Millimeter Wave Vector Analysis Calibration and Measurement Problems Caused by Common Waveguide Irregularities

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***Abstract* — This paper was prompted by an effort to develop vector network analysis calibration kits for the WR-08 through WR-03 waveguide bands. A lack of repeatability (instability) of vector network analyzer (VNA) calibrations above 90 GHz was encountered which led to the investigation of not only the calibration kit artifacts but into the "MIL SPECS MIL.-F-3922/67B-xxx" defined tolerances and actual properties of commonly available components for these waveguide bands. The following frequent sources of errors were identified:**

1) The common tendency of waveguide at these frequencies to be oversize causing the incorrect entry of the waveguide's cutoff frequency during VNA calibration.

2) Significant waveguide flange misalignment possible with current MIL SPECS specified tolerances with no widely accepted technique for precise alignment.

3) Common waveguide component irregularities that occur due to inadequately developed manufacturing and assembly processes and that are so small that they can only be discovered with microscopic examination.

***Index Terms* — Specifications, MIL-W-85/3-xxx, MIL-F-3922/67B-xxx (67B), flange alignment, oversize waveguide, forward reflection, time domain, vector network analyzer (VNA).**

I. Introduction

Full band automatic vector network analysis is currently available up to 220 GHz and in the near future up to 325 GHz. Waveguide and waveguide flange performance is now taking on elevated importance. The problem is that the practitioners of high frequency millimeter waves have significant inventories of WR-08 and smaller waveguide components that do not meet any reliable specification. The problem is also faced by those entering the field when they purchase these same components, whether new or used.[1]

The published specifications for waveguide, WR-08 and smaller, are not being adhered to. The "agency" (government sponsored) waveguide specification is MIL-W-85/3-xxx. For waveguide WR-06 and smaller, the only current vendor available does not guarantee his product will meet the above specification. Later in this discussion data will be presented which indicate that the waveguide available in these bands is commonly oversize, more significantly as the frequency increases. A second deviation from the specification is also common, that of "dog ears" in the corners of the waveguide which violates the corner radius specification. These are both manufacturing process problems. The impacts of this deviation are also examined later with presentation of both analytical and test data.

The waveguide flange presents another distinct set of problems. The only agency specification covering waveguide flanges WR-08 and smaller is MIL-F-3922/74-00x (74), commonly called the "mini-flange." The 74 flange is reasonably accurate for use in WR-08 and WR-06 but is lacking precision when applied to WR-05 and smaller. Many manufactures sell a commonly available MIL-F-3922-67B-(67B) flange adapted to WR-08 and smaller. There are no agency specifications covering such an adaptation of this flange. The 67B specification covers only WR-10 and larger waveguide. The manufacturers, in response to customer demand, have applied the 67B flange to WR-08 and smaller. The locating pin tolerances specified for the 67B when applied to WR-08 and smaller allow waveguide interface offsets ranging from $\lambda/25$ at 90 GHz to almost $\lambda/8$ at 325 GHz. This problem is not generally understood, and waveguide vendors indicate that the 67B flange has outsold the 74 flange by as much as 10:1 over the last 5 years. One of the reasons for the popularity of the 67B flange is that it is much easier to accomplish an interface for it in a block type component, i.e., mixers, multipliers, phase shifters, etc. Four manufacturers of waveguide VNA calibration kits have addressed the 67B flange locator pin tolerance issue by tightening up the locator pin tolerances and adding two additional alignment pins having even tighter tolerances. The use of these additional alignment pins is optional, allowing these "precision" 67B flanges to interface with standard 67B flanges. Detailed analysis and test data is presented exploring the impacts of the 67B flange locator pin tolerances.

The finish for the waveguide flange is also a potential problem for these frequencies. The flange face is normally lapped to achieve flatness and finish quality. Cases have been observed where the leading edges of the waveguide aperture in the flange face have become eroded. This is caused by the lapping medium welling up into the waveguide opening as the flange is lapped. The action of this excess medium is to wear down the leading edges, causing them to be rounded. This rounding of the waveguide aperture leading edge appears to have little impact on waveguide interfaces WR-10 and larger. The impact of these rounded edges on waveguide interfaces WR-08 and smaller was analyzed and tested, and the data presented herein.

