.1596	0.0022	0.0015
15.0	A & B	0.1693	0.0031	0.0024
15.0	B & C	0.1899	0.0020	0.0027
15.0	C & A	0.1618	0.0032	0.0030
16.0	A & B	0.1899	0.0017	0.0030
16.0	B & C	0.2110	0.0020	0.0034
16.0	C & A	0.1766	0.0038	0.0041
17.0	A & B	0.2060	0.0032	0.0009
17.0	B & C	0.2261	0.0030	0.0016
17.0	C & A	0.2093	0.0054	0.0015
18.0	A & B	0.2377	0.0030	0.0019
18.0	B &C	0.2458	0.0037	0.0016
18.0	C & A	0.2599	0.0069	0.0010

TABLE 6. Power Ratio measurements of WG18 to APC7 adaptor pairs

Measurement Frequency (GHz)	Mean Attenuation Adaptor A (dB)	Mean Attenuation Adaptor B (dB)	Mean Attenuation Adaptor C (dB)	Uncertainty at Measured Frequency (dB)
12.4	0.0651	0.0765	0.0958	0.0104
13.0	0.0637	0.0762	0.0821	0.0071
14.0	0.0675	0.0822	0.0922	0.0030
15.0	0.0706	0.0987	0.0912	0.0046
16.0	0.0778	0.1122	0.0989	0.0062
17.0	0.0946	0.1114	0.1147	0.0029
18.0	0.1259	0.1118	0.1340	0.0032

TABLE 7. Mean Attenuation of each adaptor measured using Power Ratio Technique

Measurement Frequency (GHz)	Results for Adaptor	Mean Attenuation (dB)	Standard Deviation (dB)	Estimated ANA Uncertainty (dB)
12.4	A	0.0699	0.0075	0.175
13.0	A	0.0640	0.0060	0.175
14.0	A	0.0689	0.0060	0.175
15.0	A	0.067	0.0092	0.175
16.0	A	0.077	0.0081	0.175
17.0	A	0.089	0.0065	0.175
18.0	A	0.114	0.0074	0.175
12.4	B	0.0936	0.0073	0.175
13.0	B	0.0799	0.0064	0.175
14.0	B	0.0881	0.0057	0.175
15.0	B	0.103	0.0086	0.175
16.0	B	0.120	0.0020	0.175
17.0	B	0.136	0.0083	0.175
18.0	B	0.122	0.0099	0.175
12.4	C	0.1080	0.0066	0.175
13.0	C	0.0856	0.0102	0.175
14.0	C	0.1032	0.0028	0.175
15.0	C	0.103	0.0048	0.175
16.0	C	0.132	0.0166	0.175
17.0	C	0.151	0.0304	0.175
18.0	C	0.171	0.0227	0.175

TABLE 8. Adaptor Removal measurements of WG18 to APC7 adaptors

Measurement Frequency (GHz)	Results for Adaptor	Mean Attenuation (dB)	Standard Deviation (dB)	Estimated ANA Uncertainty (dB)
12.4	A	0.0630	0.0033	0.131
13.0	A	0.0585	0.0012	0.131
14.0	A	0.0653	0.0035	0.131
15.0	A	0.656	0.0034	0.131
16.0	A	0.621	0.0026	0.131
17.0	A	0.706	0.0078	0.131
18.0	A	0.564	0.0147	0.131
12.4	B	0.0911	0.0078	0.131
13.0	B	0.0844	0.0079	0.131
14.0	B	0.0935	0.0107	0.131
15.0	B	0.1118	0.0111	0.131
16.0	B	0.1154	0.0093	0.131
17.0	B	0.1106	0.0115	0.131
18.0	B	0.0702	0.0136	0.131
12.4	C	0.0997	0.0047	0.131
13.0	C	0.0819	0.0035	0.131
14.0	C	0.0932	0.0067	0.131
15.0	C	0.0900	0.0068	0.131
16.0	C	0.0869	0.0061	0.131
17.0	C	0.0943	0.0087	0.131
18.0	C	0.0728	0.0077	0.131

TABLE 9. WG18 to APC7 adaptors measured using Insertable Coaxial Device Technique

Measurement Frequency (GHz)	Results for Adaptor	Mean Attenuation (dB)	Standard Deviation (dB)	Estimated ANA Uncertainty (dB)
12.4	A	0.0715	0.0028	0.044
13.0	A	0.0683	0.0008	0.044
14.0	A	0.0745	0.0025	0.044
15.0	A	0.866	0.0030	0.044
16.0	A	0.922	0.0047	0.044
17.0	A	0.878	0.0135	0.044
18.0	A	0.983	0.0098	0.044
12.4	B	0.0943	0.0044	0.044
13.0	B	0.0846	0.0036	0.044
14.0	B	0.0892	0.0005	0.044
15.0	B	01142	0.0021	0.044
16.0	B	01678	0.0059	0.044
17.0	B	01317	0.0081	0.044
18.0	B	01066	0.0027	0.044
12.4	C	0.1101	0.0056	0.044
13.0	C	0.0871	0.0013	0.044
14.0	C	0.0940	0.0025	0.044
15.0	C	0.1079	0.0017	0.044
16.0	C	0.1300	0.0028	0.044
17.0	C	0.1149	0.0084	0.044
18.0	C	0.1169	0.0062	0.044

TABLE 10. WG18 to APC7 adaptors measured using Insertable Waveguide Device Technique Technique

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F1M1 (dB)	Standard Deviation Adaptor pair F1M1 (dB)	Mismatch Uncertainty Adaptor pair F1M1 (dB)	Mean Attenuation Adaptor pair F1M2 (dB)	Standard Deviation Adaptor pair F1M2 (dB)	Mismatch Uncertainty Adaptor pair F1M2 (dB)	Mean Attenuation Adaptor pair F1M3 (dB)	Standard Deviation Adaptor pair F1M3 (dB)	Mismatch Uncertainty Adaptor pair F1M3 (dB)
26.5	0.2935	0.0016	0.0841	0.3493	0.0024	0.0985	0.3008	0.0011	0.0832
27.0	0.2292	0.0014	0.0250	0.2530	0.0019	0.0318	0.2353	0.0011	0.0249
28.0	0.2291	0.0011	0.0118	0.2470	0.0022	0.0063	0.2470	0.0010	0.0055
29.0	0.2169	0.0011	0.0180	0.2270	0.0039	0.0165	0.2182	0.0015	0.0121
30.0	0.2459	0.0012	0.0120	0.2602	0.0082	0.0119	0.2302	0.0011	0.0098
31.0	0.2524	0.0006	0.0214	0.2671	0.0068	0.0204	0.2385	0.0008	0.0185
32.0	0.2656	0.0008	0.0287	0.2862	0.0024	0.0284	0.2619	0.0010	0.0287
33.0	0.2416	0.0010	0.0114	0.2563	0.0050	0.0128	0.2327	0.0009	0.0142
34.0	0.2427	0.0008	0.0107	0.2587	0.0027	0.0125	0.2349	0.0011	0.0147
35.0	0.2472	0.0008	0.0178	0.2638	0.0022	0.0191	0.2435	0.0010	0.0193
36.0	0.2782	0.0012	0.0284	0.2961	0.0019	0.0314	0.2773	0.0016	0.0316
37.0	0.2536	0.0016	0.0042	0.2743	0.0022	0.0048	0.2613	0.0017	0.0055
38.0	0.2599	0.0010	0.0071	0.2757	0.0023	0.0099	0.2676	0.0015	0.0124
39.0	0.2648	0.0011	0.0098	0.2839	0.0032	0.0085	0.2742	0.0020	0.0059
40.0	0.2958	0.0010	0.0705	0.3359	0.0031	0.0869	0.3264	0.0023	0.0789

TABLE 11a. Power Ratio Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F2M1 (dB)	Standard Deviation Adaptor pair F2M1 (dB)	Mismatch Uncertainty Adaptor pair F2M1 (dB)	Mean Attenuation Adaptor pair F2M2 (dB)	Standard Deviation Adaptor pair F2M2 (dB)	Mismatch Uncertainty Adaptor pair F2M2 (dB)	Mean Attenuation Adaptor pair F2M3 (dB)	Standard Deviation Adaptor pair F2M3 (dB)	Mismatch Uncertainty Adaptor pair F2M3 (dB)
26.5	0.3319	0.0148	0.0835	0.3536	0.0031	0.0939	0.3283	0.0034	0.0725
27.0	0.2740	0.0111	0.0251	0.2831	0.0032	0.0328	0.2722	0.0020	0.0360
28.0	0.2772	0.0058	0.00097	0.2877	0.0032	0.0123	0.2878	0.0029	0.0123
29.0	0.2720	0.0160	0.0218	0.2752	0.0081	0.0198	0.2614	0.0038	0.0113
30.0	0.3220	0.0217	0.0216	0.3315	0.0074	0.0141	0.2979	0.0075	0.0140
31.0	0.3038	0.0123	0.0206	0.3411	0.0187	0.0212	0.3118	0.0205	0.0223
32.0	0.3251	0.0181	0.0287	0.3798	0.0266	0.0302	0.3340	0.0242	0.0304
33.0	0.3522	0.0154	0.0178	0.3926	0.0126	0.0163	0.3569	0.0184	0.0203
34.0	0.4287	0.0166	0.0270	0.4984	0.0149	0.0275	0.4210	0.0501	0.0473
35.0	0.4254	0.0427	0.0350	0.4441	0.0169	0.0212	0.4334	0.0363	0.0320
36.0	0.3931	0.0413	0.0302	0.3896	0.0100	0.0122	0.3941	0.0100	0.0127
37.0	0.3702	0.0803	0.0576	0.3384	0.0136	0.0116	0.4223	0.0666	0.0482
38.0	0.3304	0.0523	0.0387	0.3201	0.0115	0.0084	0.4161	0.1139	0.0836
39.0	0.3037	0.0154	0.0146	0.3044	0.0065	0.0086	0.3375	0.00387	0.0305
40.0	0.2837	0.0087	0.0076	0.2931	0.0033	0.0618	0.3136	0.0149	0.0390

TABLE 11b. Power Ratio Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F3M1 (dB)	Standard Deviation Adaptor pair F3M1 (dB)	Mismatch Uncertainty Adaptor pair F3M1 (dB)	Mean Attenuation Adaptor pair F3M2 (dB)	Standard Deviation Adaptor pair F3M2 (dB)	Mismatch Uncertainty Adaptor pair F3M2 (dB)	Mean Attenuation Adaptor pair F3M3 (dB)	Standard Deviation Adaptor pair F3M3 (dB)	Mismatch Uncertainty Adaptor pair F3M3 (dB)
26.5	0.3063	0.0018	0.1035	0.3294	0.0013	0.1003	0.3098	0.0019	0.0820
27.0	0.2739	0.0020	0.0378	0.2868	0.0015	0.0403	0.2794	0.0020	0.0305
28.0	0.2881	0.0022	0.0154	0.3057	0.0018	0.0174	0.3071	0.0026	0.0120
29.0	0.2701	0.0016	0.0243	0.2798	0.0019	0.0242	0.2700	0.0026	0.0176
30.0	0.3083	0.0019	0.0132	0.3201	0.0028	0.0122	0.2943	0.0034	0.0126
31.0	0.2977	0.0040	0.0142	0.3195	0.0031	0.0142	0.2910	0.0038	0.0250
32.0	0.3177	0.0048	0.0222	0.3459	0.0023	0.0224	0.3039	0.0067	0.0218
33.0	0.3313	0.0037	0.0195	0.3502	0.0044	0.0202	0.3151	0.0025	0.0210
34.0	0.3222	0.0045	0.0312	0.3445	0.0066	0.0350	0.3178	0.0033	0.0382
35.0	0.3105	0.0070	0.0094	0.3238	0.0038	0.0088	0.3092	0.0080	0.0116
36.0	0.3357	0.0056	0.0151	0.3567	0.0049	0.0231	0.3381	0.0043	0.0250
37.0	0.3205	0.0050	0.0053	0.3382	0.0045	0.0084	0.3258	0.0033	0.0093
38.0	0.3150	0.0031	0.0095	0.3214	0.0031	0.0076	0.3148	0.0034	0.0104
39.0	0.3172	0.0033	0.0124	0.3236	0.0024	0.0132	0.3167	0.0029	0.0121
40.0	0.3440	0.0021	0.0372	0.3542	0.0018	0.0488	0.3595	0.0025	0.0584

TABLE 11c. Power Ratio Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation of Adaptor M1 (dB)	Standard Deviation Adaptor M1 (dB)	ANA Uncertainty Adaptor M1 (dB)	Mean Attenuation of Adaptor M2 (dB)	Standard Deviation Adaptor M2 (dB)	ANA Uncertainty Adaptor M2 (dB)	Mean Attenuation of Adaptor M3 (dB)	Standard Deviation Adaptor M3 (dB)	ANA Uncertainty Adaptor M3 (dB)
26.5	0.1525	0.0137	0.175	0.1666	0.0161	0.171	0.1493	0.0120	0.175
27.0	0.1497	0.0072	0.175	0.1591	0.0088	0.175	0.1514	0.0064	0.175
28.0	0.1337	0.0065	0.175	0.1435	0.0078	0.175	0.1491	0.0062	0.175
29.0	0.1251	0.0050	0.175	0.1361	0.0068	0.175	0.1233	0.0058	0.175
30.0	0.1546	0.0065	0.175	0.1648	0.0064	0.175	0.1479	0.0070	0.175
31.0	0.1327	0.0104	0.175	0.1476	0.0095	0.175	0.1246	0.0085	0.175
32.0	0.1521	0.0109	0.175	0.1786	0.0127	0.175	0.1466	0.0076	0.175
33.0	0.1107	0.0172	0.175	0.1334	0.0166	0.175	0.1028	0.0216	0.175
34.0	0.20910	0.0094	0.175	0.1146	0.0094	0.175	0.0912	0.0131	0.175
35.0	0.1313	0.0089	0.175	0.1520	0.0065	0.175	0.1350	0.0028	0.175
36.0	0.1590	0.0121	0.175	0.1833	0.0118	0.175	0.1713	0.0084	0.175
37.0	0.1334	0.0045	0.175	0.1542	0.0033	0.175	0.1469	0.0060	0.175
38.0	0.1742	0.0074	0.175	0.1897	0.0069	0.175	0.1865	0.0050	0.175
39.0	0.1537	0.0052	0.175	0.1593	0.0053	0.175	0.1547	0.0036	0.175
40.0	0.1277	0.0097	0.175	0.1391	0.0085	0.175	0.1291	0.0114	0.175

TABLE 12. Adaptor Removal Measurements of WG22 to Type 'K' Male adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F1M1 (dB)	Standard Deviation Adaptor pair F1M1 (dB)	ANA Uncertainty Adaptor pair F1M1 (dB)	Mean Attenuation Adaptor pair F1M2 (dB)	Standard Deviation Adaptor pair F1M2 (dB)	ANA Uncertainty Adaptor pair F1M2 (dB)	Mean Attenuation Adaptor pair F1M3 (dB)	Standard Deviation Adaptor pair F1M3 (dB)	ANA Uncertainty Adaptor pair F1M3 (dB)
26.5	0.2647	0.0065	0.131	0.2718	0.0092	0.131	0.2556	0.0046	0.131
27.0	0.2708	0.0023	0.131	0.2663	0.0034	0.131	0.2730	0.0017	0.131
28.0	0.2283	0.0036	0.131	0.2335	0.0070	0.131	0.2406	0.0019	0.131
29.0	0.2243	0.0053	0.131	0.2248	0.0062	0.131	0.2214	0.0014	0.131
30.0	0.2693	0.0057	0.131	0.2693	0.0059	0.131	0.2611	0.0003	0.131
31.0	0.2113	0.0108	0.131	0.2178	0.0059	0.131	0.2035	0.0017	0.131
32.0	0.2578	0.0137	0.131	0.2753	0.0028	0.131	0.2580	0.0020	0.131
33.0	0.2427	0.0133	0.131	0.2463	0.0047	0.131	0.2279	0.0043	0.131
34.0	0.2558	0.0188	0.131	0.2596	0.0009	0.131	0.2521	0.0020	0.131
35.0	0.2682	0.0183	0.131	0.2721	0.0011	0.131	0.2690	0.0010	0.131
36.0	0.3441	0.0078	0.131	0.3425	0.0126	0.131	0.3436	0.0117	0.131
37.0	0.2705	0.0127	0.131	0.2715	0.0022	0.131	0.2751	0.0007	0.131
38.0	0.2627	0.0114	0.131	0.2662	0.0033	0.131	0.2728	0.0009	0.131
39.0	0.2747	0.0104	0.131	0.2712	0.0072	0.131	0.2776	0.0066	0.131
40.0	0.3092	0.0156	0.131	0.3193	0.0041	0.131	0.3104	0.0029	0.131

TABLE 13a. Insertable Coaxial Device Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F2M1 (dB)	Standard Deviation Adaptor pair F2M1 (dB)	ANA Uncertainty Adaptor pair F2M1 (dB)	Mean Attenuation Adaptor pair F2M2 (dB)	Standard Deviation Adaptor pair F2M2 (dB)	ANA Uncertainty Adaptor pair F2M2 (dB)	Mean Attenuation Adaptor pair F2M3 (dB)	Standard Deviation Adaptor pair F2M3 (dB)	ANA Uncertainty Adaptor pair F2M3 (dB)
26.5	0.2879	0.0028	0.131	0.3028	0.0066	0.131	0.2903	0.0084	0.131
27.0	0.3078	0.0022	0.131	0.3205	0.0012	0.131	0.3184	0.0121	0.131
28.0	0.2594	0.0029	0.131	0.2802	0.0116	0.131	0.2822	0.0121	0.131
29.0	0.2663	0.0035	0.131	0.2809	0.0051	0.131	0.2705	0.0083	0.131
30.0	0.3090	0.0117	0.131	0.3233	0.0063	0.131	0.3152	0.0103	0.131
31.0	0.2674	0.0216	0.131	0.2877	0.0016	0.131	0.2636	0.0076	0.131
32.0	0.3109	0.0072	0.131	0.3417	0.0093	0.131	0.3136	0.0059	0.131
33.0	0.3307	0.0084	0.131	0.3551	0.0192	0.131	0.3225	0.0118	0.131
34.0	0.3988	0.0207	0.131	0.4419	0.0182	0.131	0.4497	0.0381	0.131
35.0	0.3568	0.0362	0.131	0.3983	0.0339	0.131	0.4066	0.0296	0.131
36.0	0.4259	0.0249	0.131	0.4361	0.0222	0.131	0.4257	0.0182	0.131
37.0	0.3137	0.0029	0.131	0.3132	0.0063	0.131	0.3084	0.0079	0.131
38.0	0.3078	0.0039	0.131	0.3144	0.0017	0.131	0.3166	0.0057	0.131
39.0	0.3057	0.0057	0.131	0.3024	0.0078	0.131	0.3012	0.0047	0.131
40.0	0.3153	0.0034	0.131	0.3185	0.0038	0.131	0.3129	0.0089	0.131

TABLE 13b. Insertable Coaxial Device Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F3M1 (dB)	Standard Deviation Adaptor pair F3M1 (dB)	ANA Uncertainty Adaptor pair F3M1 (dB)	Mean Attenuation Adaptor pair F3M2 (dB)	Standard Deviation Adaptor pair F3M2 (dB)	ANA Uncertainty Adaptor pair F3M2 (dB)	Mean Attenuation Adaptor pair F3M3 (dB)	Standard Deviation Adaptor pair F3M3 (dB)	ANA Uncertainty Adaptor pair F3M3 (dB)
26.5	0.3099	0.0063	0.131	0.3207	0.0046	0.131	0.3103	0.0136	0.131
27.0	0.3370	0.0087	0.131	0.3465	0.0016	0.131	0.3402	0.0147	0.131
28.0	0.2816	0.0058	0.131	0.3031	0.0050	0.131	0.3017	0.0121	0.131
29.0	0.2891	0.0100	0.131	0.3084	0.0059	0.131	0.2795	0.0089	0.131
30.0	0.3173	0.0100	0.131	0.3422	0.0095	0.131	0.3079	0.0094	0.131
31.0	0.2713	0.0152	0.131	0.2985	0.0076	0.131	0.2565	0.0059	0.131
32.0	0.3098	0.0169	0.131	0.3453	0.0047	0.131	0.2947	0.0049	0.131
33.0	0.3028	0.0171	0.131	0.3301	0.0116	0.131	0.2933	0.0017	0.131
34.0	0.3223	0.0185	0.131	0.3445	0.0117	0.131	0.3121	0.0039	0.131
35.0	0.3070	0.0133	0.131	0.3184	0.0068	0.131	0.3040	0.0035	0.131
36.0	0.4017	0.0108	0.131	0.4090	0.0161	0.131	0.4055	0.0083	0.131
37.0	0.3091	0.0069	0.131	0.3172	0.0039	0.131	0.3184	0.0050	0.131
38.0	0.3060	0.0052	0.131	0.3121	0.0043	0.131	0.3192	0.0069	0.131
39.0	0.3333	0.0124	0.131	0.3244	0.0072	0.131	0.3345	0.0029	0.131
40.0	0.3268	0.0075	0.131	0.3342	0.0058	0.131	0.3414	0.0063	0.131

TABLE 13c. Insertable Coaxial Device Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F1M1 (dB)	Standard Deviation Adaptor pair F1M1 (dB)	ANA Uncertainty Adaptor pair F1M1 (dB)	Mean Attenuation Adaptor pair F1M2 (dB)	Standard Deviation Adaptor pair F1M2 (dB)	ANA Uncertainty Adaptor pair F1M2 (dB)	Mean Attenuation Adaptor pair F1M3 (dB)	Standard Deviation Adaptor pair F1M3 (dB)	ANA Uncertainty Adaptor pair F1M3 (dB)
26.5	0.2384	0.0081	0.044	0.2483	0.0121	0.044	0.2343	0.0058	0.044
27.0	0.2257	0.0060	0.044	0.2277	0.0108	0.044	0.2270	0.0073	0.044
28.0	0.2216	0.0018	0.044	0.2235	0.0094	0.044	0.2386	0.0102	0.044
29.0	0.2155	0.0037	0.044	0.2189	0.0043	0.044	0.2148	0.0108	0.044
30.0	0.2165	0.0039	0.044	0.2302	0.0021	0.044	0.2093	0.0075	0.044
31.0	0.2441	0.0048	0.044	0.2563	0.0039	0.044	0.2292	0.0073	0.044
32.0	0.2372	0.0047	0.044	0.2439	0.0038	0.044	0.2306	0.0067	0.044
33.0	0.2302	0.0078	0.044	0.2296	0.0045	0.044	0.2204	0.0052	0.044
34.0	0.2166	0.0096	0.044	0.2284	0.0057	0.044	0.2167	0.0082	0.044
35.0	0.2188	0.0078	0.044	0.2344	0.0061	0.044	0.2214	0.0054	0.044
36.0	0.2272	0.0049	0.044	0.2414	0.0071	0.044	0.2351	0.0082	0.044
37.0	0.2174	0.0093	0.044	0.2292	0.0079	0.044	0.2251	0.0098	0.044
38.0	0.2230	0.0078	0.044	0.2379	0.0046	0.044	0.2348	0.0101	0.044
39.0	0.2357	0.0075	0.044	0.2498	0.0056	0.044	0.2427	0.0075	0.044
40.0	0.2680	0.0151	0.044	0.2964	0.0114	0.044	0.2819	0.0103	0.044

TABLE 14a. Insertable Waveguide Device Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F2M1 (dB)	Standard Deviation Adaptor pair F2M1 (dB)	ANA Uncertainty Adaptor pair F2M1 (dB)	Mean Attenuation Adaptor pair F2M2 (dB)	Standard Deviation Adaptor pair F2M2 (dB)	ANA Uncertainty Adaptor pair F2M2 (dB)	Mean Attenuation Adaptor pair F2M3 (dB)	Standard Deviation Adaptor pair F2M3 (dB)	ANA Uncertainty Adaptor pair F2M3 (dB)
26.5	0.2729	0.0112	0.044	0.2800	0.0104	0.044	0.2732	0.0124	0.044
27.0	0.2586	0.0100	0.044	0.2628	0.0106	0.044	0.2651	0.0110	0.044
28.0	0.2516	0.0057	0.044	0.2601	0.0071	0.044	0.2760	0.0116	0.044
29.0	0.2514	0.0060	0.044	0.2615	0.0070	0.044	0.2547	0.0121	0.044
30.0	0.2676	0.0064	0.044	0.2829	0.0061	0.044	0.2610	0.0092	0.044
31.0	0.2968	0.0066	0.044	0.3132	0.0092	0.044	0.2930	0.0066	0.044
32.0	0.3163	0.0271	0.044	0.3264	0.0307	0.044	0.3198	0.0072	0.044
33.0	0.3060	0.0162	0.044	0.3062	0.0197	0.044	0.3007	0.0105	0.044
34.0	0.2894	0.0031	0.044	0.2962	0.0012	0.044	0.2880	0.0056	0.044
35.0	0.3022	0.0132	0.044	0.3095	0.0127	0.044	0.2991	0.0030	0.044
36.0	0.3105	0.0069	0.044	0.3196	0.0057	0.044	0.43102	0.0029	0044
37.0	0.3330	0.0253	0.044	0.3476	0.0353	0.044	0.3455	0.0234	0.044
38.0	0.3232	0.0226	0.044	0.3381	0.0304	0.044	0.3435	0.0227	0.044
39.0	0.3082	0.0174	0.044	0.3182	0.0241	0.044	0.3300	0.0280	0.044
40.0	0.3210	0.0093	0.044	0.3383	0.0140	0.044	0.3392	0.0150	0.044

TABLE 14b. Insertable Waveguide Device Measurements of WG22 to Type 'K' adaptors

Measurement Frequency (GHz)	Mean Attenuation Adaptor pair F3M1 (dB)	Standard Deviation Adaptor pair F3M1 (dB)	ANA Uncertainty Adaptor pair F3M1 (dB)	Mean Attenuation Adaptor pair F3M2 (dB)	Standard Deviation Adaptor pair F3M2 (dB)	ANA Uncertainty Adaptor pair F3M2 (dB)	Mean Attenuation Adaptor pair F3M3 (dB)	Standard Deviation Adaptor pair F3M3 (dB)	ANA Uncertainty Adaptor pair F3M3 (dB)
26.5	0.2956	0.0069	0.044	0.3029	0.0131	0.044	0.2944	0.0139	0.044
27.0	0.2877	0.0050	0.044	0.2988	0.0142	0.044	0.2923	0.0155	0.044
28.0	0.2822	0.0030	0.044	0.3028	0.0134	0.044	0.3038	0.0118	0.044
29.0	0.2764	0.0051	0.044	0.2925	0.0065	0.044	0.2767	0.0059	0.044
30.0	0.2707	0.0069	0.044	0.2923	0.0044	0.044	0.2666	0.0056	0.044
31.0	0.2656	0.0065	0.044	0.2942	0.0024	0.044	0.2635	0.0086	0.044
32.0	0.2710	0.0091	0.044	0.2923	0.0008	0.044	0.2654	0.0102	0.044
33.0	0.2959	0.0067	0.044	0.3045	0.0056	0.044	0.2871	0.0077	0.044
34.0	0.2772	0.0071	0.044	0.2917	0.0120	0.044	0.2817	0.0063	0.044
35.0	0.2576	0.0110	0.044	0.2699	0.0156	0.044	0.2610	0.0063	0.044
36.0	0.2579	0.0135	0.044	0.2768	0.0200	0.044	0.2661	0.0113	0.044
37.0	0.2599	0.0117	0.044	0.2782	0.0187	0.044	0.2703	0.0145	0.044
38.0	0.2675	0.0128	0.044	0.2771	0.0150	0.044	0.2717	0.0126	0.044
39.0	0.2813	0.0124	0.044	0.2954	0.0111	0.044	0.2862	0.0065	0.044
40.0	0.3022	0.0171	0.044	0.3198	0.0117	0.044	0.3130	0.0077	0.044

TABLE 14c. Insertable Waveguide Device Measurements of WG22 to Type 'K' adaptors

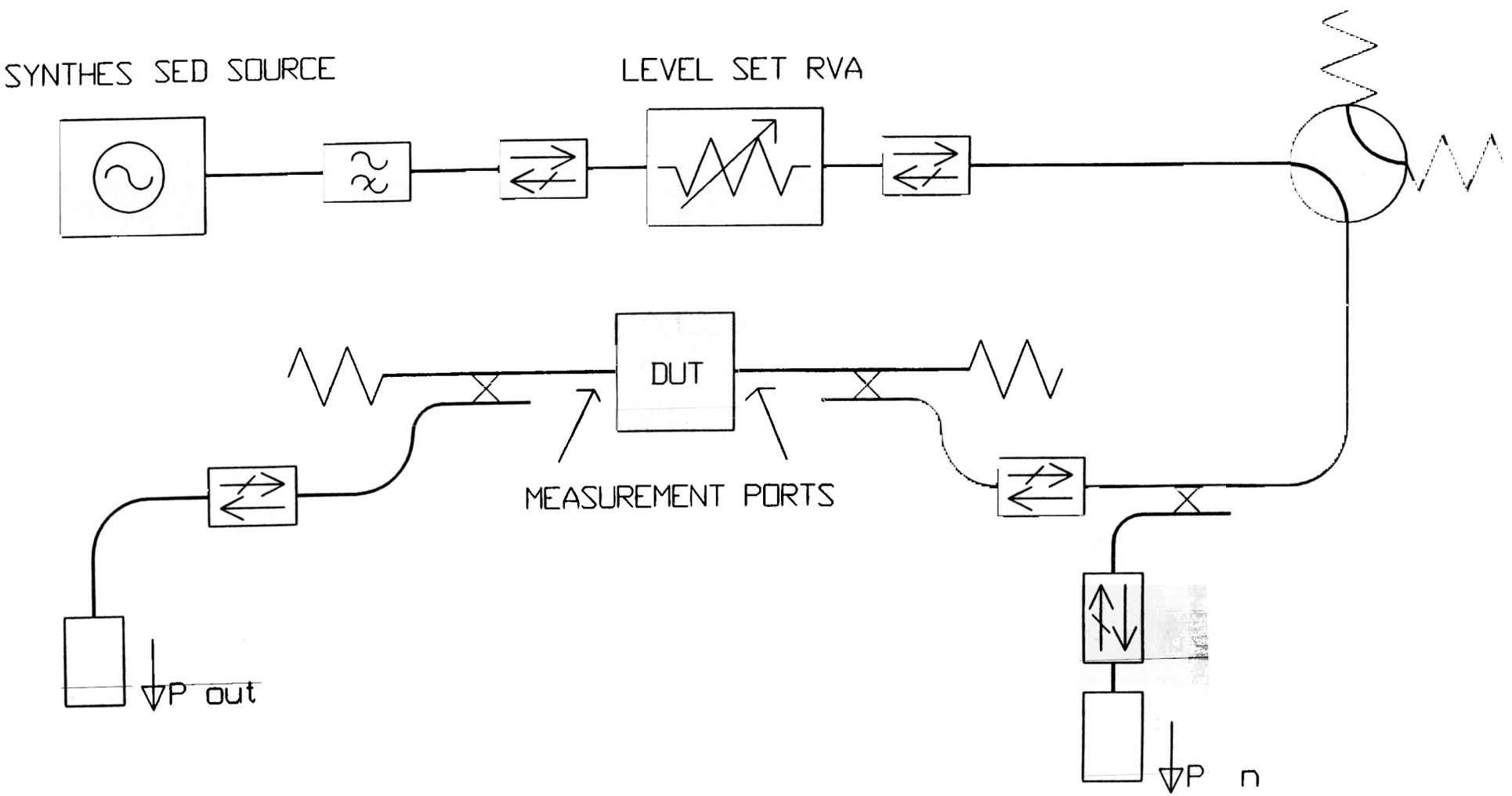


Figure Power Ratio measurement system

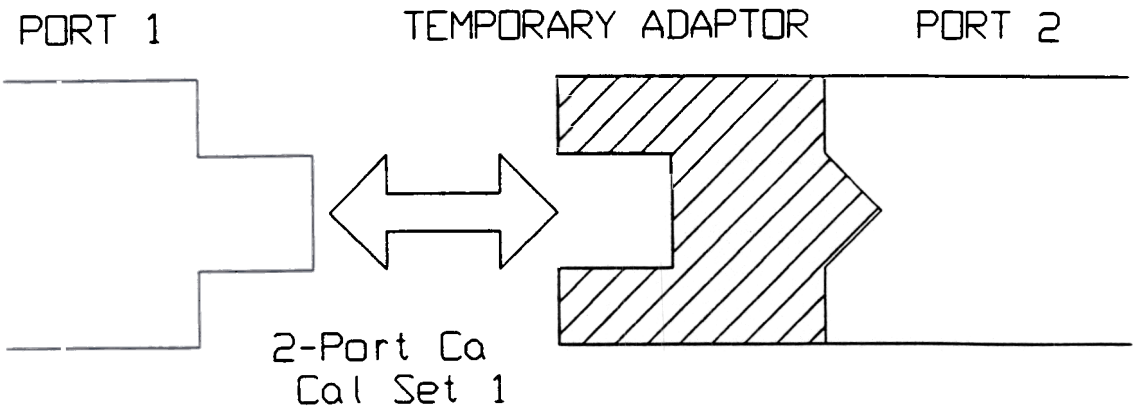
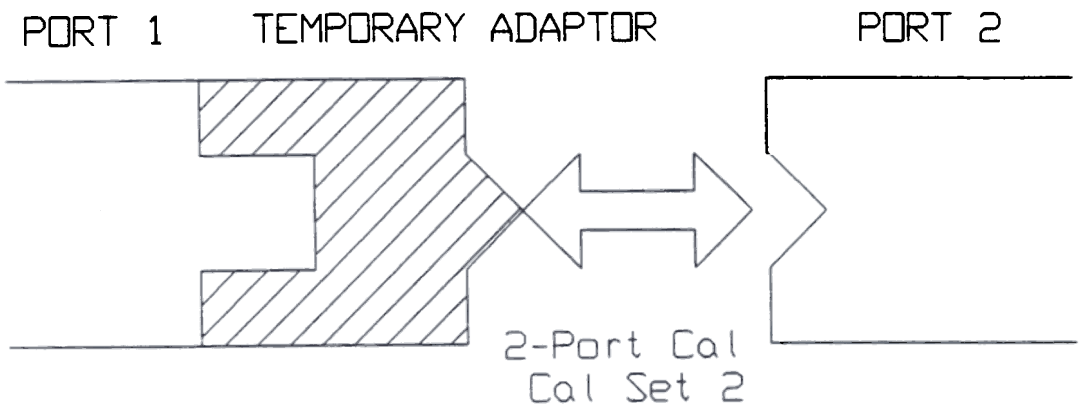
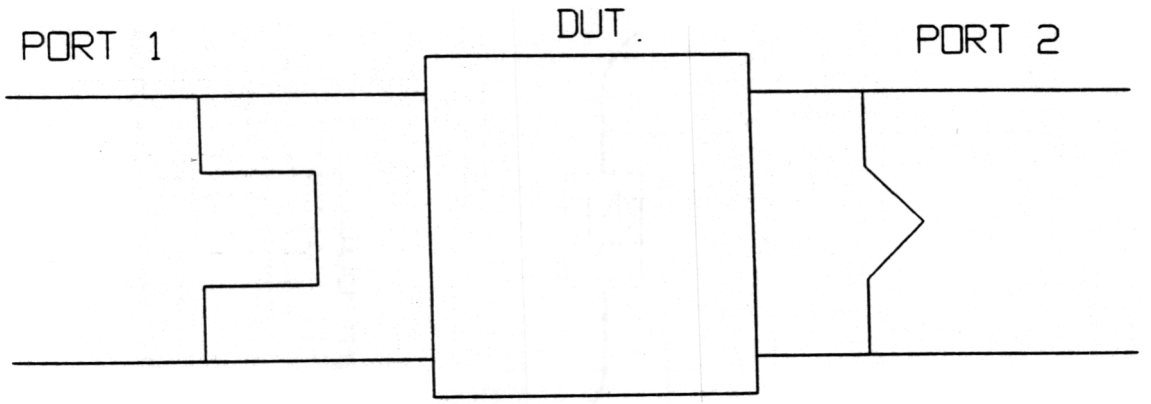