This paper will examine the effects of the out of tolerance waveguide and the 67B waveguide flange locator pin tolerance impacts. Section II of the paper deals with the physical measurement of the above phenomena and the analysis of the impacts using the Ansoft High Frequency Structure Simulator (HFSS). Section III describes the results of actual testing. Section IV explores some of the potential impacts of the waveguide irregularities on the VNA measurements and calibration. For brevity, only data taken using a WR-05 (140 to

220 GHz) VNA examining the S11, S21 and time domain aspects of these phenomena will be shown.

II. Mechanical Measurement and Simulation

*A. Errors allowed by MIL-W-85/3-*xxx *tolerances or caused by oversize deviation and common deformity*

A table containing the inside dimensions and their tolerances (both in inches), is presented below for reference purposes.

Waveguide Dimensions and Tolerances for WR-08 and above

EIA WR-	Broad wall (width) a	Narrow wall (height) b	Tolerance +/- a & b	Corner Radius max.
08	.080	.040	.0003	.002
06	.065	.0325	.0003	.002
05	.051	.0255	.0003	.002
04	.043	.0215	.0003	.001
03	.034	.0170	.0003	.001

During the development effort of waveguide calibration kits for WR-08 and smaller, the impact of the waveguide's dimensional accuracy vs. its cutoff frequency was encountered. More than fifty samples of waveguide covering WR-08 through WR-03 were examined using a toolmaker's microscope with accuracy of 0.0001 inches and a VNA system with WR-15, WR-10, WR-08 and WR-05 capabilities. A definite pattern of waveguide being increasingly oversize as frequency increased was discovered. To help define the source of this pattern, the potential differences possible in the waveguide cutoff frequency as allowed by the MIL-W-85/3 waveguide specifications were calculated. Fig. 1 is graphical representation of the percent of error in cutoff frequency allowed by the MIL-W-85/3 specifications.

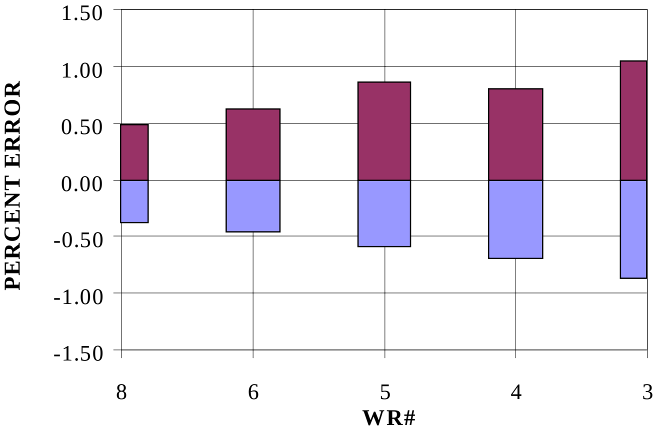


Fig. 1, Error range for cut-off frequency, using published specifications.

Waveguide for these frequencies is manufactured by drawing round tube into shape around a rectangular mandrel. Removal of the mandrel from the waveguide is difficult due to the small components involved. Some additional clearance is allowed by the manufacturer to expedite this removal process. Additionally the thin wall of the waveguide can easily overreact to the forming. The placement of the drawing rollers allows “ears” to be formed projecting outward from the corners of the waveguide. These are commonly referred to as “dog ears.” The work tolerances applied, and elasticity of the waveguide material, yield the oversize dimension and deformation observed. Figure. 2 is an illustration of the dimensional property observed in a typical sample of new WR-06 waveguide.

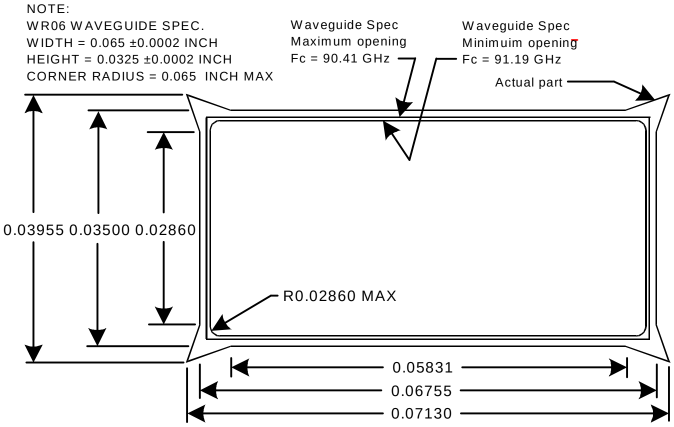


Fig. 2, WR-06 Waveguide opening.