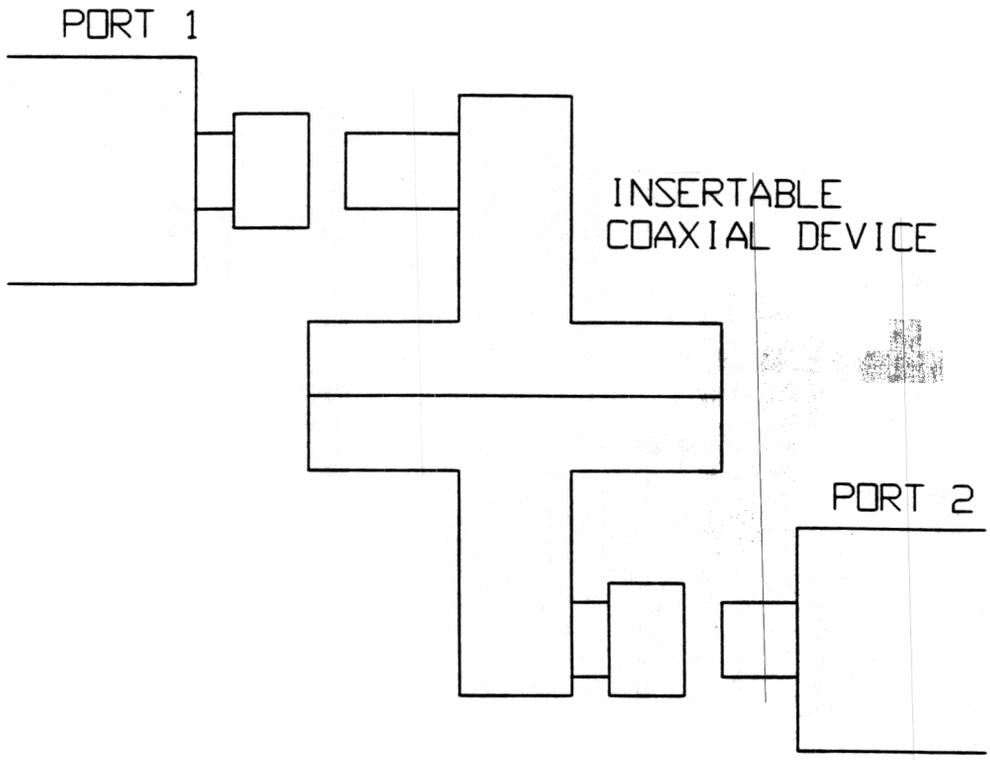
Figure 2a Cal brate Port 1



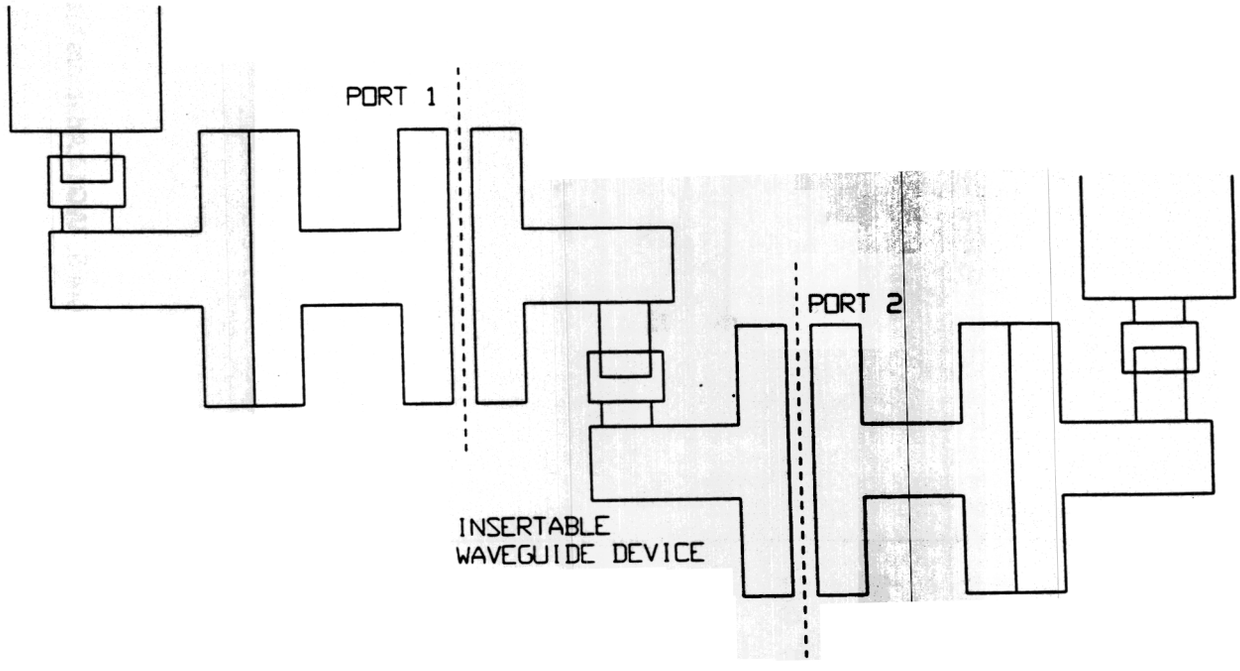
F gure 2b Cal brate Port 2



F gure 2c Measurement of DUT



F gure 3 ANA Measurement of Coaxial Device



F gure 4 ANA Measurement of waveguide Device

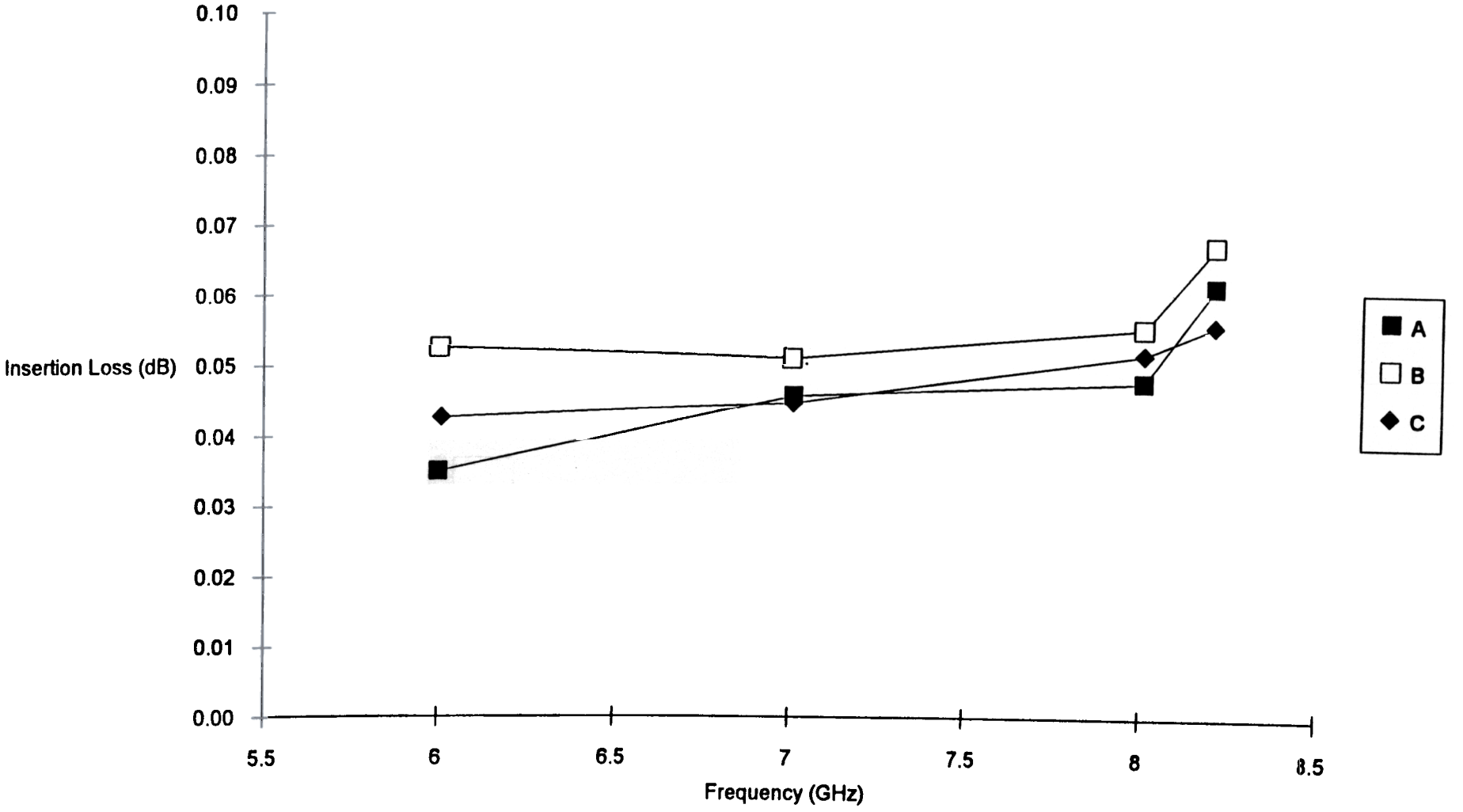


Figure 5. WG14 Adaptors Measured using Power Ratio Technique

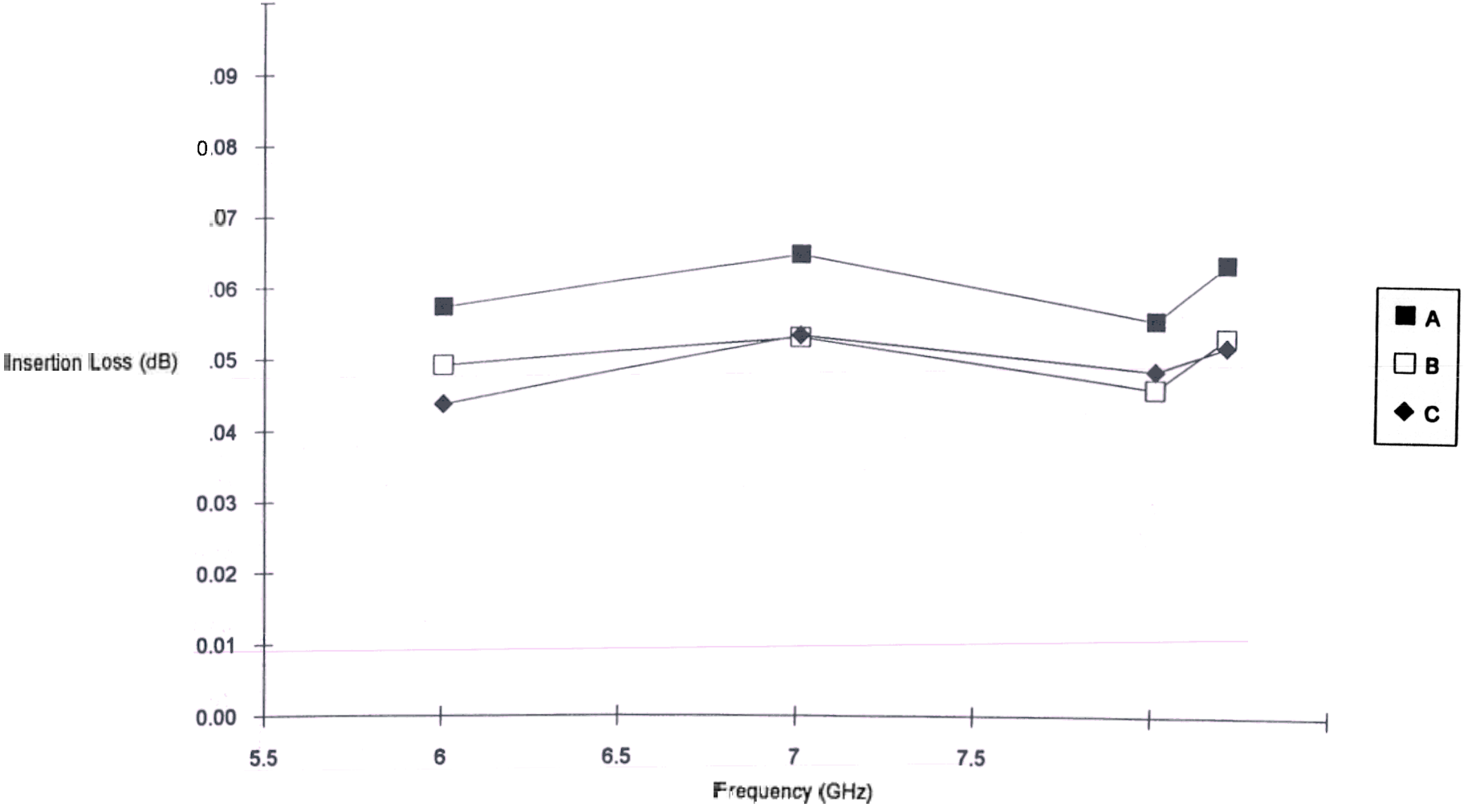


Figure 6. WG14 Adaptors Measured using adaptor Removal Technique

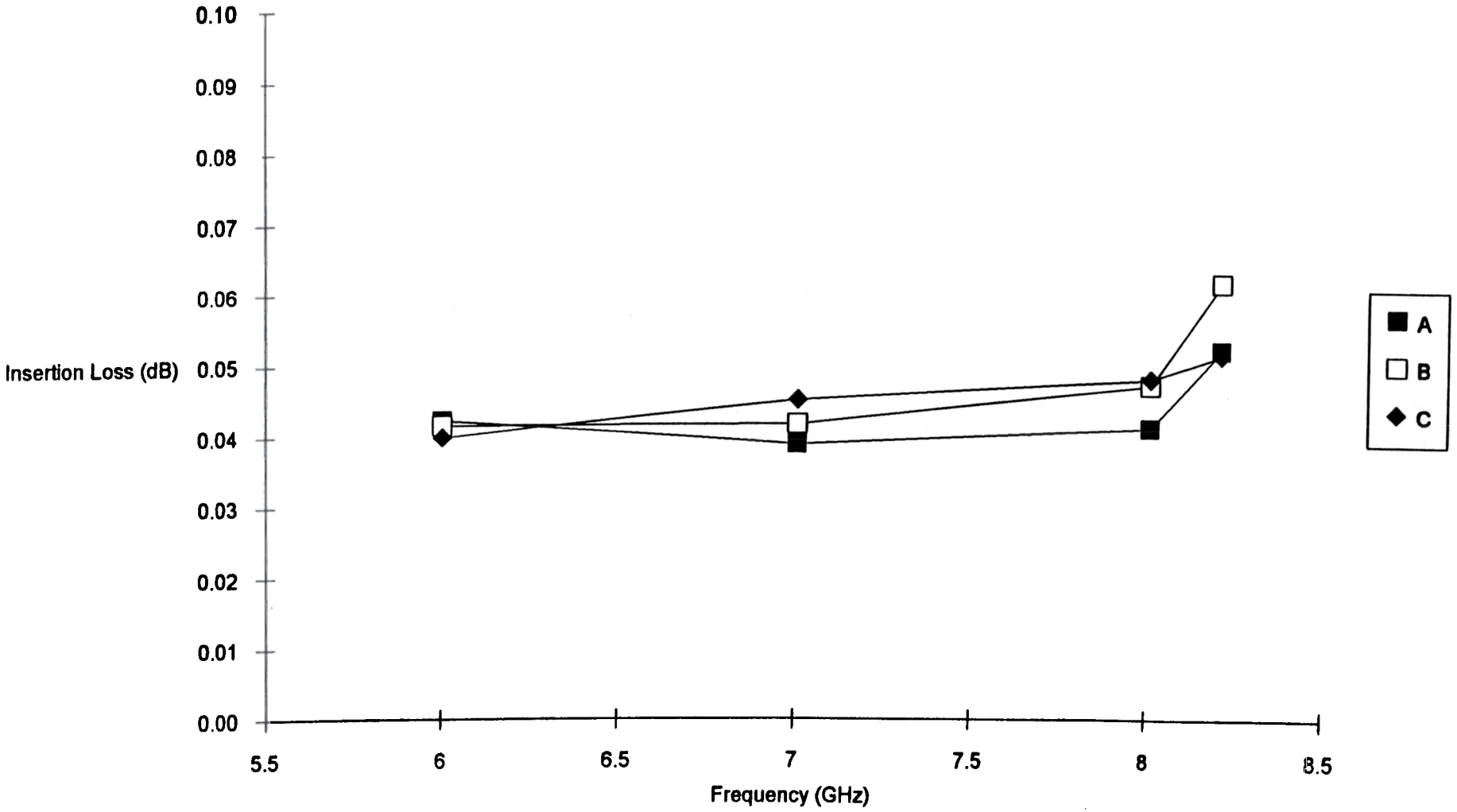


Figure 7. WG14 Adaptors Measured using Insertable Coaxial Device Technique

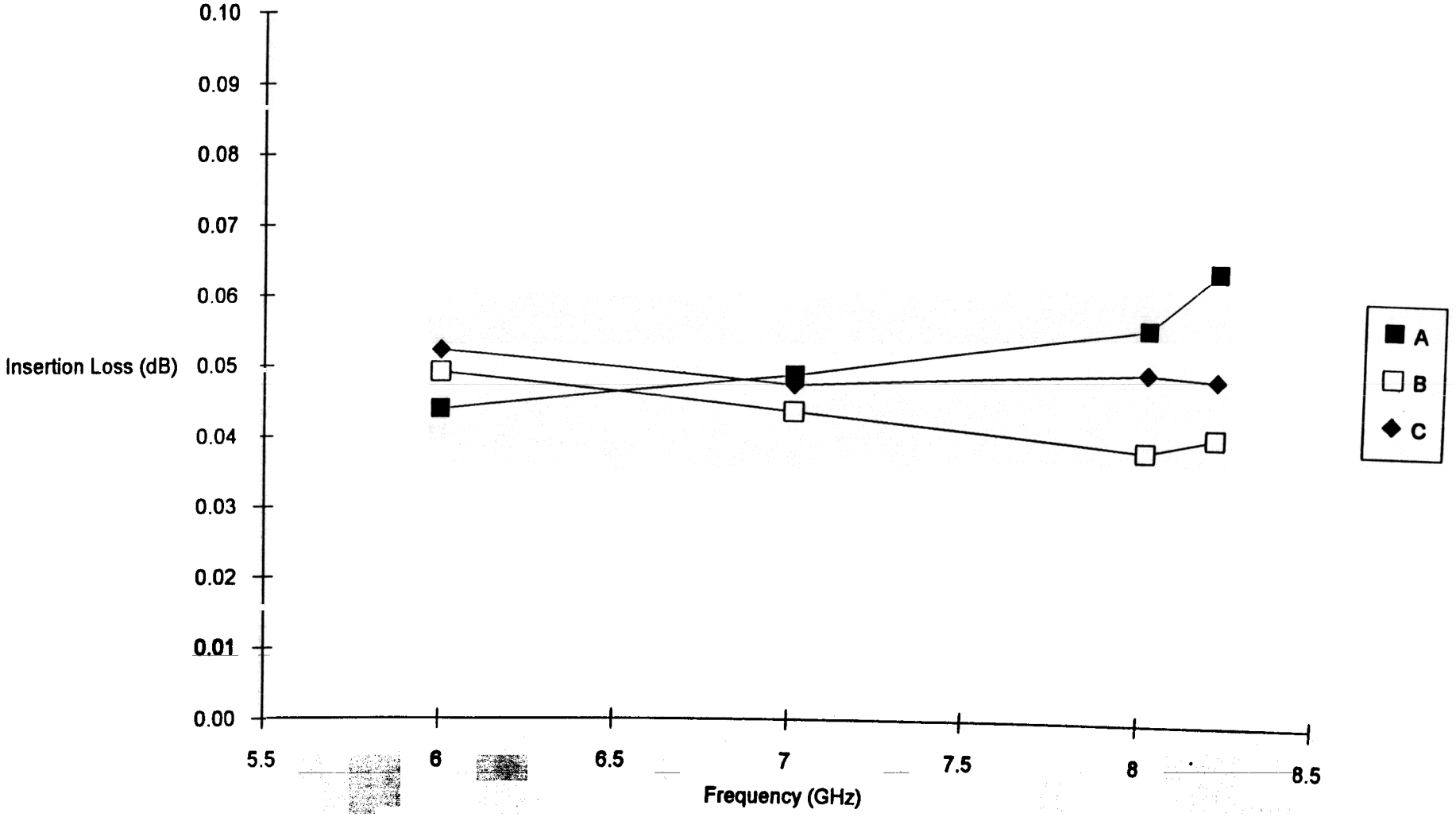


Figure 8. WG14 Adaptors Measured using Insertable Waveguide Device Technique

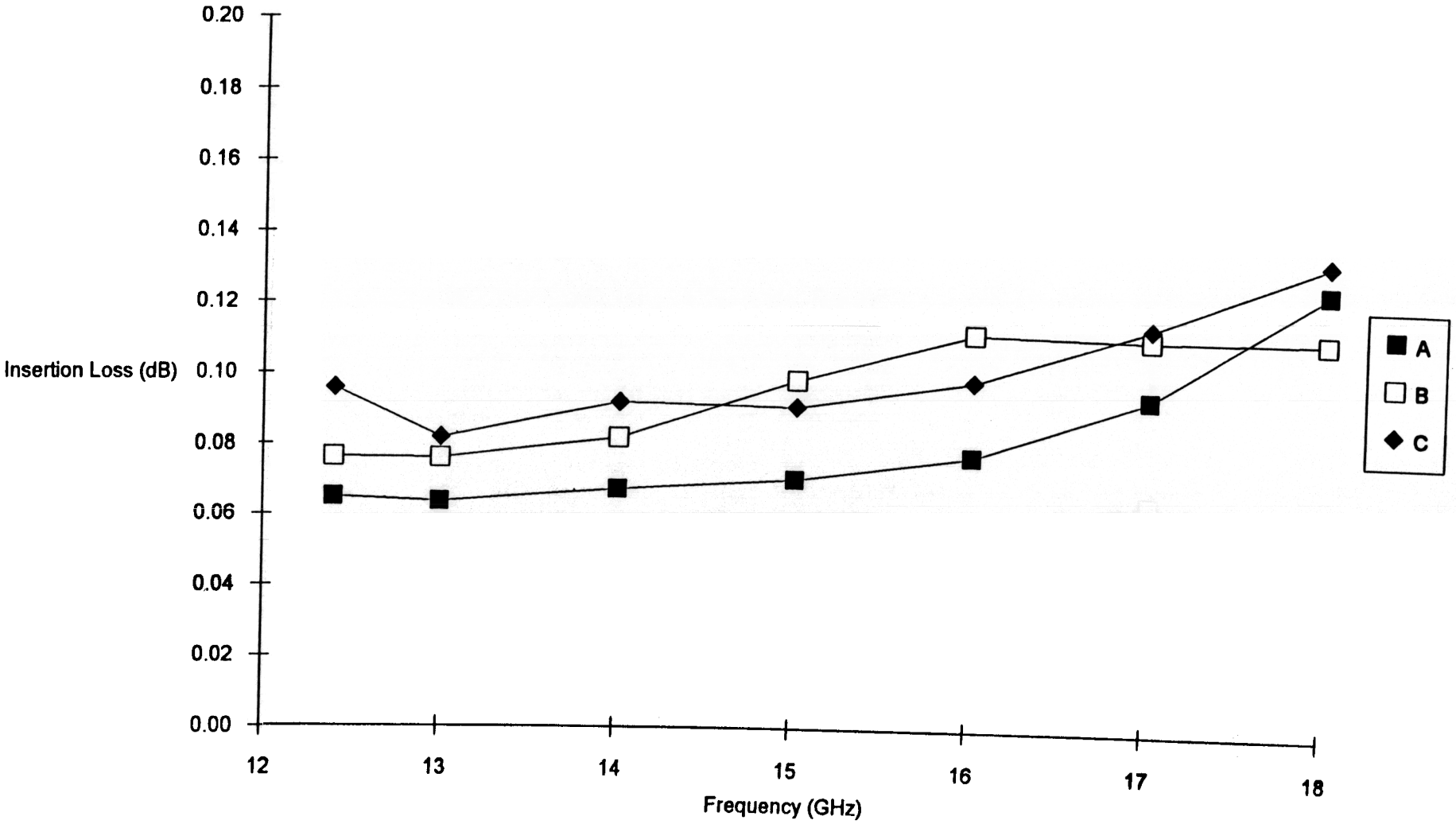


Figure 9. WG18 Adaptors Measured using Power Ratio Technique

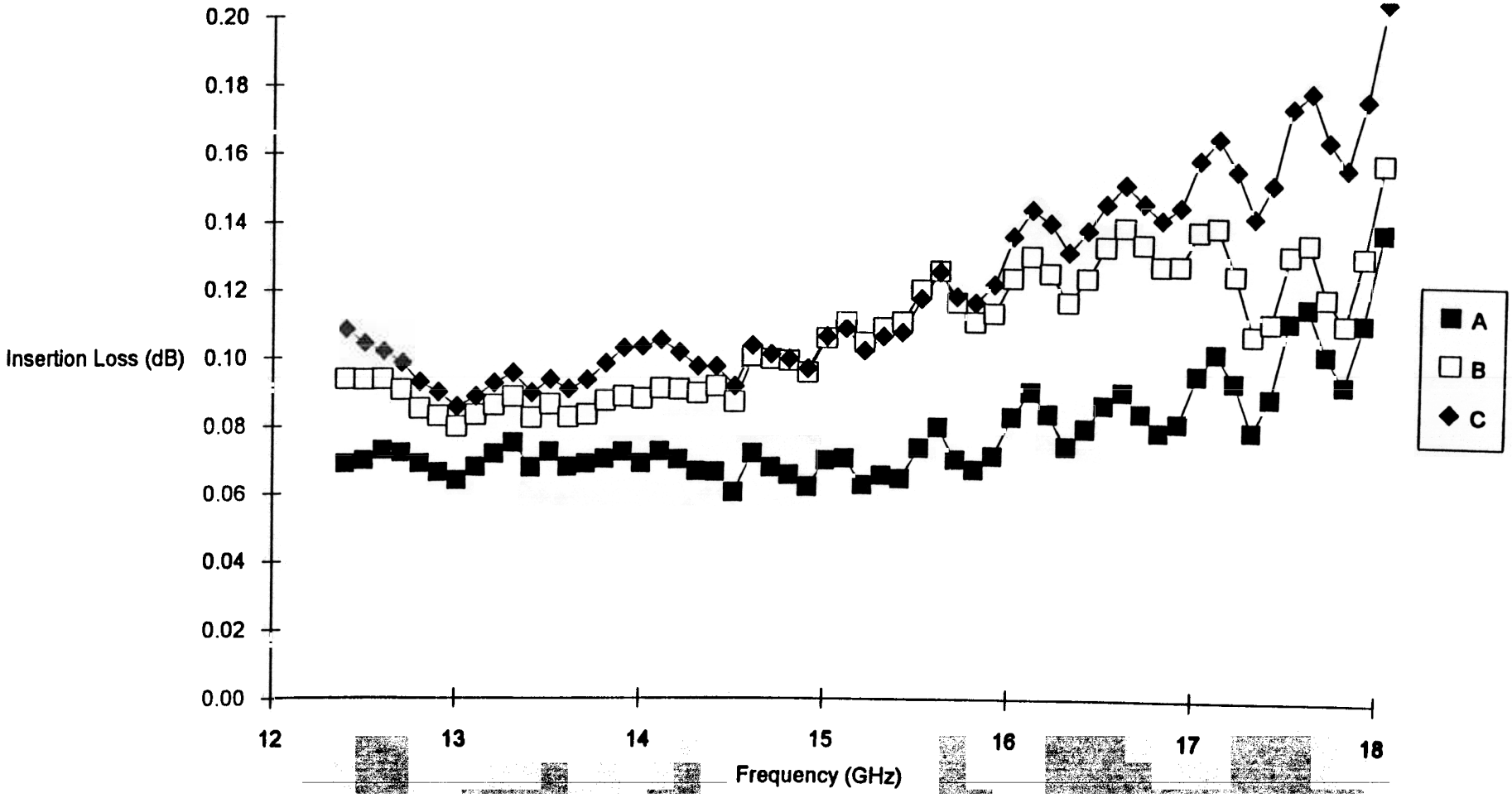


Figure 10. WG18 Adaptors Measured using Adaptor Removal Technique

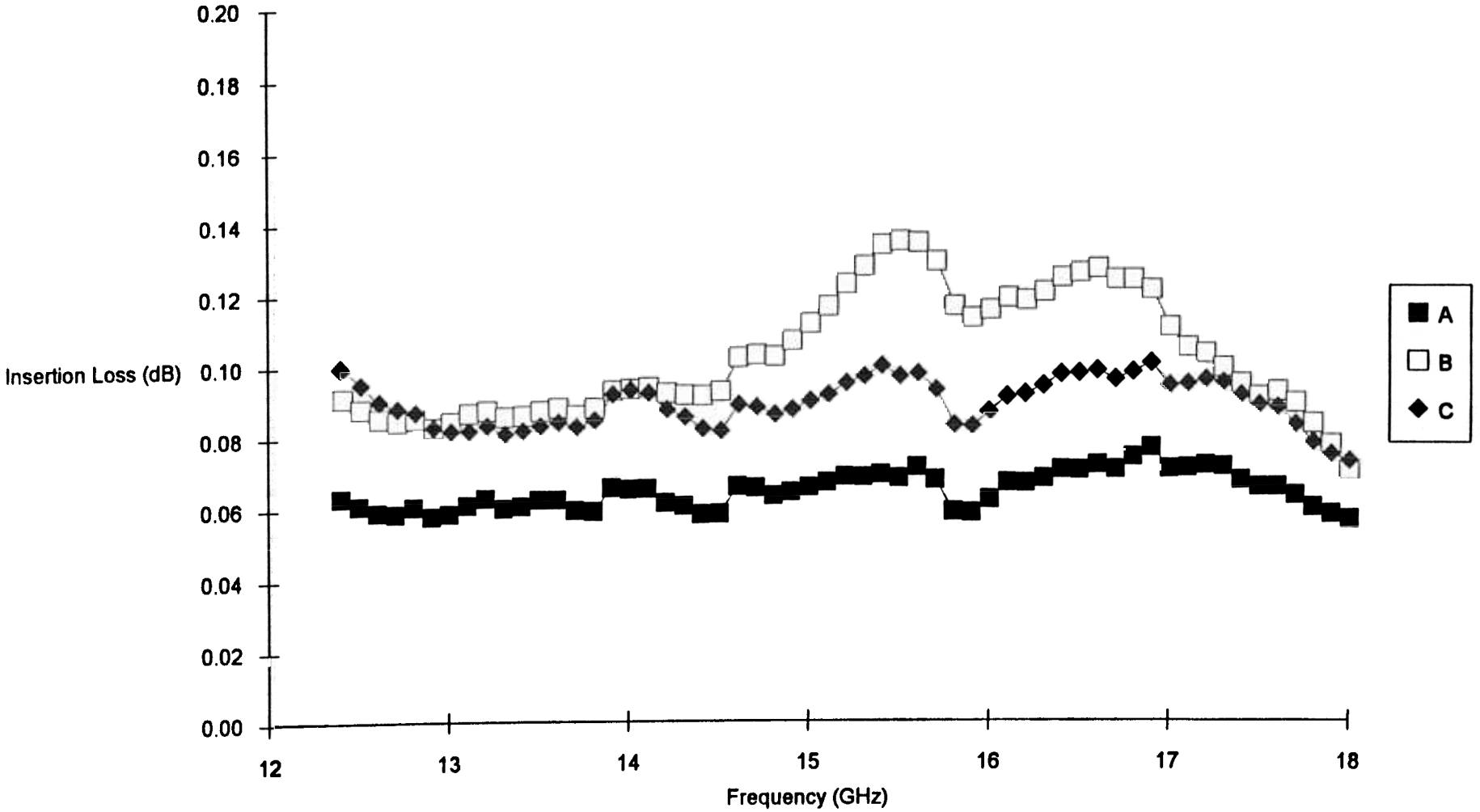


Figure 11. WG18 Adaptors Measured using Insertable Coaxial Device Technique

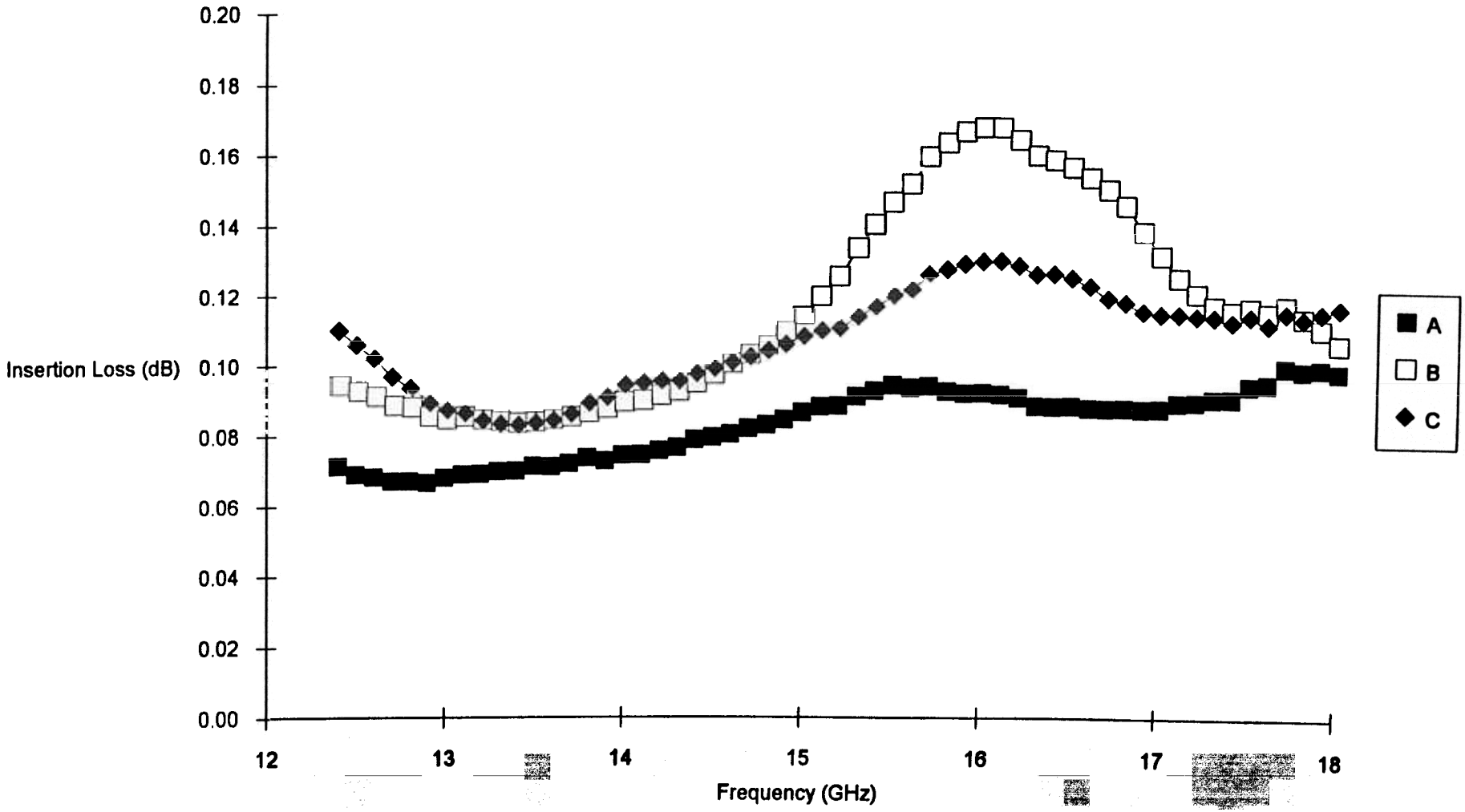


Figure 12. WG18 Adaptors Measured using Insertable Waveguide Device Technique

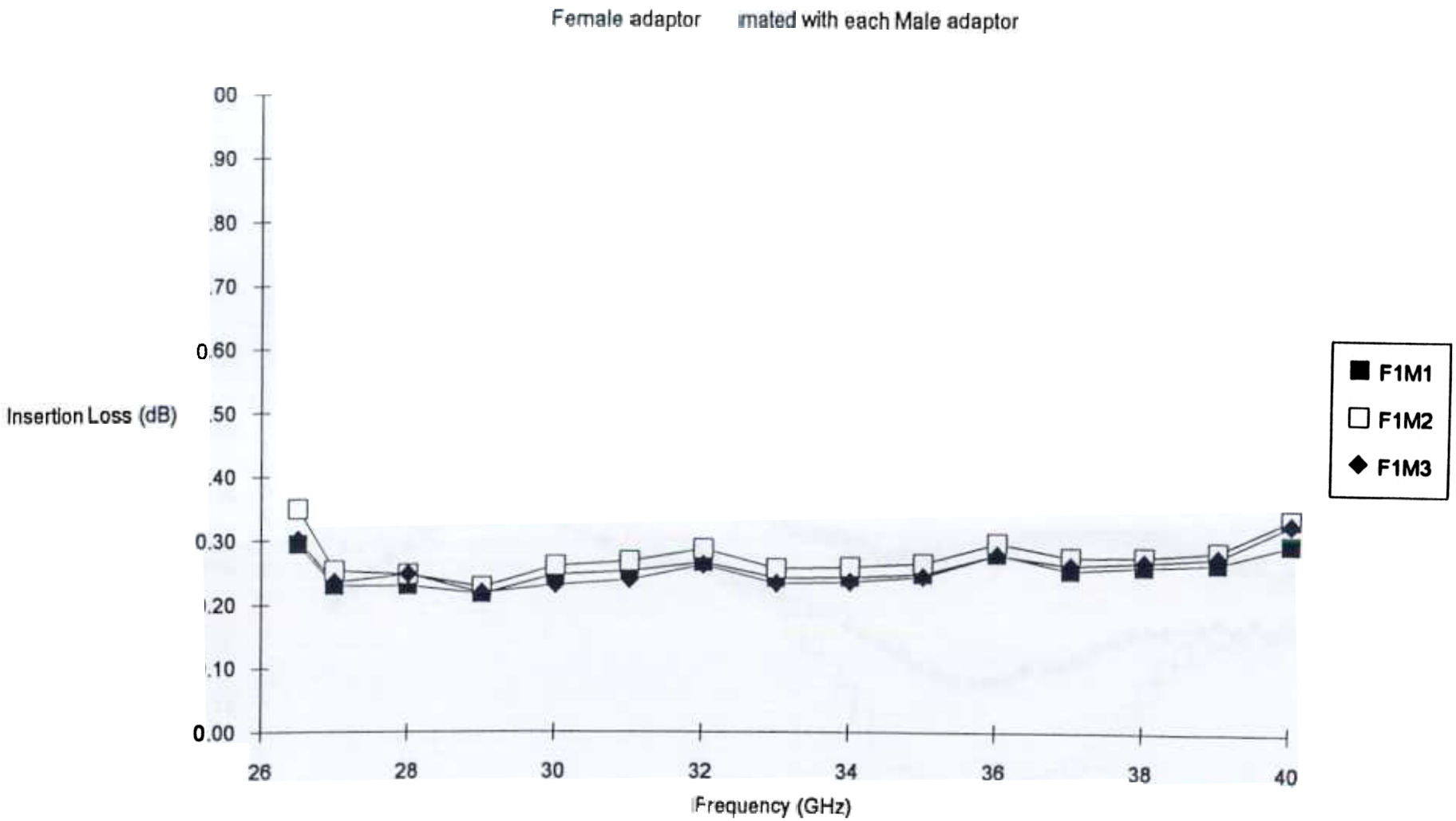


Figure 3a. Power Ratio Measurement of WG22 to K Adaptor Pairs

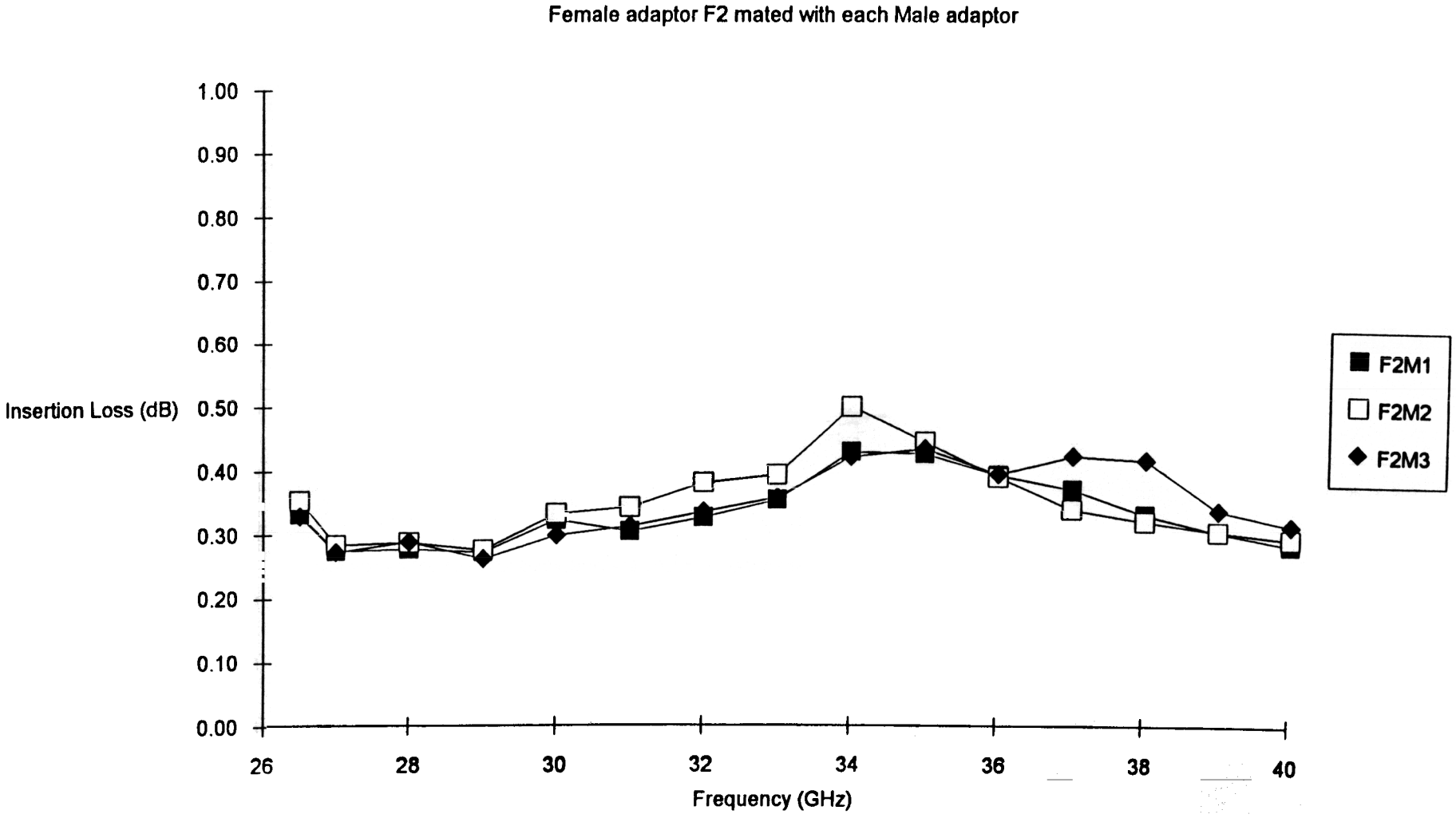


Figure 13b. Power Ratio measurement of WG22 to K Adaptor Pairs

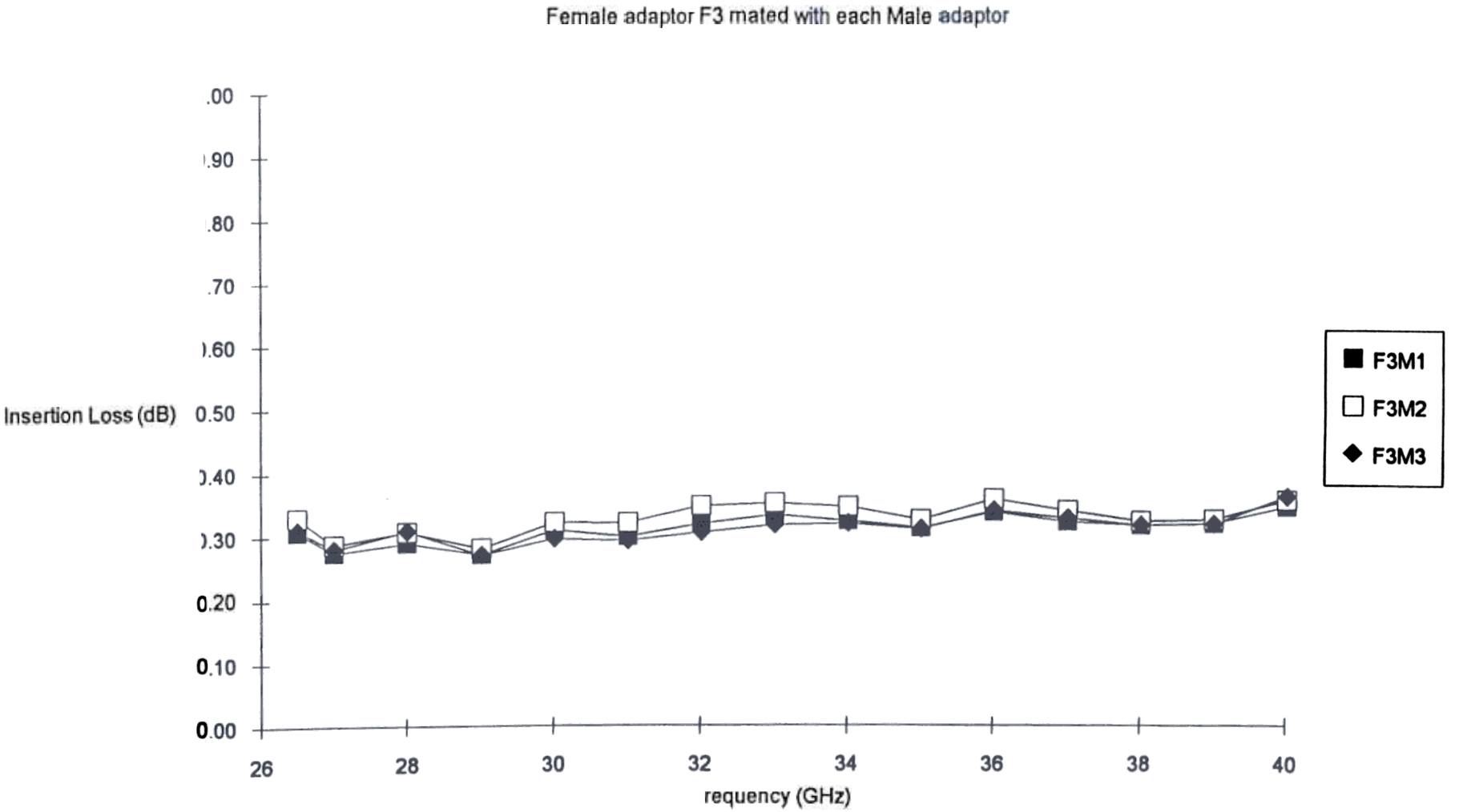


Figure 3c. Power Ratio measurement of WG22 to **K** Adaptor Pairs

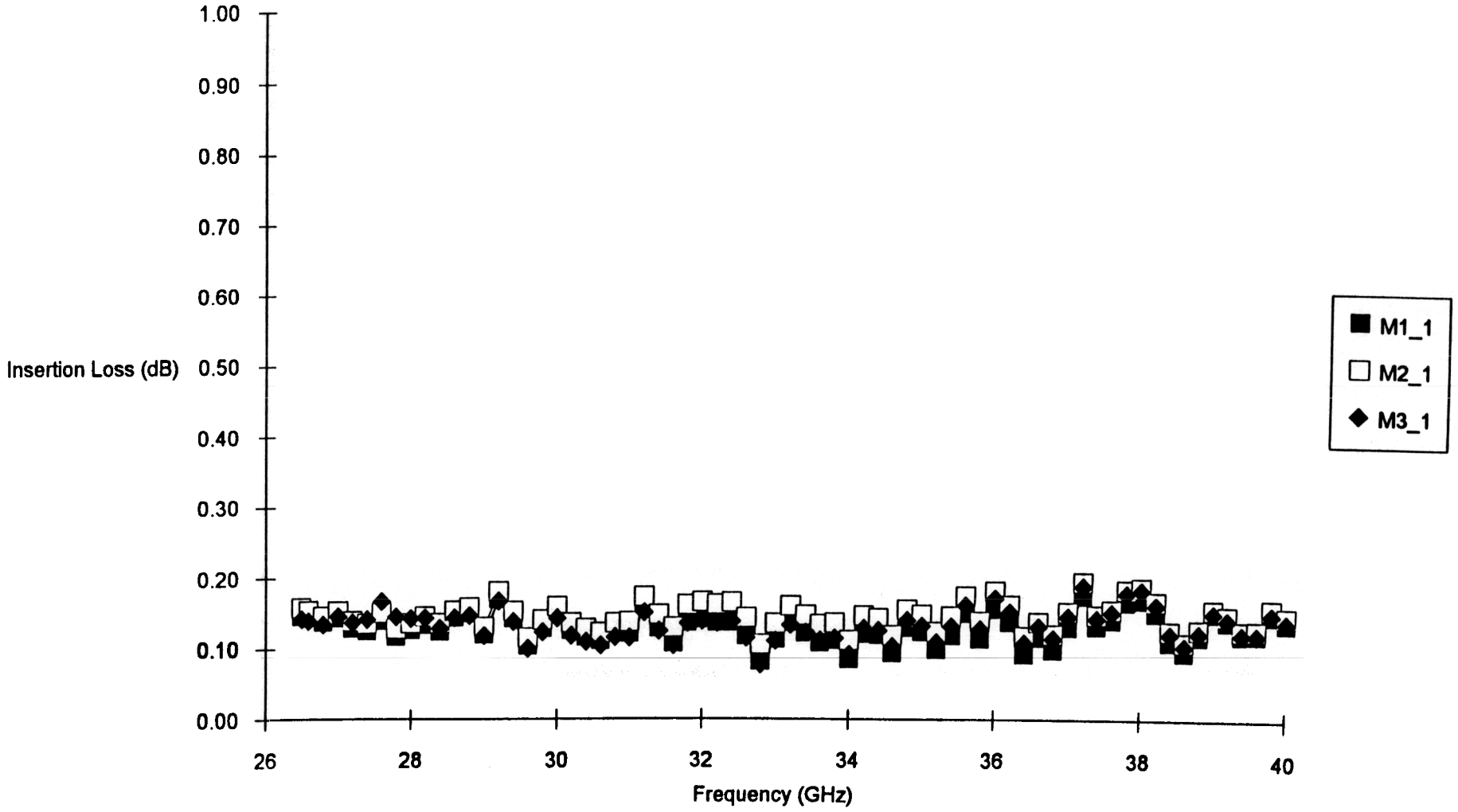


Figure 14a. Adaptor Removal measurements of WG22 to 'K' Male adaptors - M1 used as the Calibration Adaptor

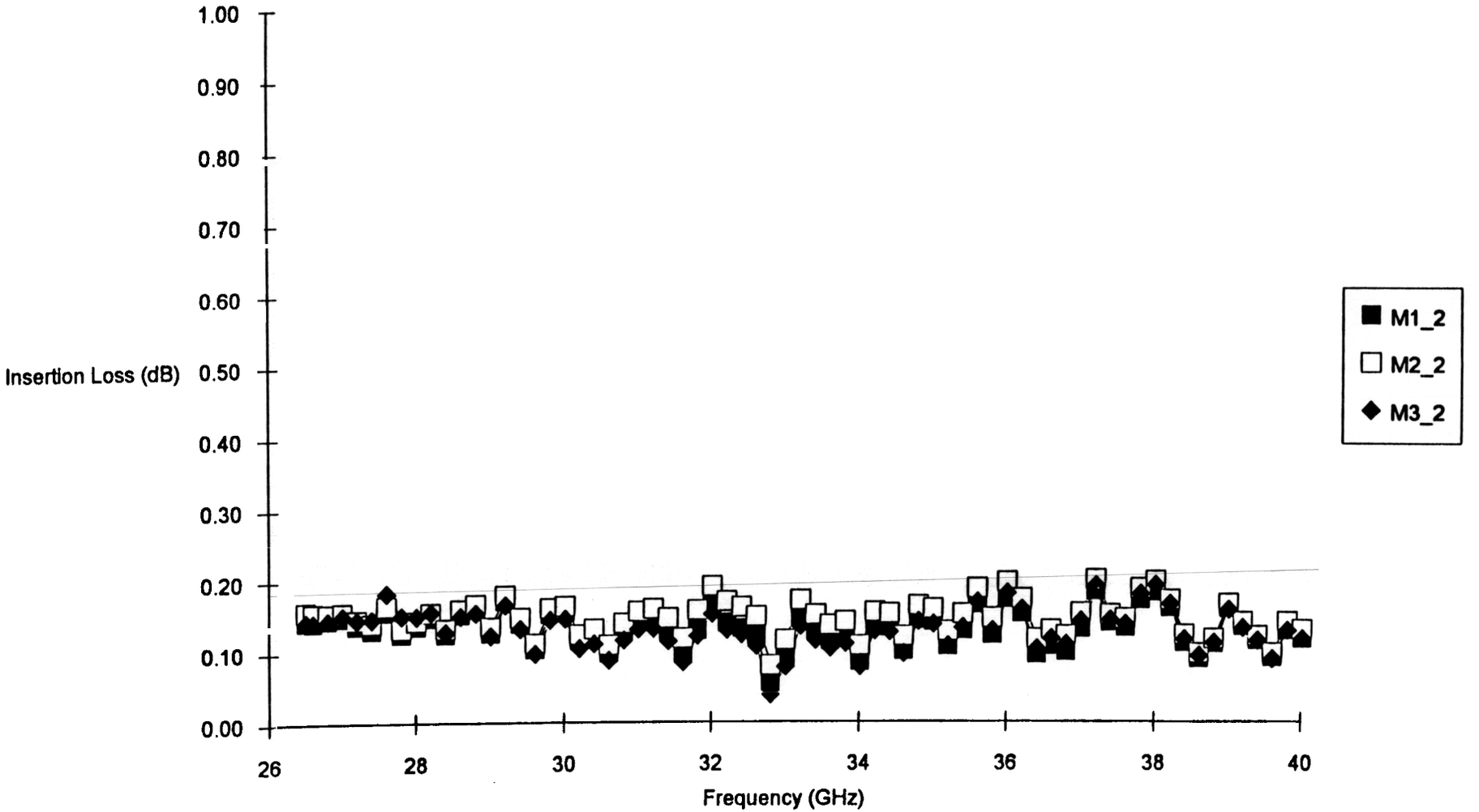


Figure 14b. Adaptor Removal measurements of WG22 to 'K' Male adaptors - M2 used as Calibration Adaptor