Shown in Fig 2 are the maximum and minimum dimensions specified for WR-06 waveguide. The measured oversize dimensions and “dog ears” are illustrated. The performance of this section of waveguide was simulated using “HFSS” and plotted vs. the performance of a waveguide “in specification” and one which was oversize without the “dog ears” in Fig. 3.

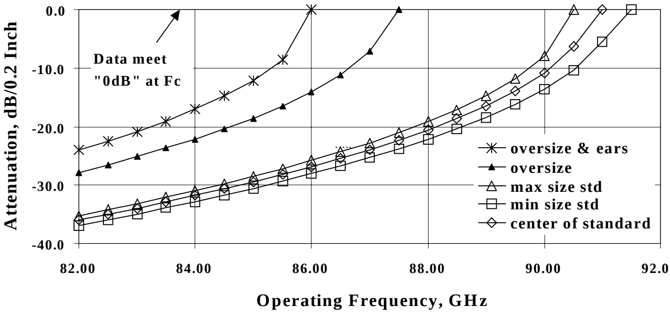


Fig. 3, Theoretical and observed cutoff frequencies for WR-06 waveguide.

The calculations presented are based on a theoretical lossless waveguide 0.2 inches long. The agency specified tolerances allow for a difference of +/- 0.5 GHz in cutoff frequency. The oversize characteristic resulted in a calculated 3.5 GHz lower cutoff frequency. When adding the effects of the “dog ears” to the oversize waveguide the simulation shows a 5 GHz lower cutoff frequency characteristic.

Machining of waveguide, using split block techniques, or the electroforming of waveguide are both inherently more accurate in all dimensional parameters for the waveguide bands above 90 GHz. Waveguide components manufactured with these two processes are the basis of all of the precision calibration kits available in the marketplace. The three major disadvantages effecting components manufactured with these processes are: 1) cost, 2) inability to easily support convoluted shapes and 3) the limited length that can be achieved for longer section of waveguide, six to eight inches maximum for split block machining and one to two inches for electroforming.

B. Waveguide alignment errors allowed by alignment pin position tolerances

For reference, drawings of the standard 67B and precision 67B flange are presented as Fig.4 and Fig. 5.

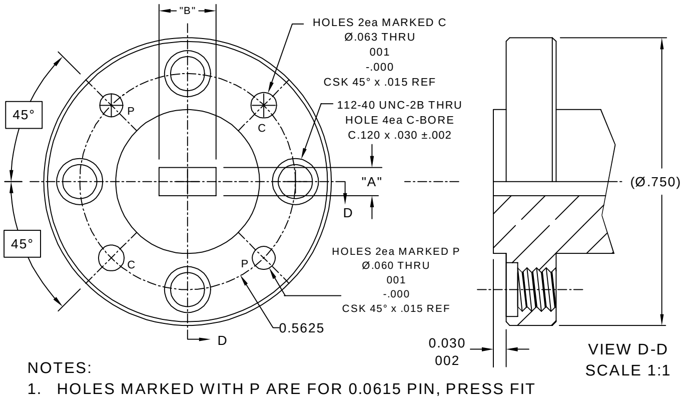


Fig. 4, Standard MIL-F-3922-67B- (67B) flange adapted to WR-08 and smaller.