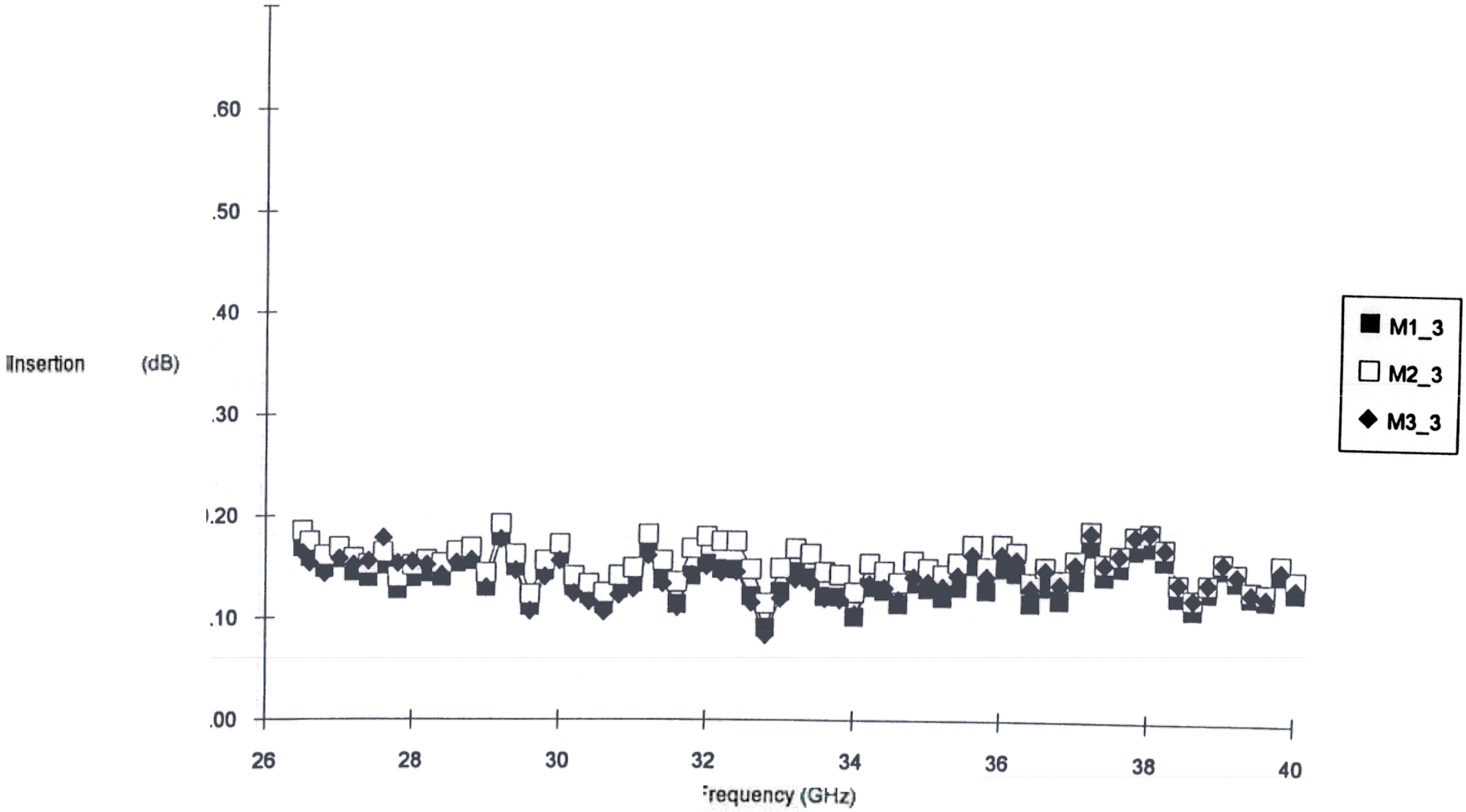


Figure 4c Adaptor emoval measurements of WG22 to 'K' Male adaptors M3 used Calibration Adaptor

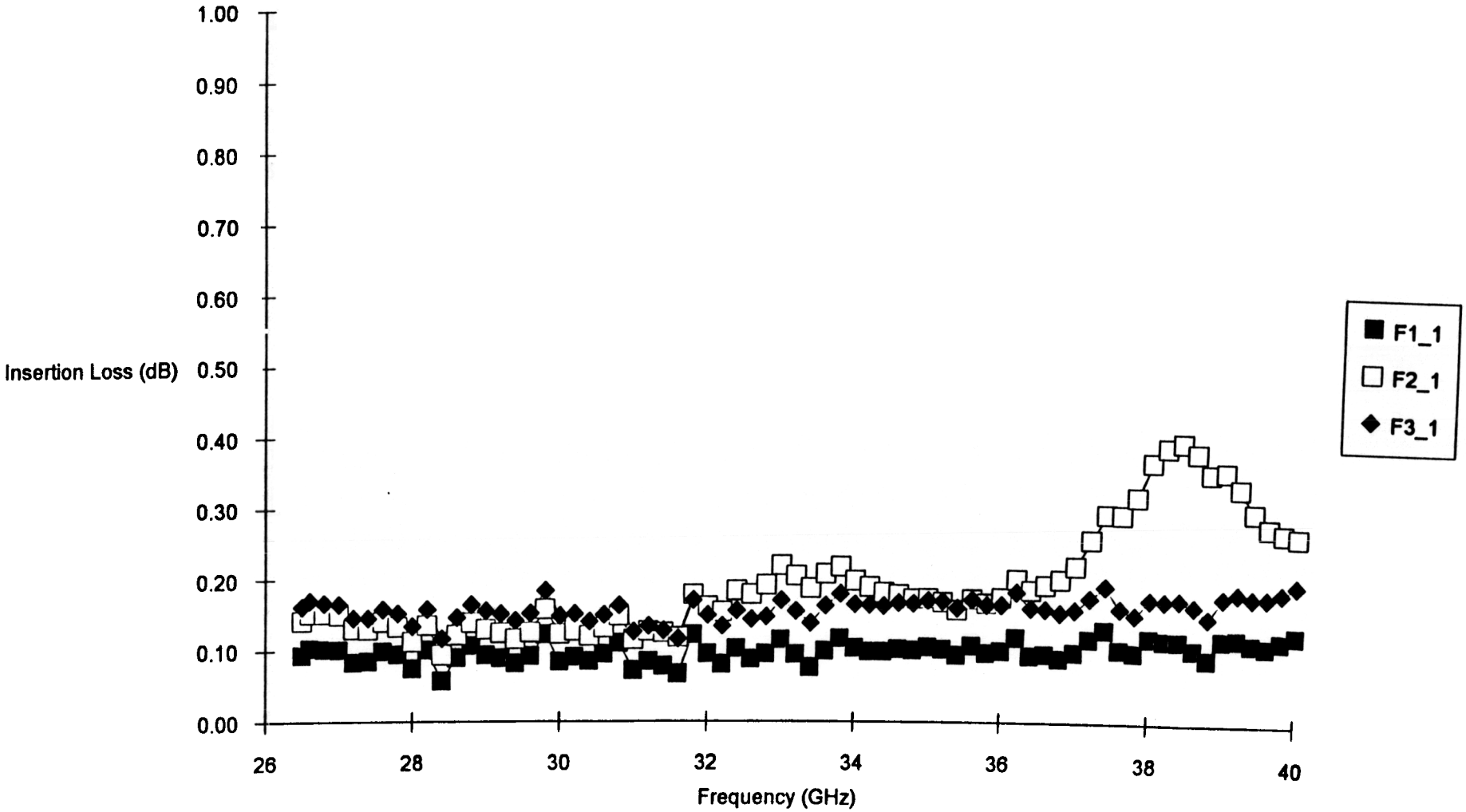


Figure 15a. Adaptor Removal measurements of WG22 to 'K' Female adaptors - F1 used as Calibration Adaptor

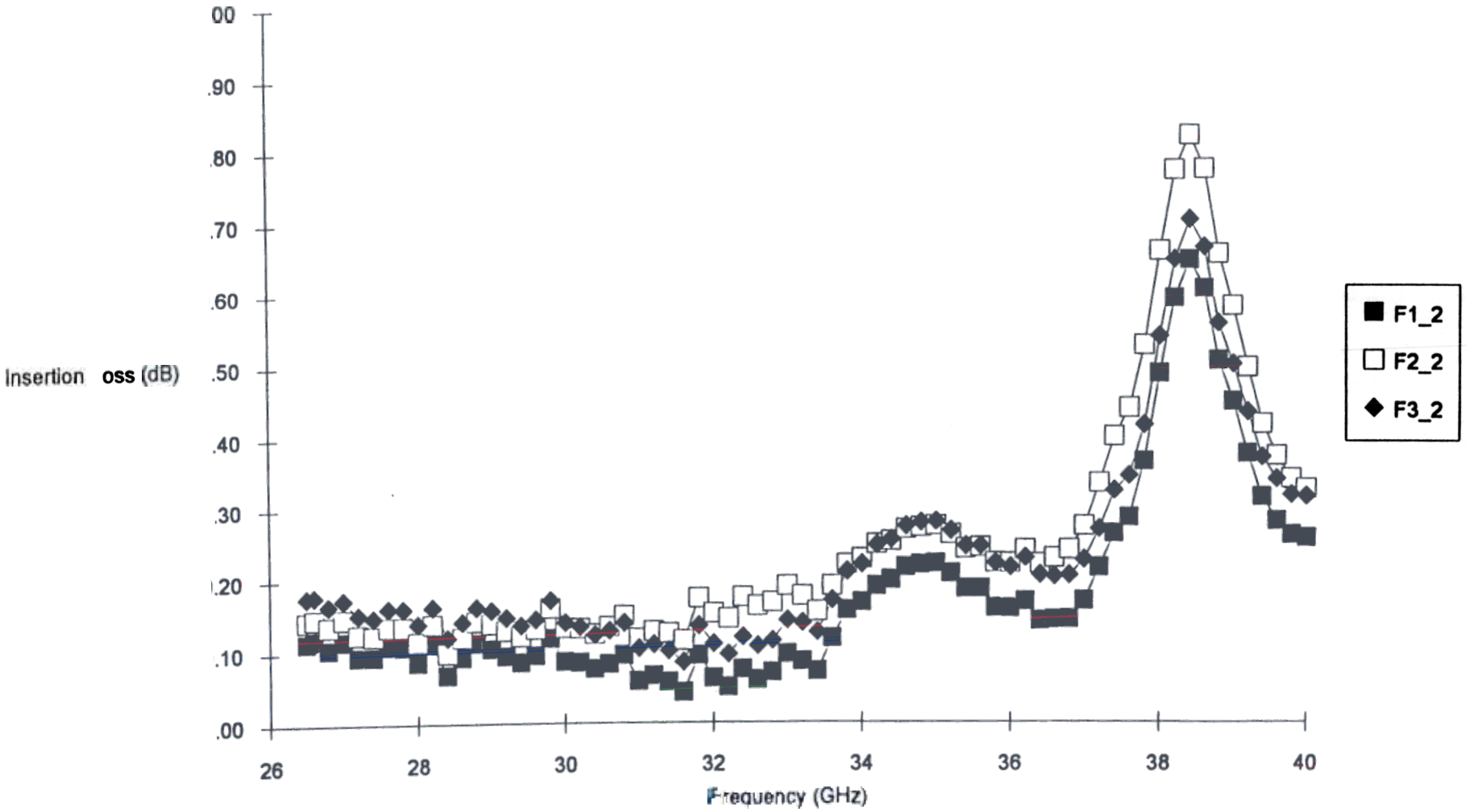


Figure 5b Adaptor Removal measurements of WG22 to 'K' Female adaptors F2 used Calibration Adaptor

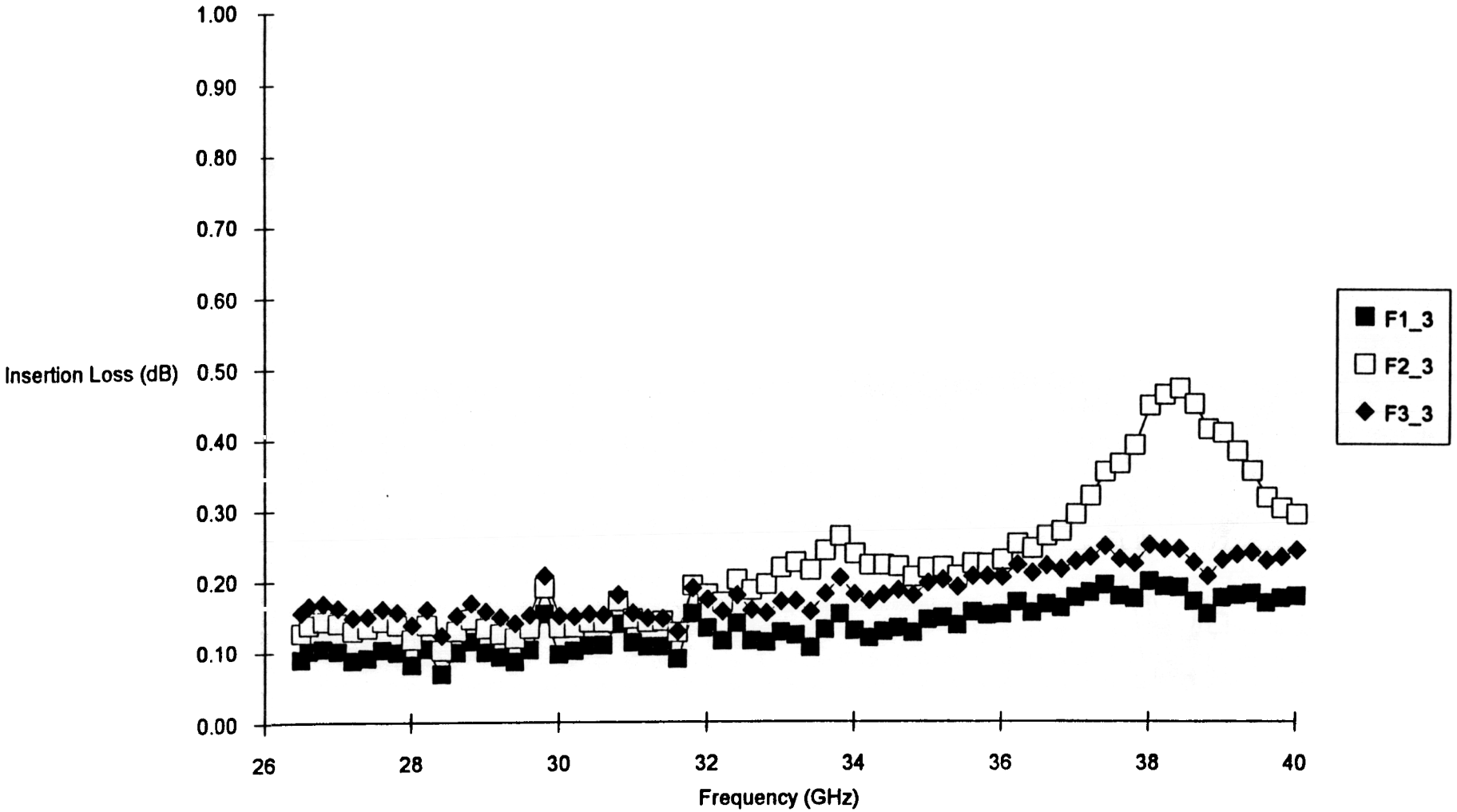


Figure 15c. Adaptor Removal measurements of WG22 to 'K' Female adaptors - F3 used as Calibration Adaptor

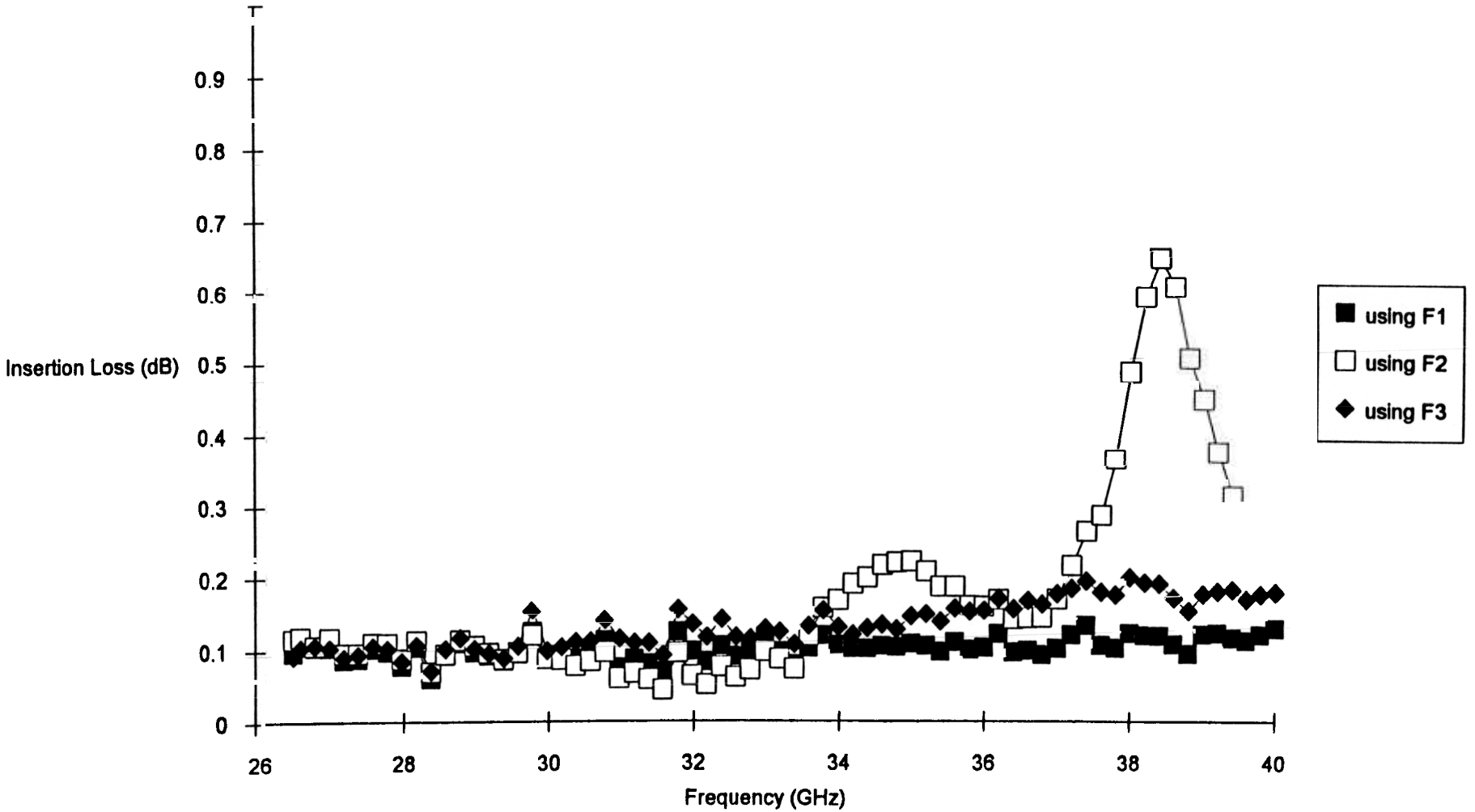


Figure 16. Comparison of Adaptor Removal measurements on WG22 to 'K' Female Adaptor F1

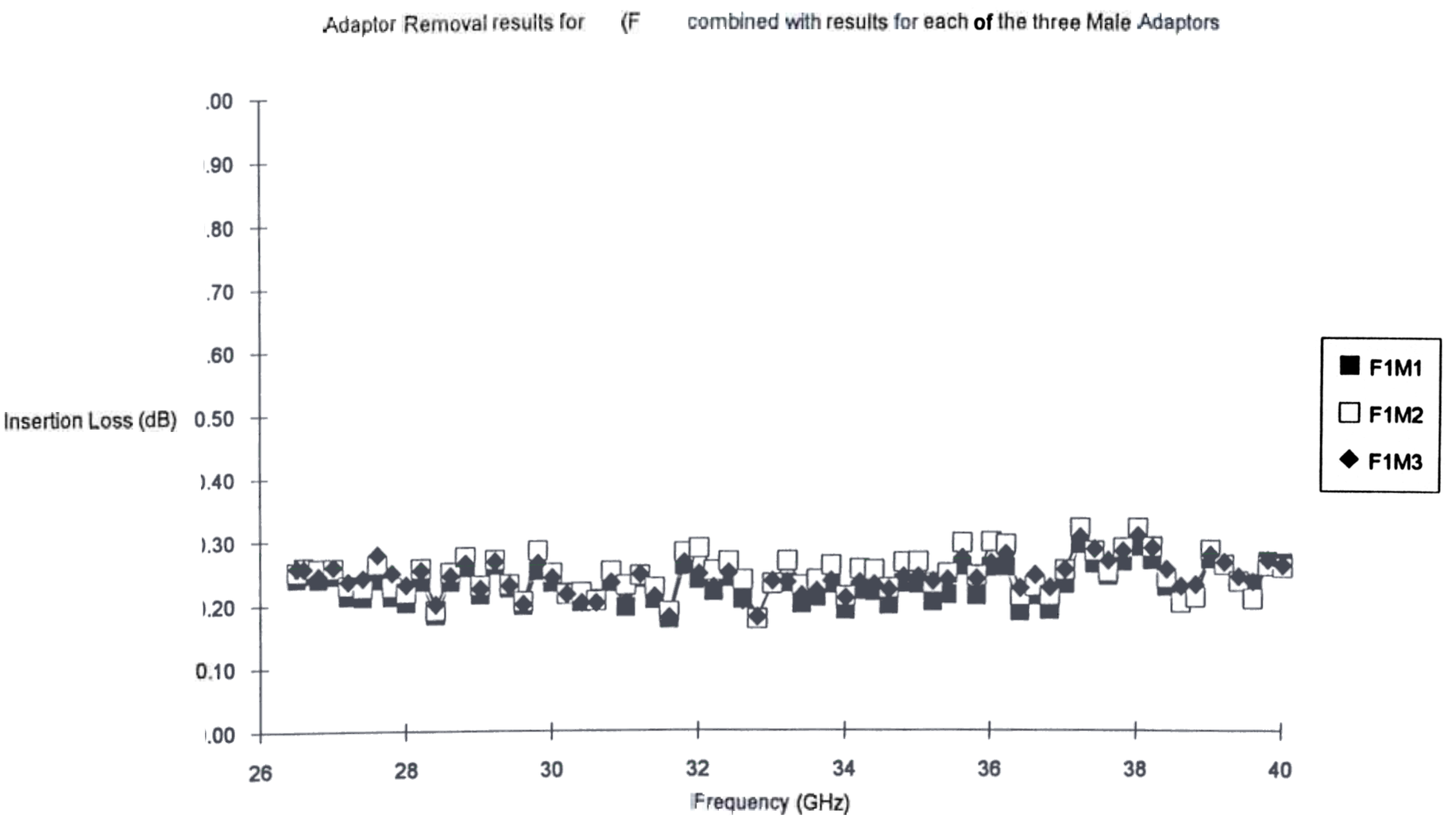


Figure 7a. Combined Insertion Loss of WG22 to 'K' Adaptor Pairs F1M1 F1M2 F1M3

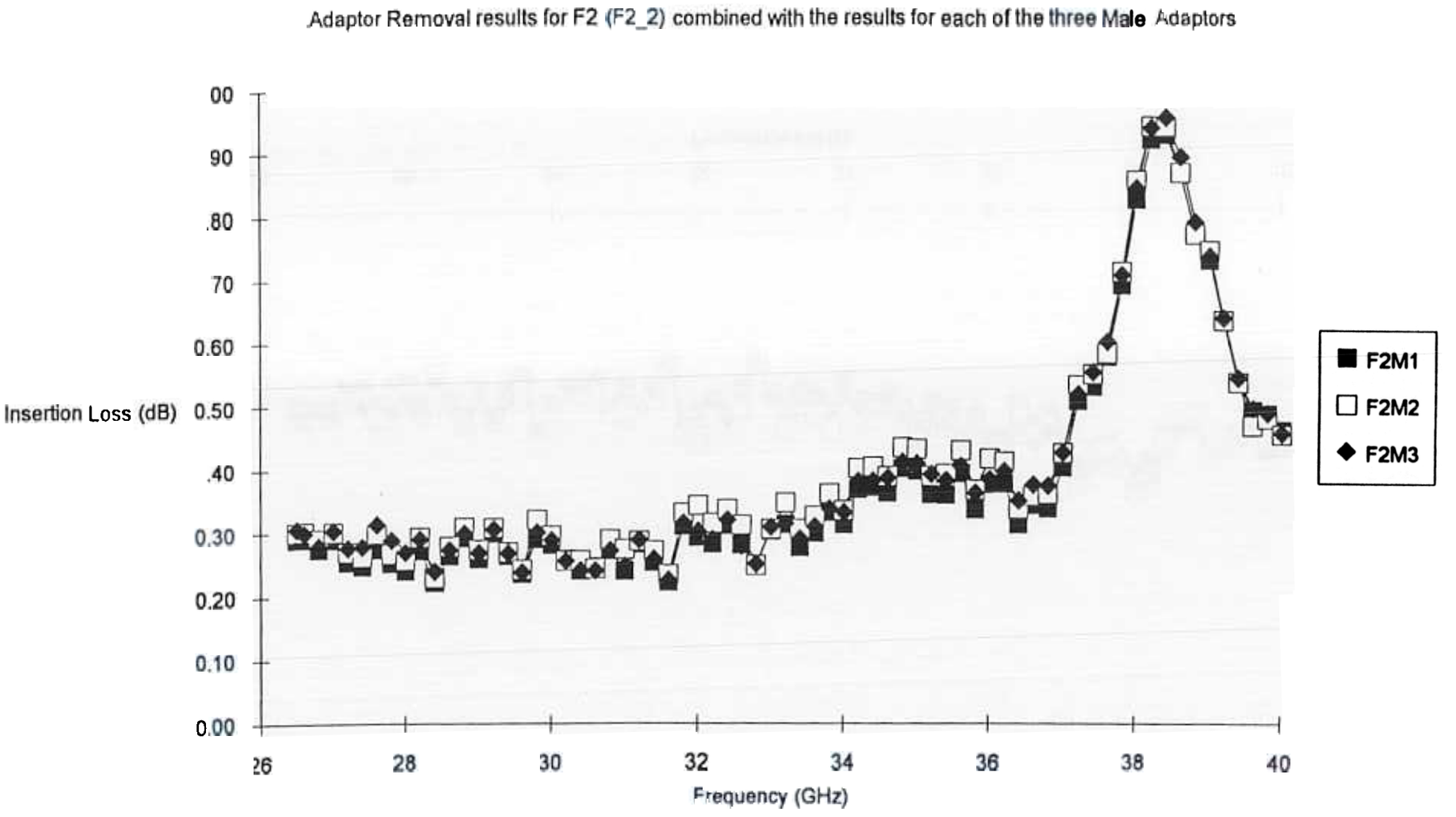


Figure 7b. Combined Insertion Loss of WG22 to 'K' Adaptor Pairs F2M1 F2M2 F2M3

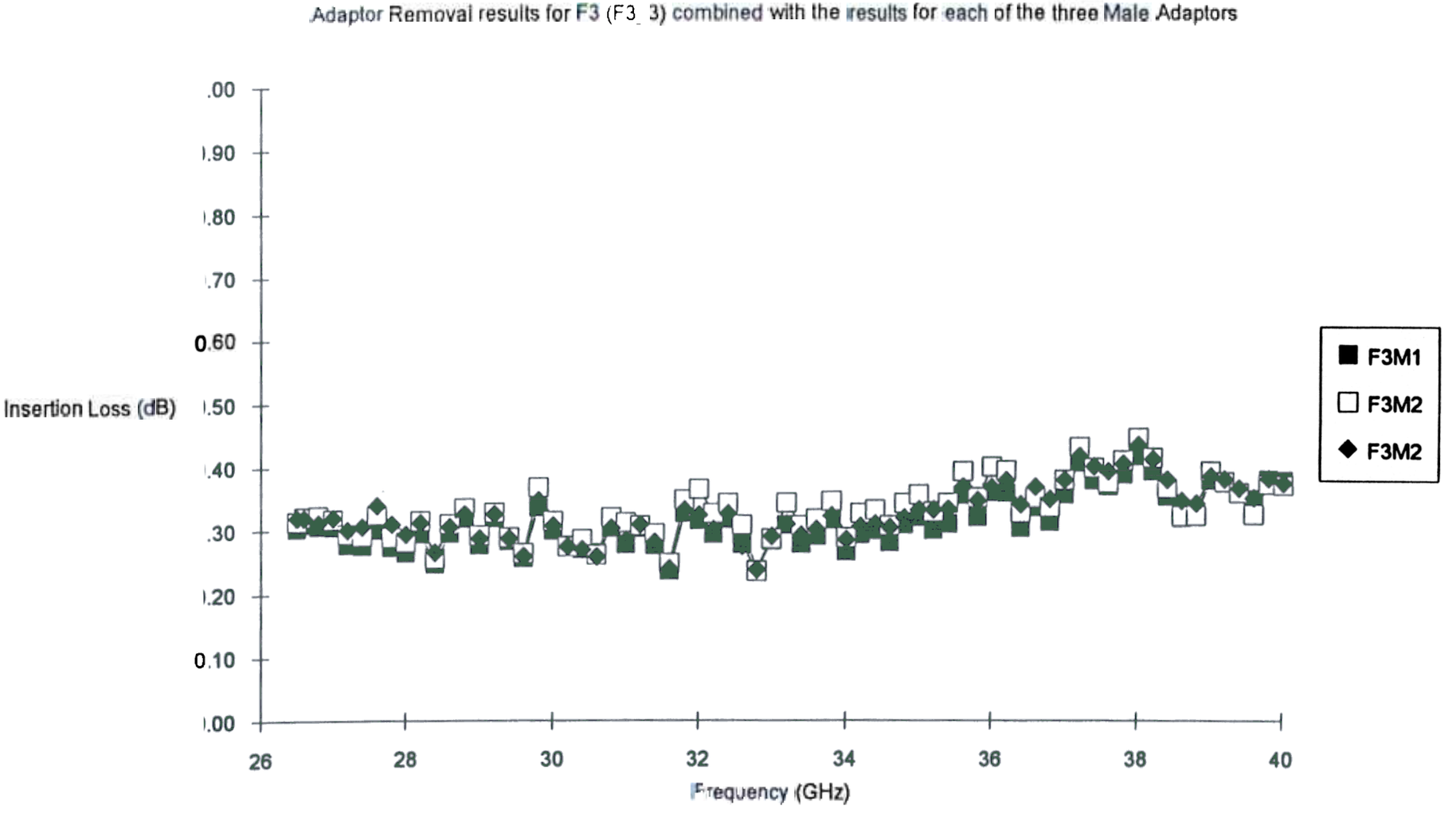


Figure 7c. Combined Insertion Loss of Adaptor Pairs F3M1, F3M2 F3M3

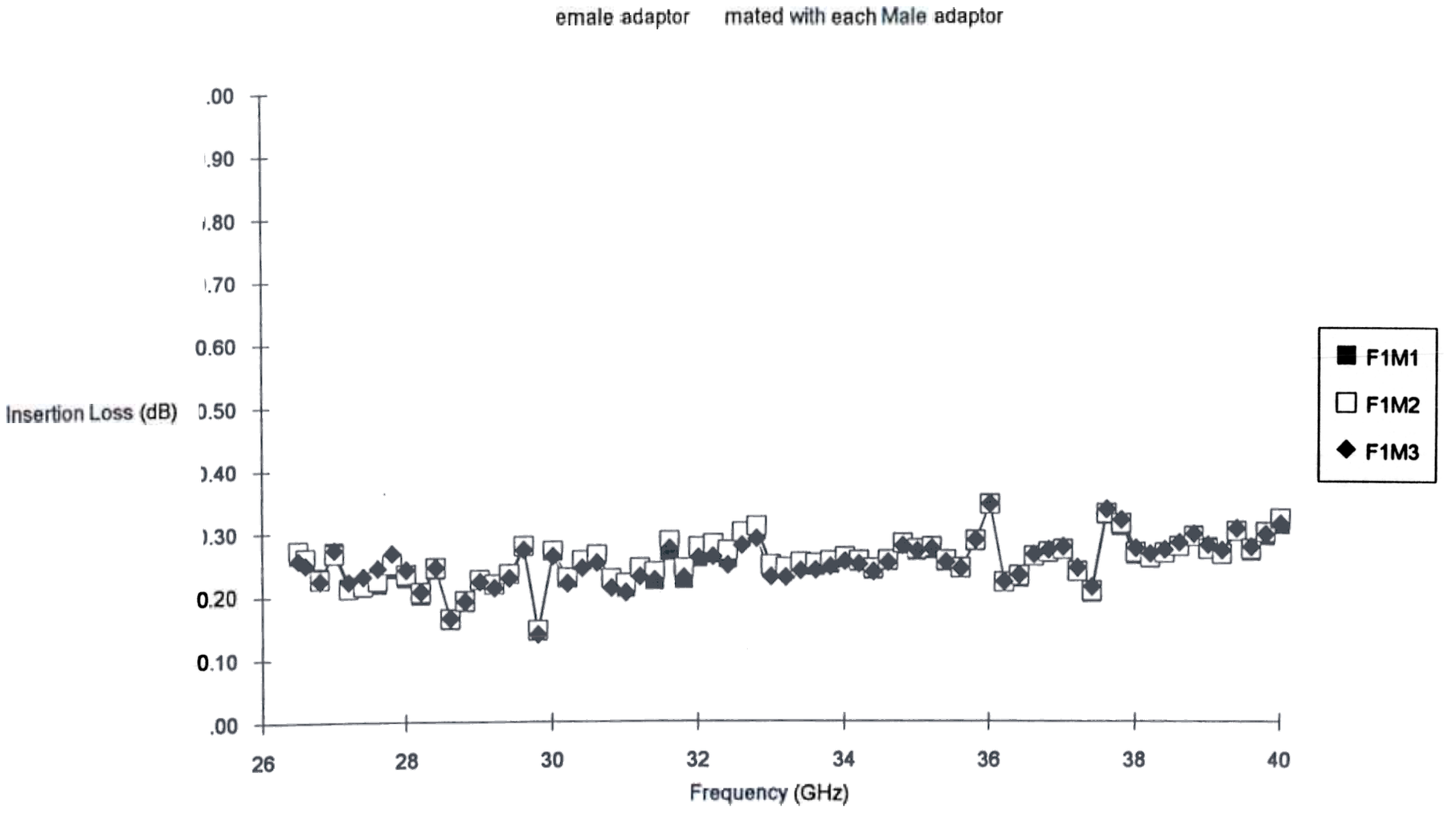


Figure 18a. Insertable Coaxial Device measurement of WG22 to K Adaptors

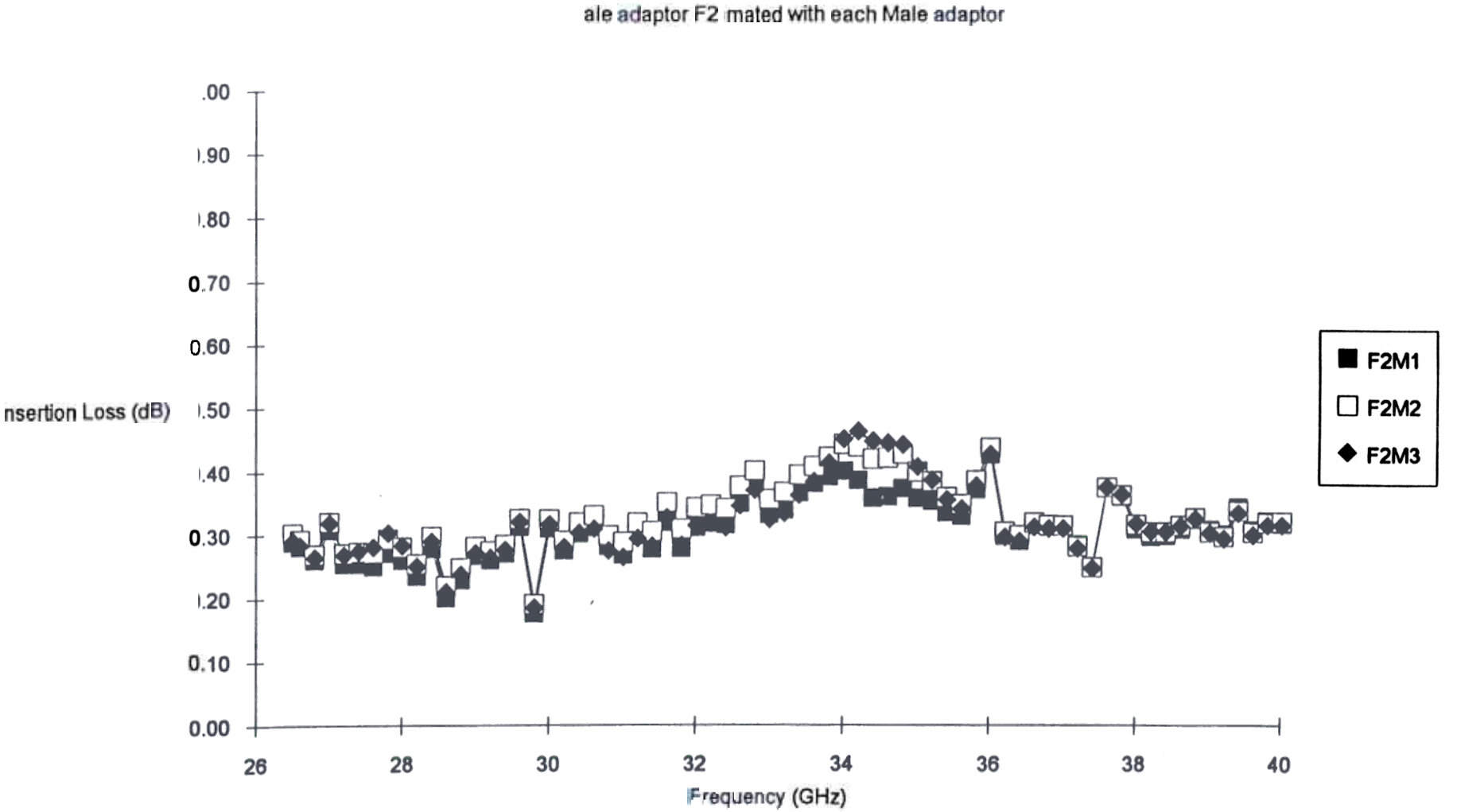


Figure 18b. Insertable Coaxial Device measurement of WG22 to K Adaptors

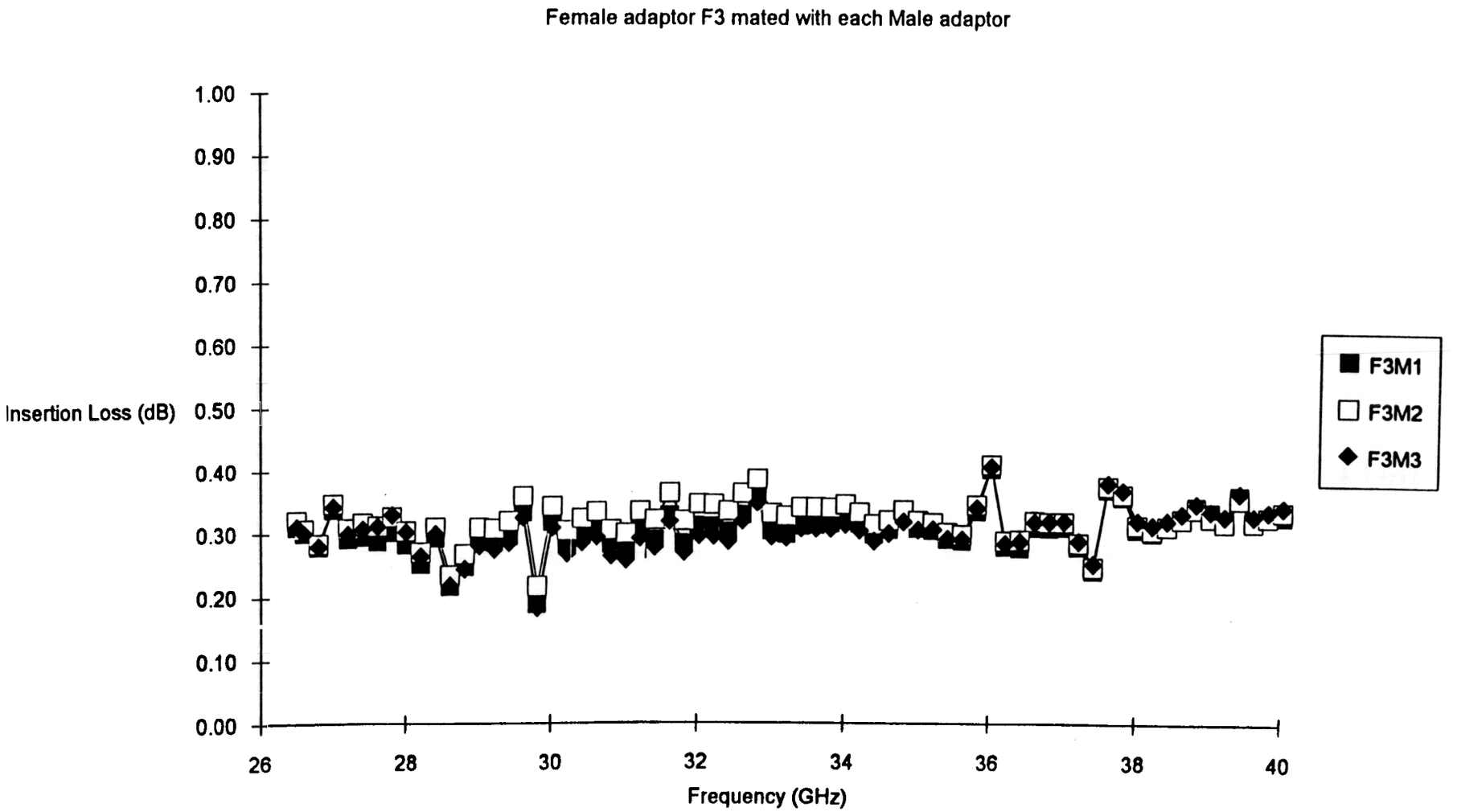


Figure 18c. Insertable Coaxial Device measurement of WG22 to K Adaptors

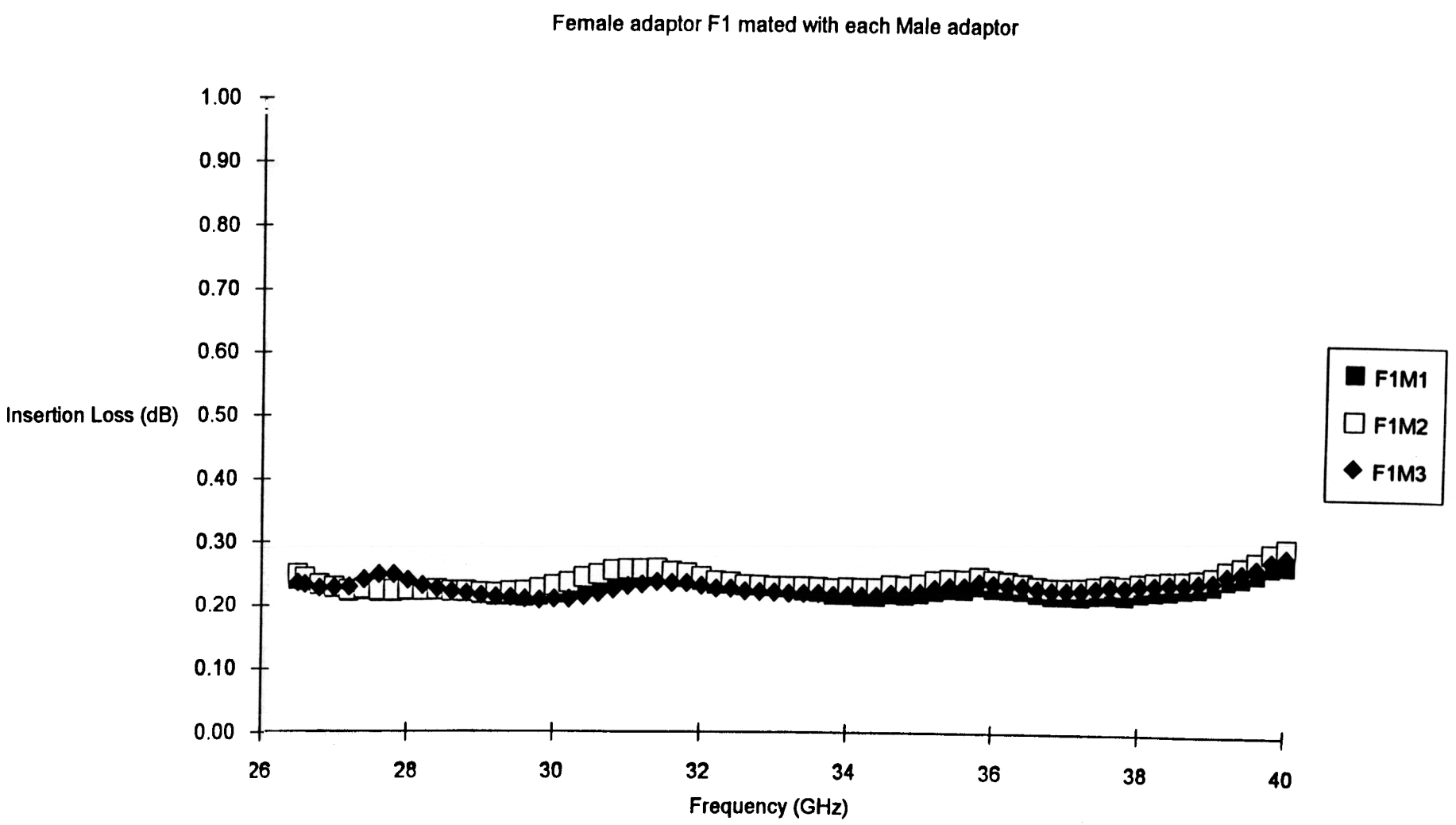