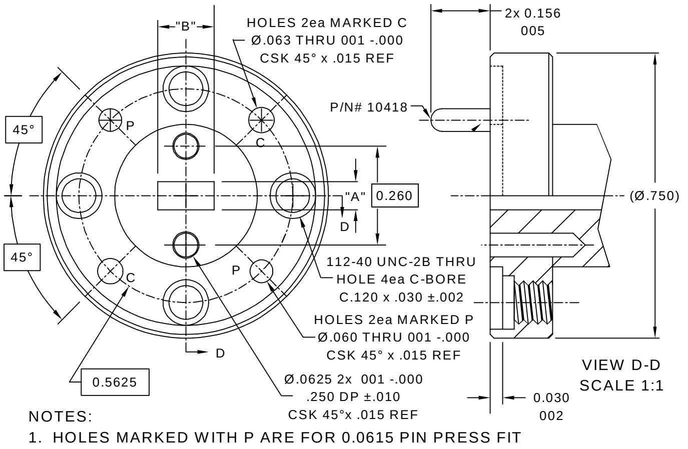
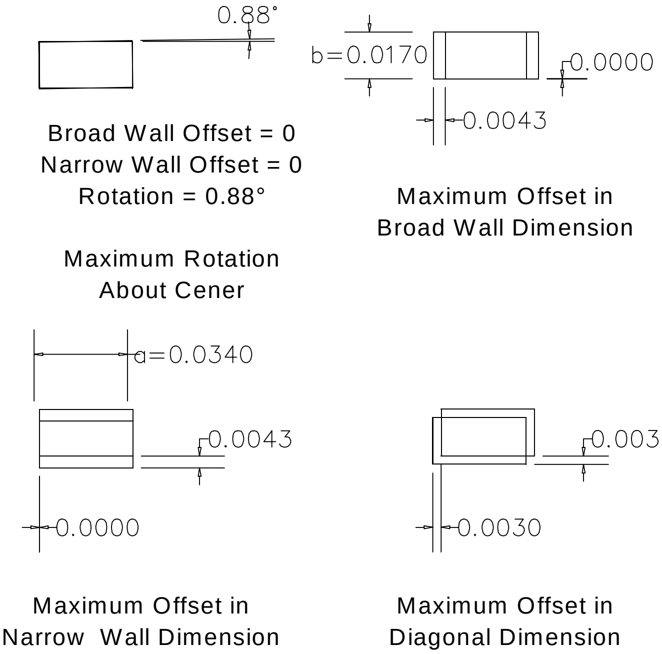


Fig. 5, Precision MIL-F-3922-67B- (67B) flange adapted to WR-08 and smaller.

The alignment of waveguide sections is dependent on the proper positioning of the flange alignment pins based on the true center of the waveguide aperture within the flange. In the 67B specification the position of the alignment pins and holes have specified tolerances. The achievement of the proper placement of these pins is dependent upon the accuracy with which the true center of the waveguide aperture can be determined and the translation of that point to the setup of the computer controlled machine being used for drilling the holes. Touch-off edge finding has been found to be barely possible for WR-08 waveguide and not practical for WR-06 and smaller. Most waveguide component manufacturers use precision drill jigs or precision centering with a center finding microscope mounted in their drilling machine or a combination of both. After numerous discussions with waveguide component manufacturers, it was decided that the center finding process and its possible errors would not be addressed in this investigation; only the errors allowed by the 67B tolerances are examined here.



Broad Wall Offset = 0
Narrow Wall Offset = 0
Rotation = 0.88°

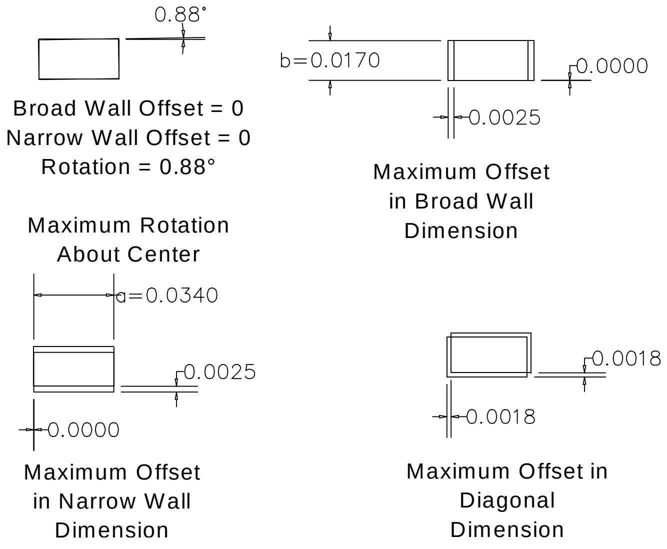
Maximum Rotation
About Cener

Maximum Offset in
Broad Wall Dimension

Maximum Offset in
Narrow Wall Dimension

Maximum Offset in
Diagonal Dimension

Fig. 6, Standard WR-03.



Broad Wall Offset = 0
Narrow Wall Offset = 0
Rotation = 0.88°

Maximum Rotation
About Center

Maximum Offset
in Broad Wall
Dimension

Maximum Offset
in Narrow Wall
Dimension

Maximum Offset in
Diagonal
Dimension

Fig. 7, Precision WR-03.