Figure 19a. Insertable Waveguide Device measurements of WG22 to K Adaptors

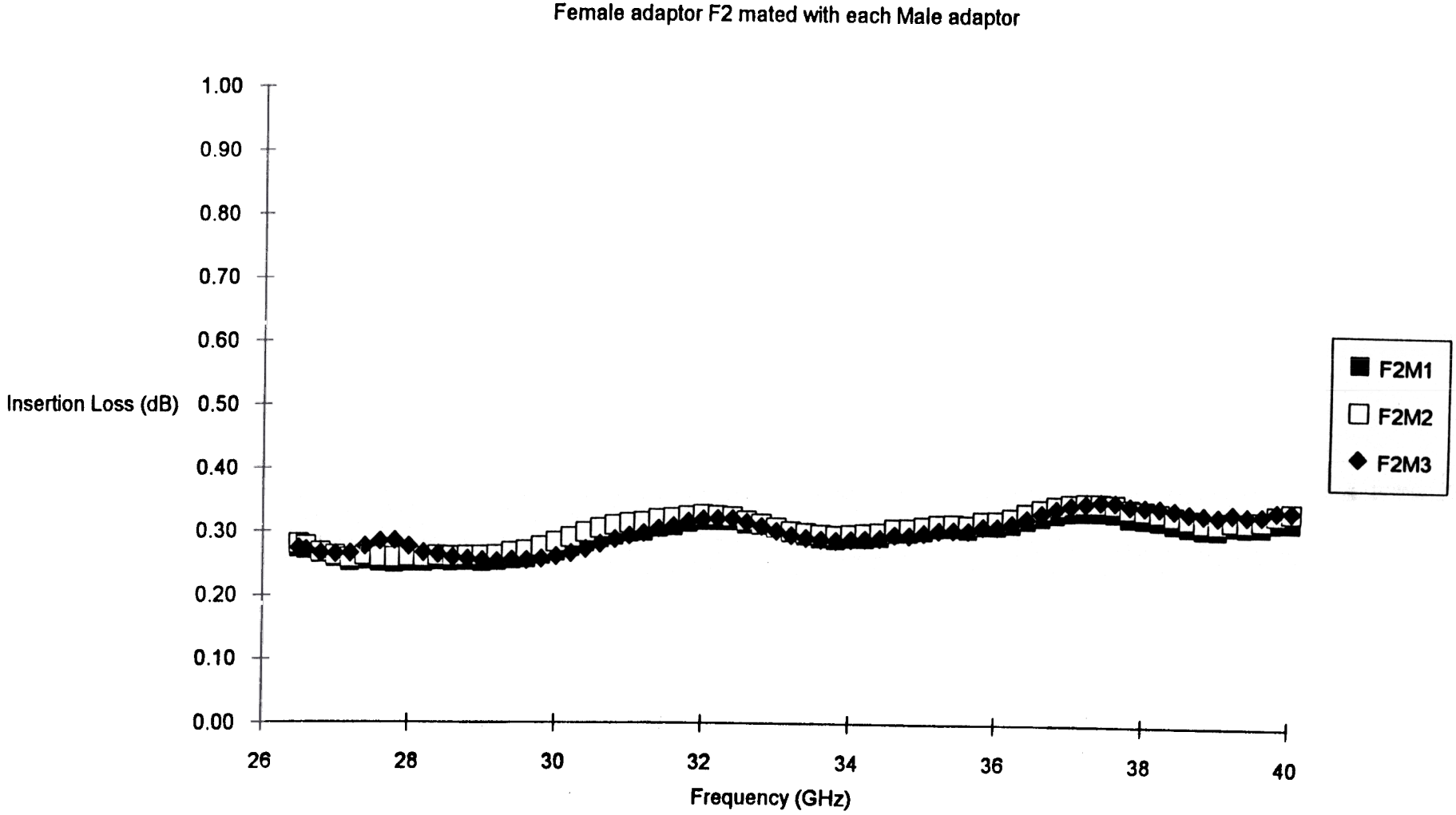


Figure 19b. Insertable Waveguide Device measurements of WG22 to K Adaptors

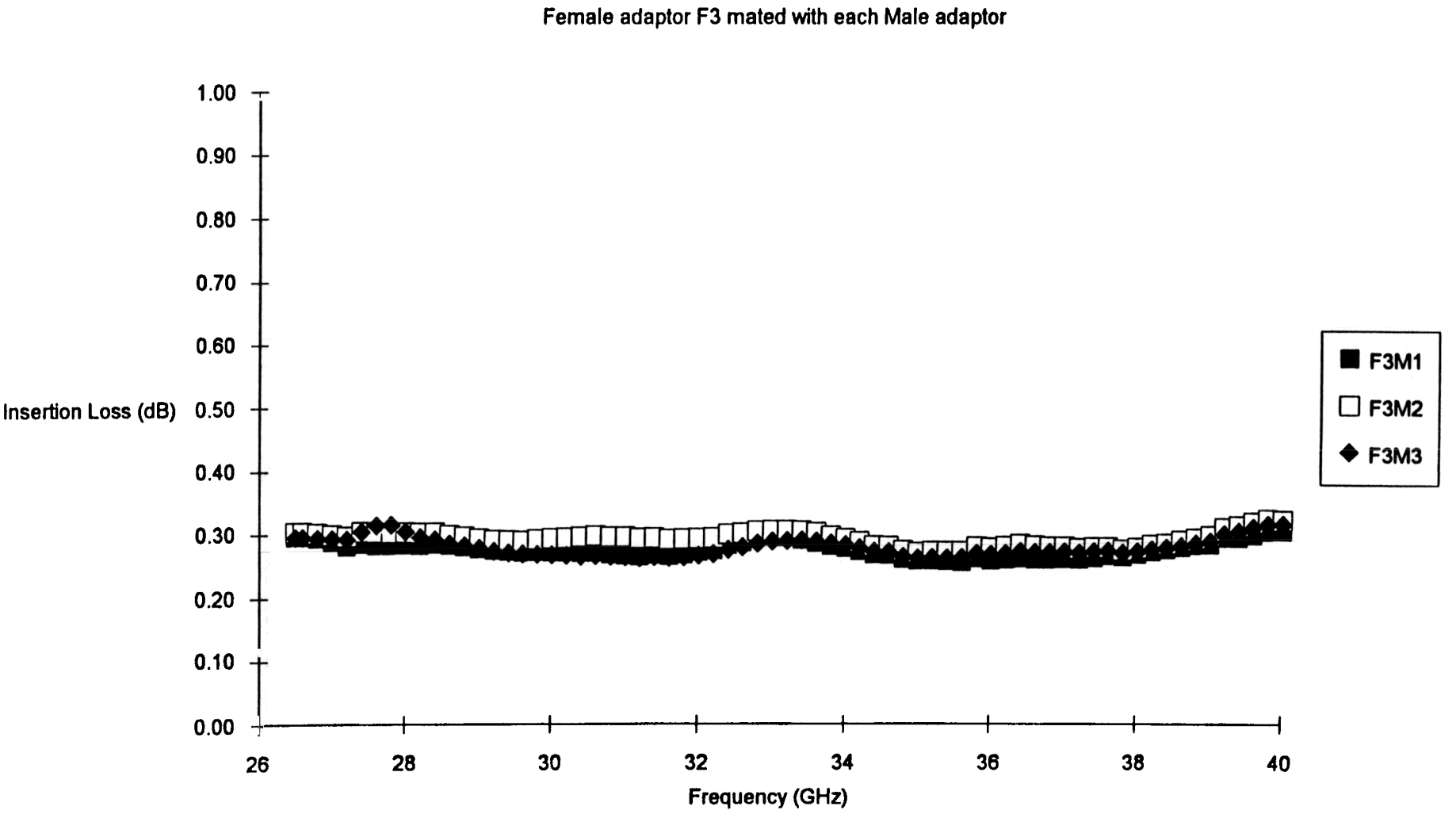


Figure 19c. Insertable Waveguide Device measurements of WG22 to K Adaptors

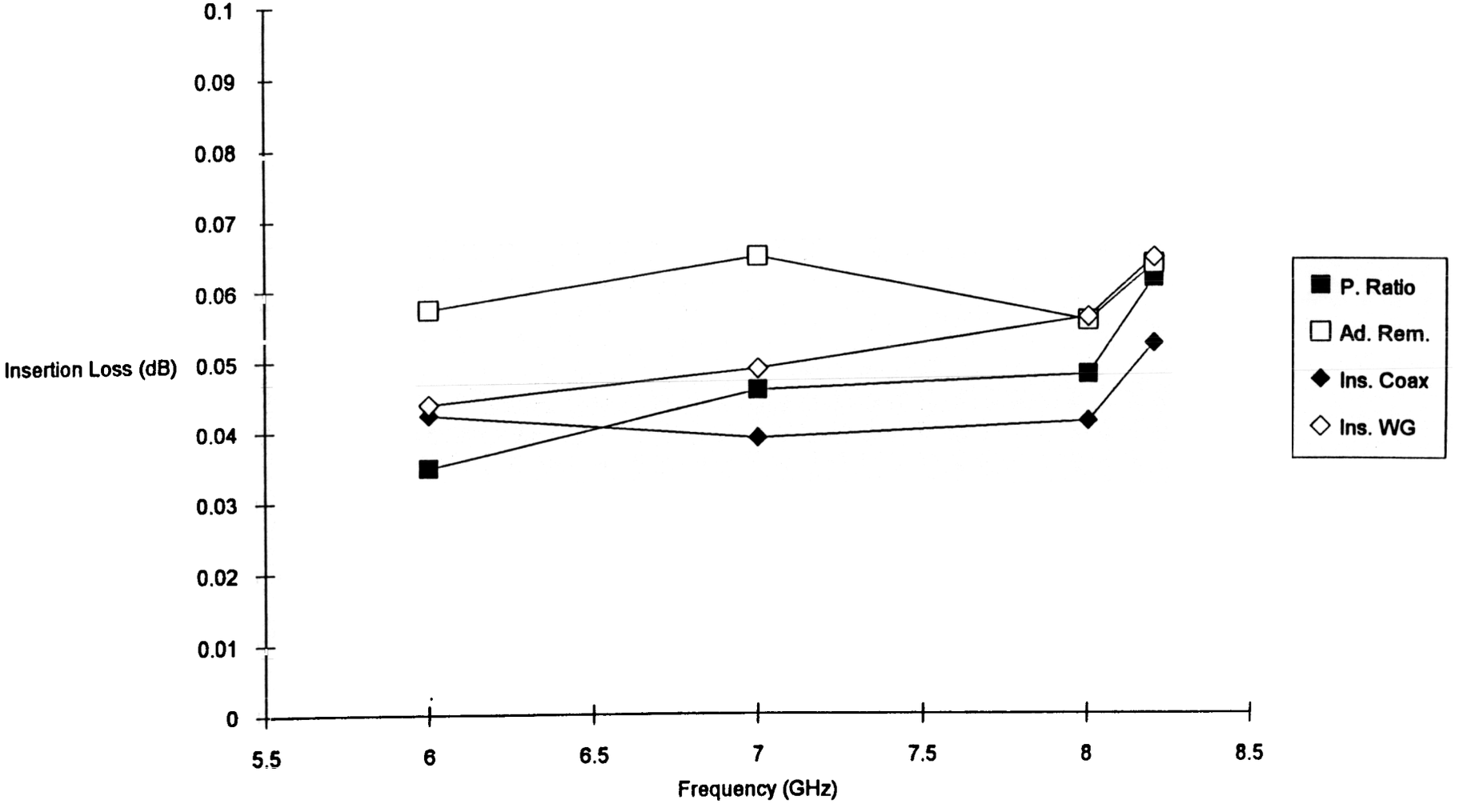


Figure 20a. WG14 to APC 7 Adaptor A measured by all four Measurement Techniques

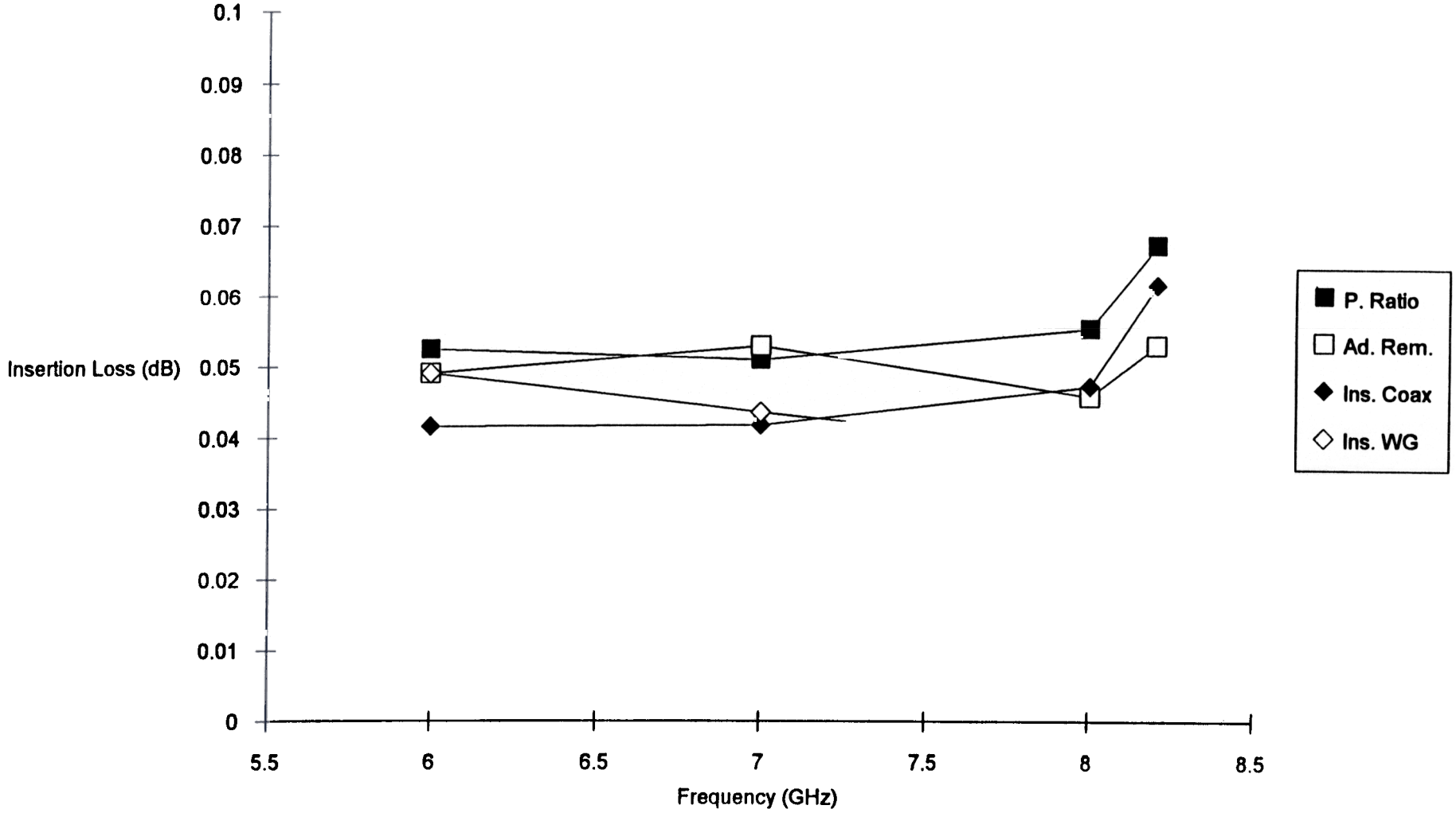


Figure 20b. WG14 to APC 7 Adaptor B measured by all four Measurement Techniques

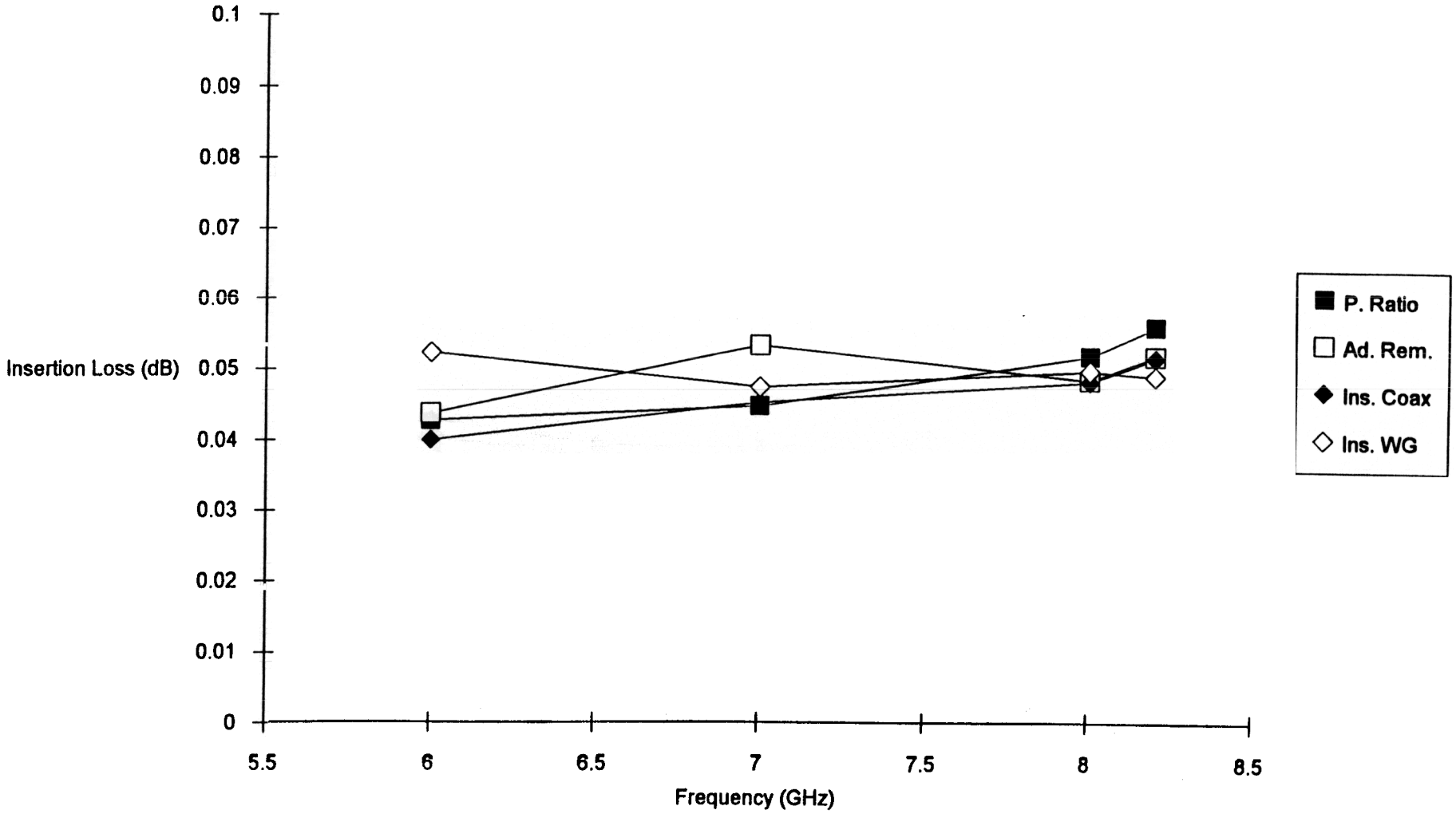


Figure 20c. WG14 to APC 7 Adaptor C measured by all four Measurement Techniques

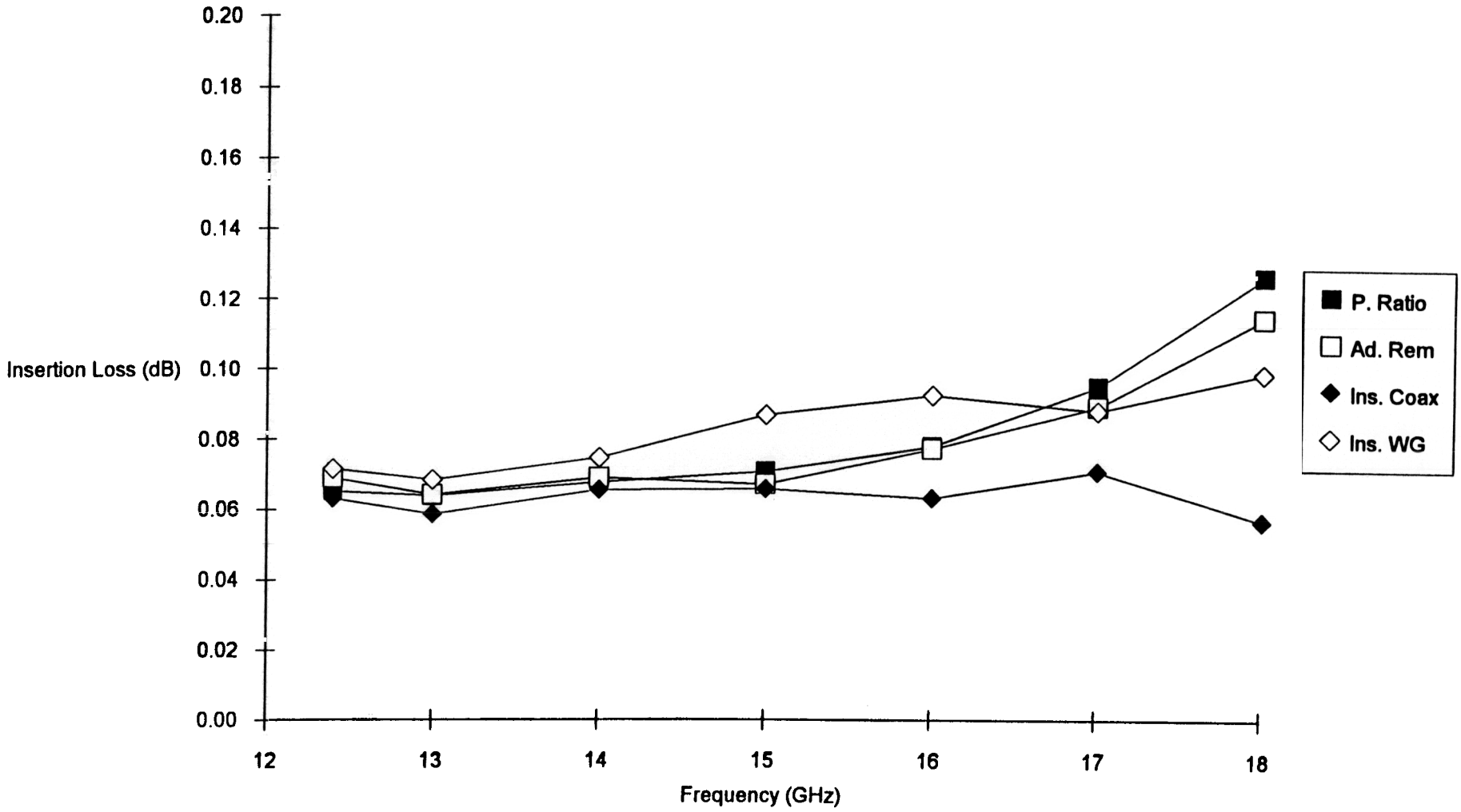