The deviations from true alignment were calculated for four misaligned positions. The four positions were: broad wall, narrow wall, diagonal and rotated. These four positions represent the major axial deviations which could be readily modeled. The absolute magnitude of misalignments (offsets) are the same for all waveguide bands, WR08 through WR-03, based on the 67B flange specification. The magnitude shown in each case is the algebraic worst case sum of each of the tolerances, i.e., the tolerance of the placement of the hole circle for the alignment pins and holes about the true center of the waveguide aperture, the tolerance allowed error in rotational position for the alignment pins and alignment holes and the allowed tolerance on the diameter of the alignment pins and alignment holes. The offset from true alignment for the 67B flange used for WR-03 is illustrated in Fig. 6. The offset from true alignment for the precision 67B flange used for WR-03 is illustrated in Fig. 7. The true alignment is improved by over 50% through the use of the precision 67B flange.

The dimensional tolerances illustrated in Fig. 6 and Fig. 7 assume a perfect waveguide and 25°C temperature. Both are based on the Geometric Tolerance in MIL-F-3922/67B-03.

HFSS S11 simulations were run on all four of the above misalignment positions. For reference, a simulation of a "perfect" WR-10 waveguide thru section is shown in each chart. Figures 8 and 9 illustrate the S11 degradation from perfect alignment for the broad wall offset of the standard 67B flange (0.0043 inch offset) and the precision 67B flange (0.0025 inch offset) for various waveguide bands.

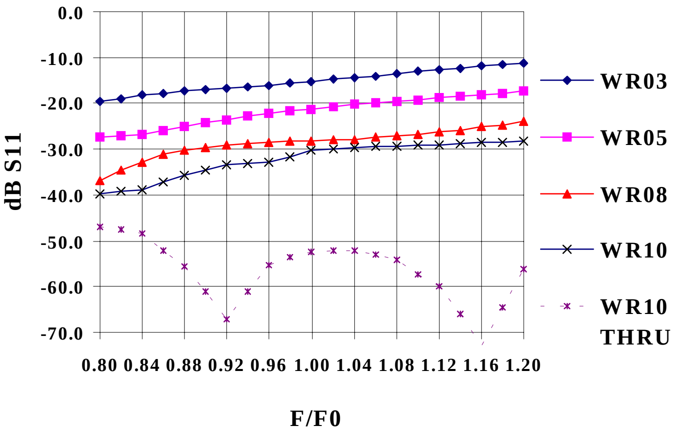


Fig. 8, Broad wall offset = 0.0043 inches.

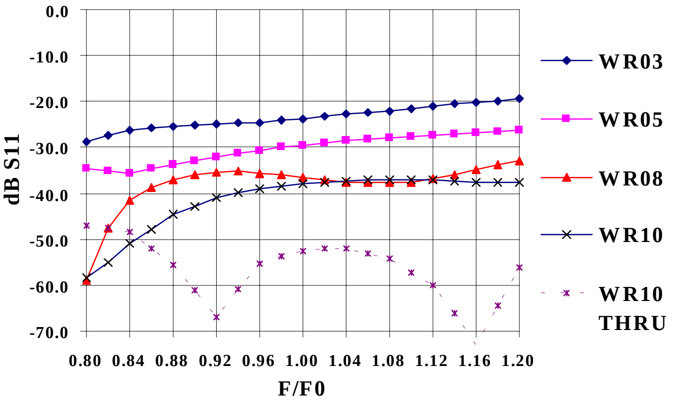


Fig. 9, Broad wall offset = 0.0025 inches.

Figures 10 and 11 illustrate the S11 degradation from perfect alignment for the narrow wall offset of the standard 67B flange (0.0043 inch offset) and the precision 67B flange (0.0025 inch offset) for various waveguide bands. It will be noted that while the dimensional offsets of the broad wall and the narrow wall are the same, the effect of the broad wall offset is more destructive.

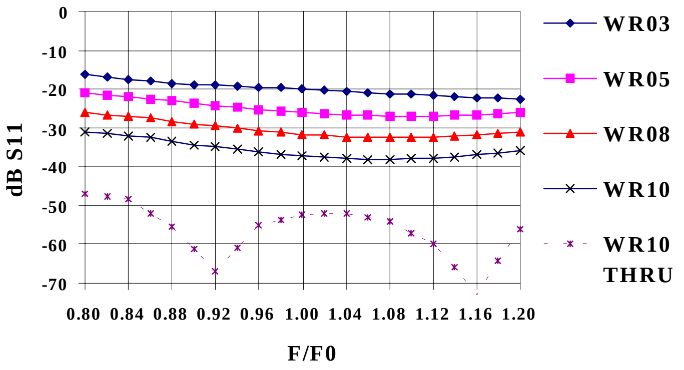


Fig. 10, Narrow wall offset = 0.0043 inches.

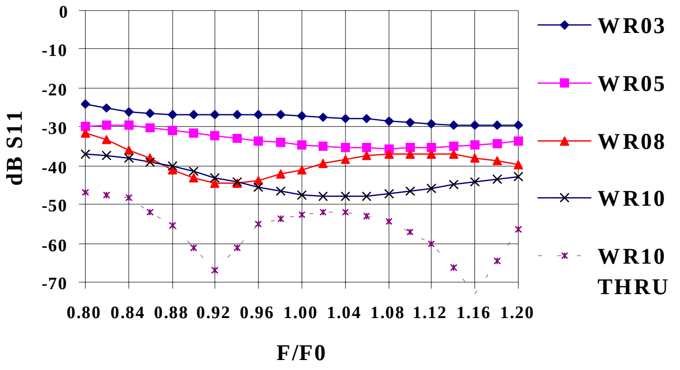


Fig. 11, Narrow wall offset = 0.0025 inches.

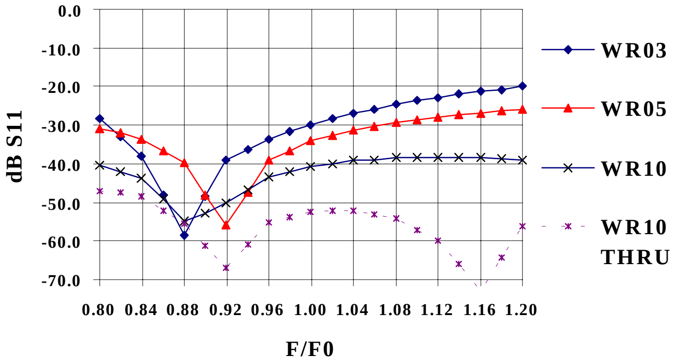


Fig. 12, Diagonal offset = 0.0030 inches.

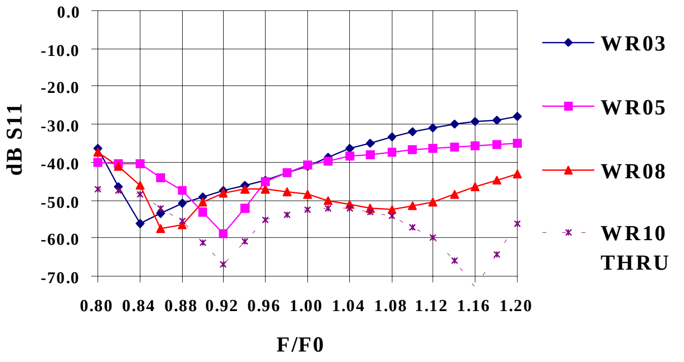


Fig. 13, Diagonal offset = 0.0018 inches.

Figures 12 and 13 illustrate the S11 degradation from perfect alignment for the diagonal offset of the standard 67B flange (0.0030 inch offset) and the precision 67B flange (0.0018inch offset) for various waveguide bands.

Figure 14 illustrates the S11 degradation from perfect alignment for the rotational offset of the standard 67B flange and precision 67B flange (both 0.88 deg. offset) for various waveguide bands. This offset is analogous to a step twist.

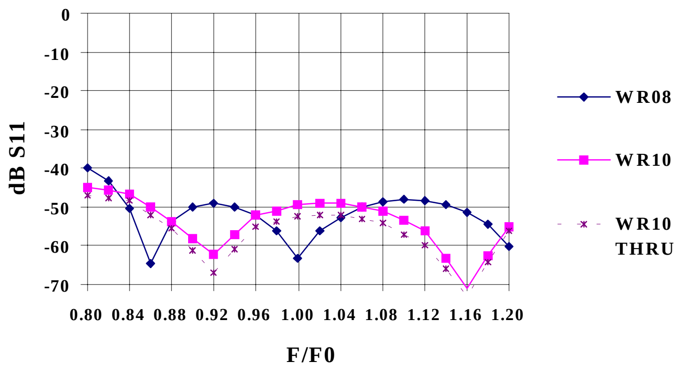


Fig. 14, Rotation = 0.88°.