Figure 21a. WG18 to APC 7 Adaptor A measured by all four Measurement Techniques

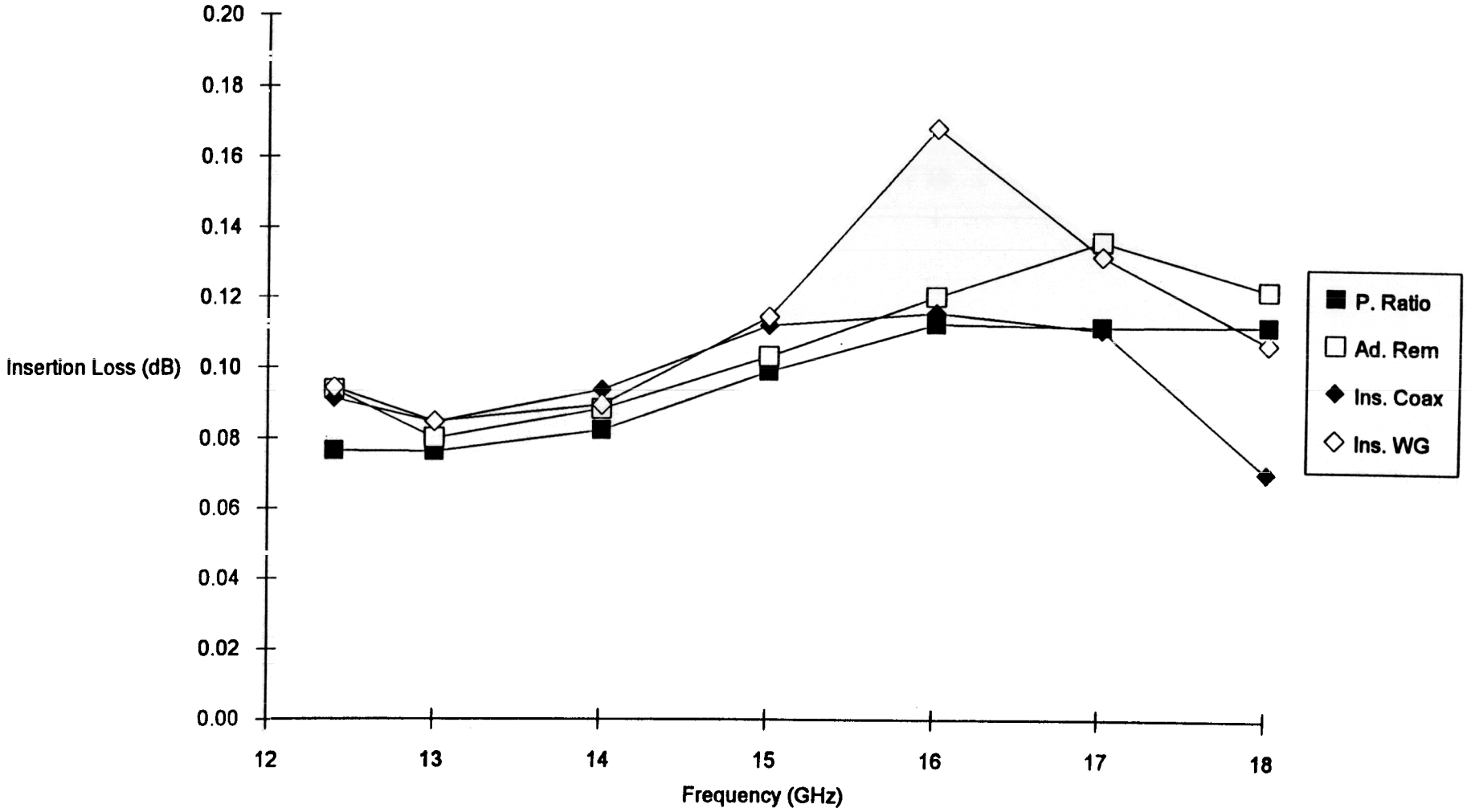


Figure 21b. WG18 to APC 7 Adaptor B measured by all four Measurement Techniques

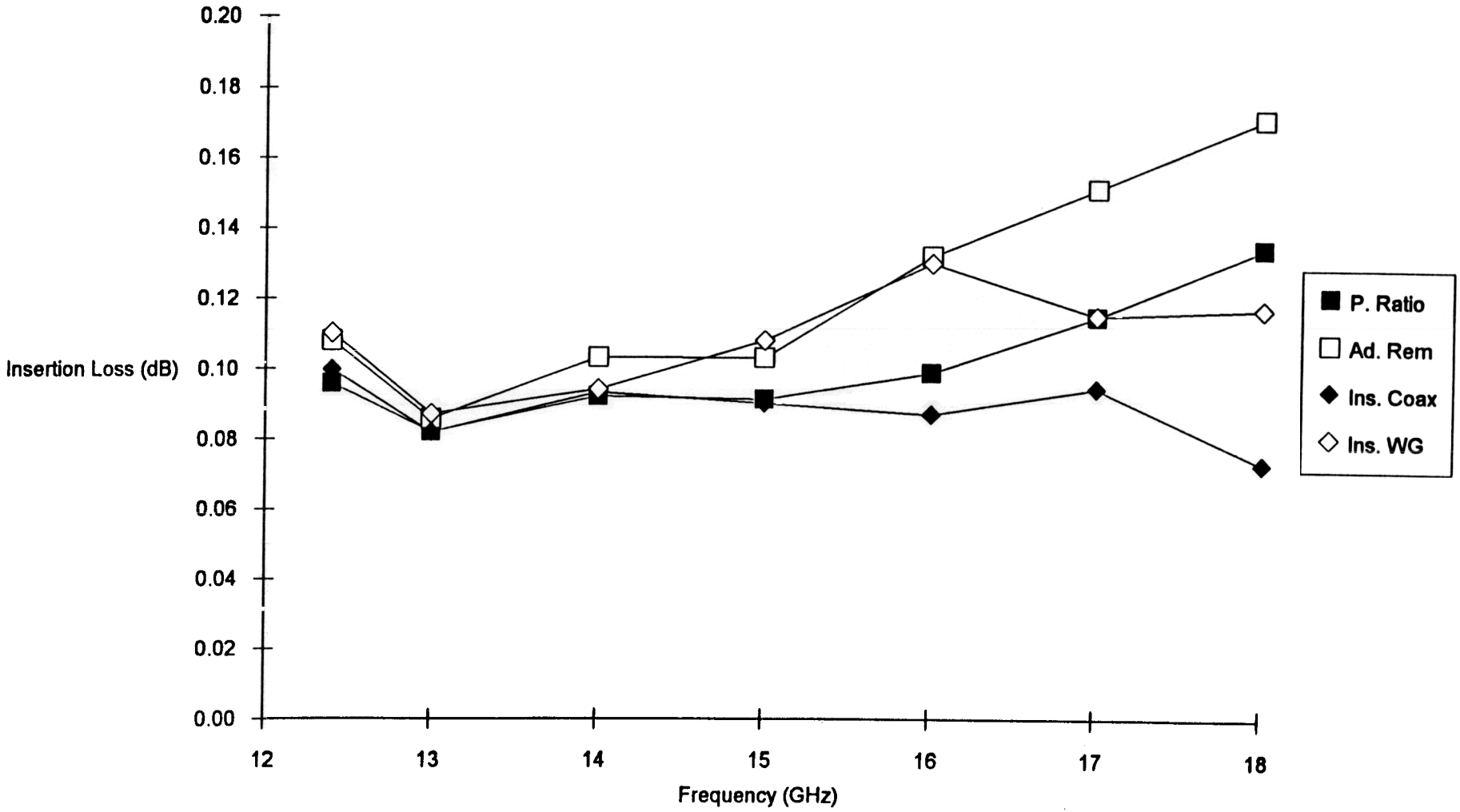


Figure 21c. WG18 to APC 7 Adaptor C measured by all four Measurement Techniques

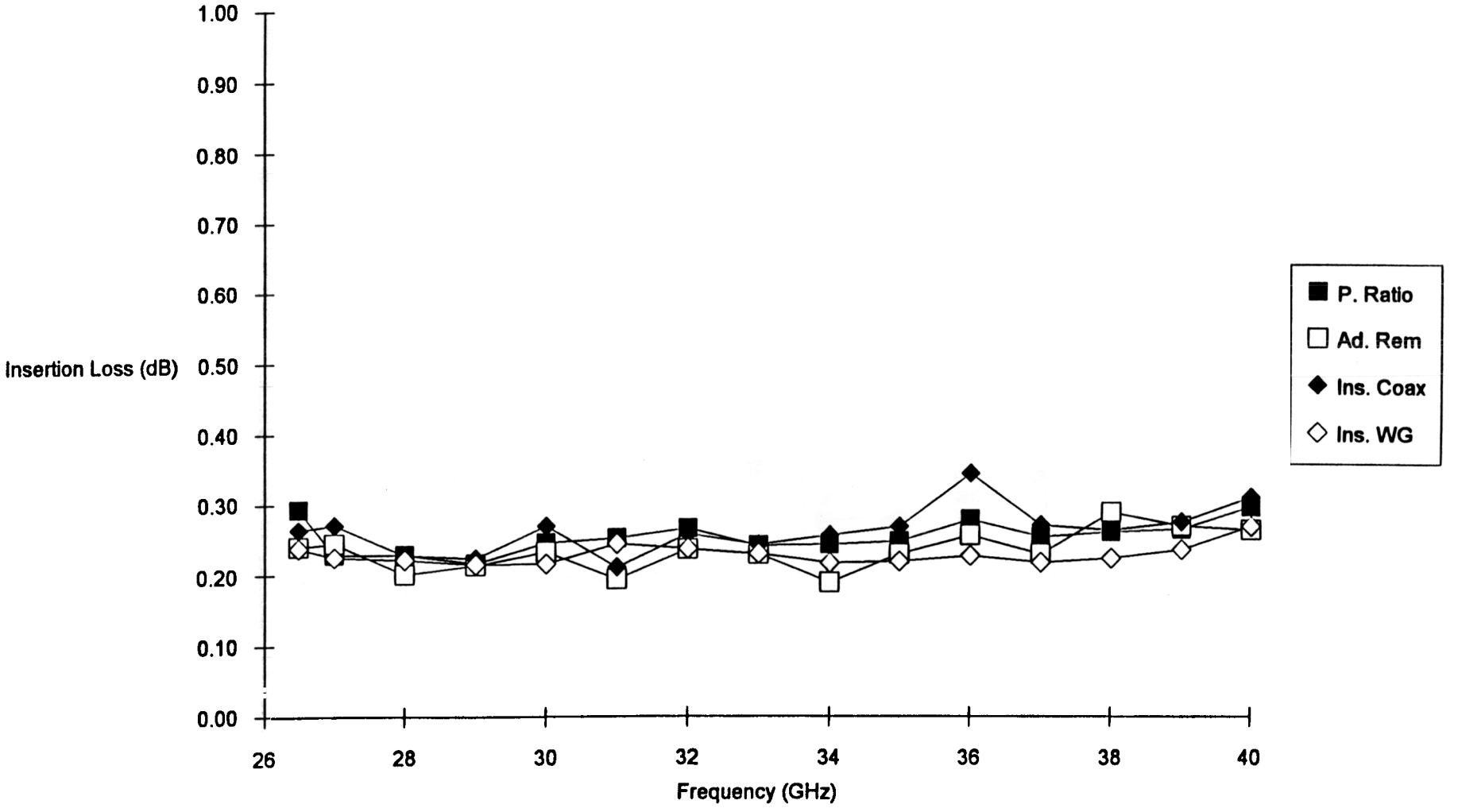


Figure 22a. WG22 to 'K' Adaptor Pair F1M1measured by all four Measurement Techniques

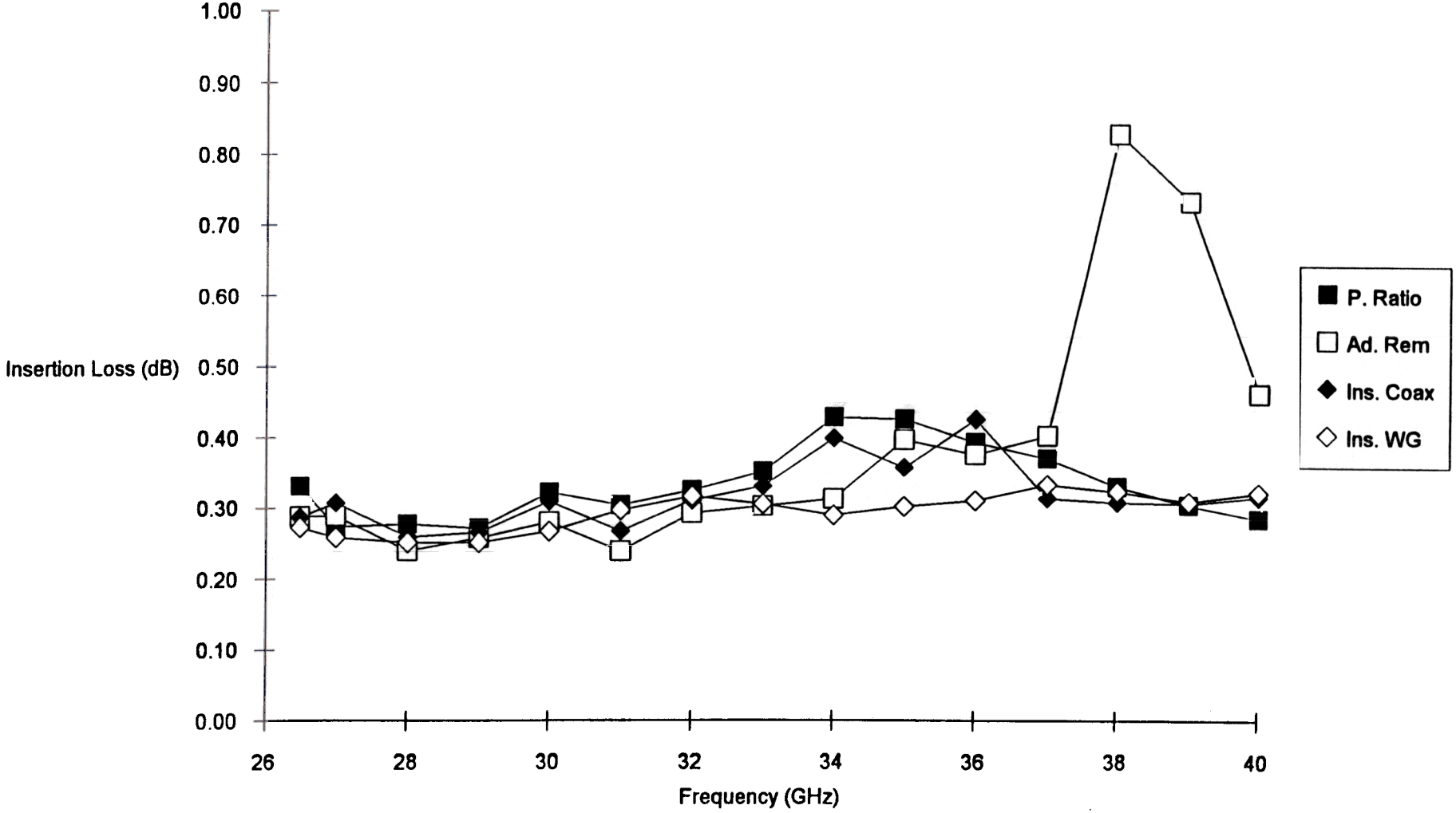


Figure 22b. WG22 to 'K' Adaptor Pair F2M1 measured by all four Measurement Techniques

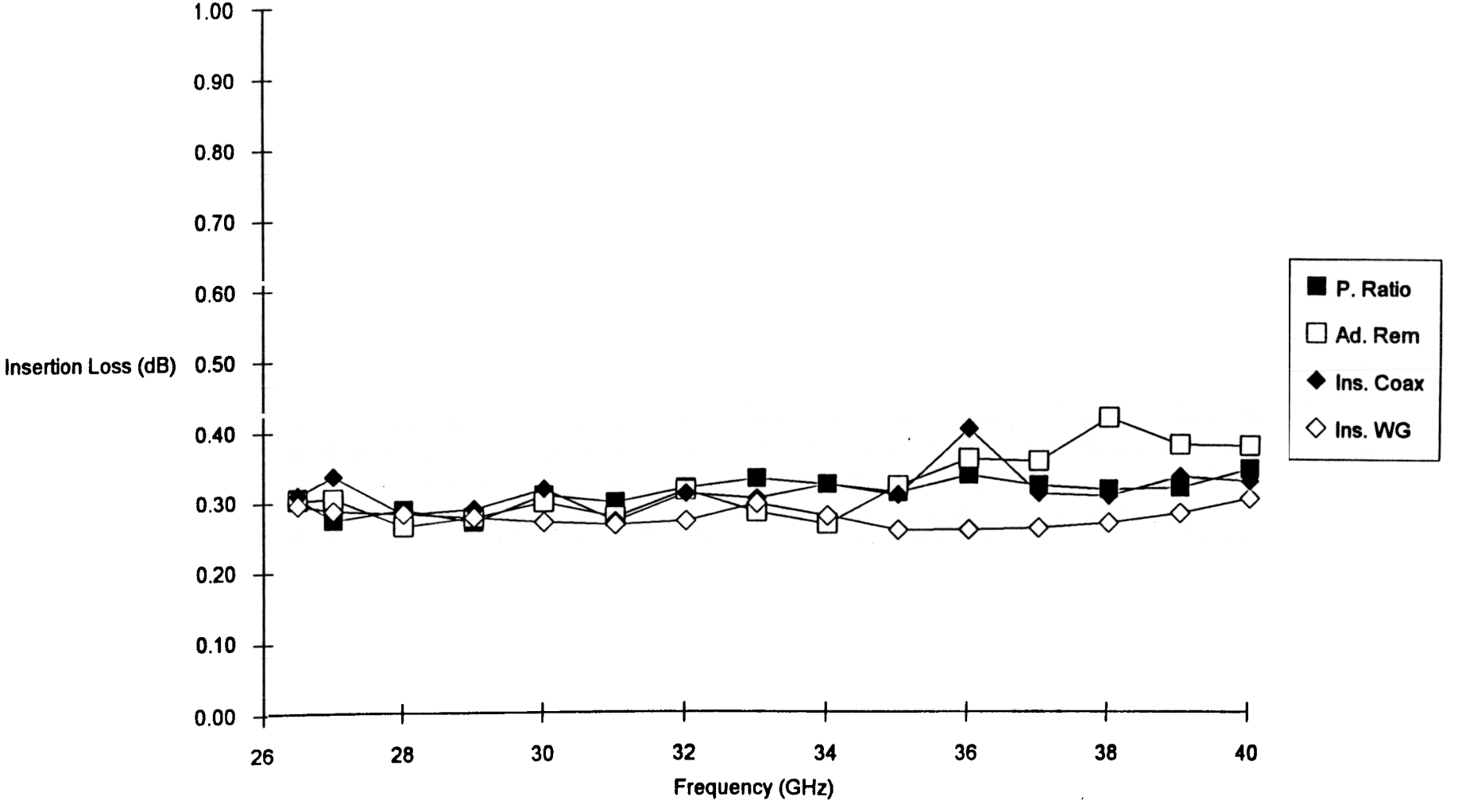


Figure 22c. WG22 to 'K' Adaptor Pair F3M1 maesured by all four Measurement Techniques