From the simulations it would appear that the rotational offset or even the diagonal offset would be preferable to the broad wall or narrow wall offsets. Unfortunately, the authors could not discover any reliable methods of achieving any of the offsets repeatably. To gain appreciation for the potential results of these offsets, the effect of the worst case offset, broad wall, was plotted in percentage of wavelength vs. frequency for both the standard 67B flange and the precision 67B flange as shown in Fig. 15.

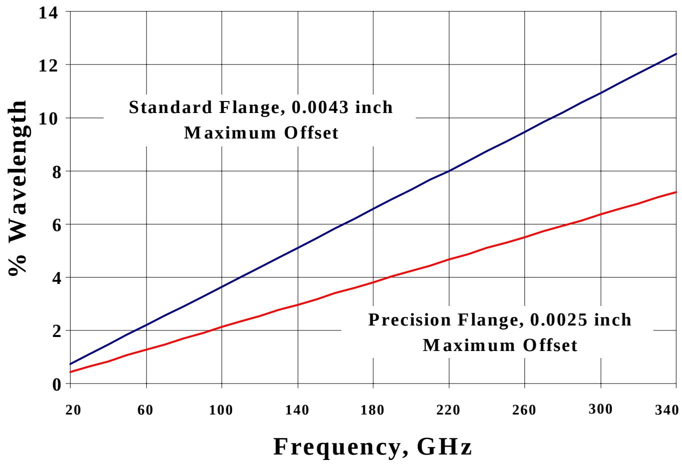


Fig. 15, Maximum flange alignment error as a % of wavelength vs. frequency.

C. The effects of rounding on the leading edges of the waveguide aperture in the flange.

An extensive search was conducted for specifications for the finish quality of the 67B and 74 flanges. No agency specification could be identified. References were found to NBS studies of the performance of various waveguide finishes in WR-15 which apparently did not result in specifications. MIT Lincoln Labs did publish specifications for the finish of the waveguide flange face for their projects. While the MIT specifications have not been adopted into any agency specification, their flange face finish specification of 16 micro-inches has been used by many commercial waveguide component vendors. Following through the application of this specification, one would assume that a perfectly sharp leading edge on the waveguide aperture of the flange face is inherent. What is the definition of perfectly sharp corner?

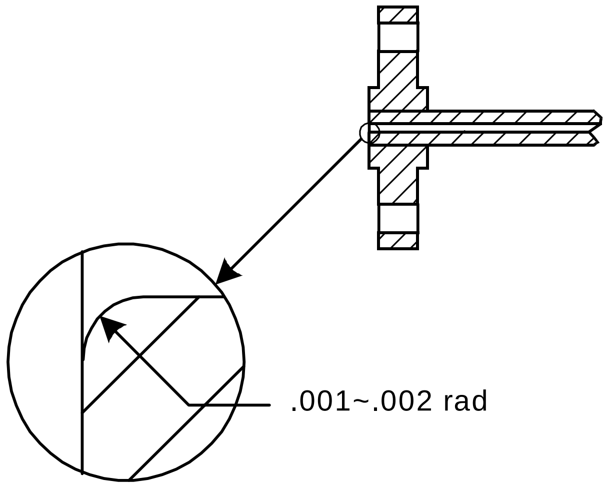


Fig.16, Leading edge rounding

A problem in one of the author's first WR-05 waveguide VNA calibration kits, that lead to this investigation, was rounded leading edges in the 67B flange face waveguide aperture of a 1/4λ waveguide calibration shim. A reliable calibration could not be achieved. Upon inspection it was discovered that significant rounding of the waveguide leading edge had occurred. The component was remade and the problem was solved. Figure 16 is an illustration of the rounding, which was found on all four edges. The author's experiments and consultations with several waveguide component vendors lead to the conclusion that this rounding resulted from erosion of the edge material caused by excess lapping medium welling up into the waveguide aperture.

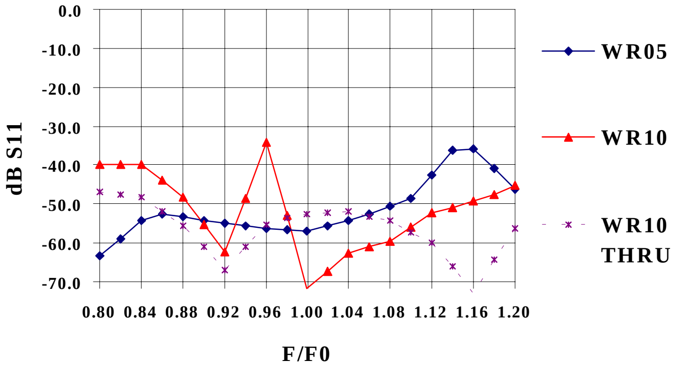


Fig. 17, Leading edge rounding, R = 0.0020

The degree of rounding encountered should not have caused the degree of calibration problem that was encountered. It is probable that the rounded leading edge exacerbated the effects of one of the flange misalignment possibilities to a degree that was destructive to the calibration process. The simulation of only the rounded edge is shown in Fig. 17.

III. Electrical Measurement

A. The measurement methodology

The S11 measurements were accomplished using a one path reflection calibration with a current model automated vector network analyzer and frequency extensions for WR-10, WR-08 and WR-05. The waveguide cutoff frequency was made using S21 measurements with the same equipment but using a one path, two port 8 term calibration. The techniques employed included: full waveguide band frequency response, time (distance) domain response of the waveguide component string, time domain with gating around the discontinuity of interest and frequency domain with gating applied. Shown in Figures 18 and 19 respectively are the WR-05 source match (25 dB) and directivity (40 dB) results achieved after the reflection calibration.

Figure 20 is the time domain plot of a precision one inch waveguide section terminated with a precision short. The waveguide flanges utilize the two additional locating pins and tend to verify the results shown in Figures 18 and 19. Marker 1 is at the interface of the test port to the one inch precision waveguide section and is an indicator of the quality of the test set directivity. Marker 2 is the distance to the short, which is equal to the one inch (2.5 cm) waveguide section. Marker 3 is at the second reflection of precision short and is an indicator of the test set source match.

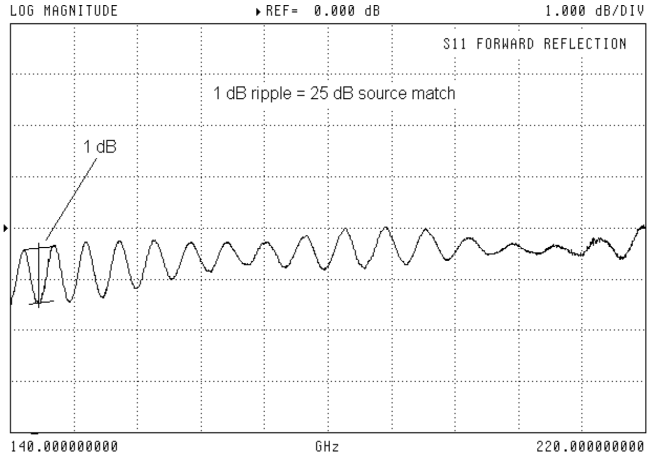


Fig. 18, Test set source match.

B. The measurement of the oversize waveguide impacts, WR-03 waveguide example.

The definition of cutoff frequency is that frequency (λc), for a desired mode, below which the wave is incapable of being propagated in the waveguide. Because of the limited dynamic range of the measurement system, attenuation levels above 70 dB could not be measured. For purposes of this effort, cutoff frequency has been defined for practical purposes as that frequency at which the wave is attenuated 40 dB for a 2 inch waveguide section. This level was chosen because it was well above the noise floor and thus was very repeatable and easily identified. The measurements were then conservative in that actual waveguide cutoff was even lower in frequency than that of the practical model selected. Dozens of waveguide sections, in various bands were measured. WR-03 was chosen for illustration as being the most problematical. In Figure 21, Marker 1 is placed at the theoretical cutoff frequency for WR-03 waveguide, 173.28 GHz. The 40 dB cutoff frequency displayed at Marker 2 and is at 163.1 GHz. A VNA calibration made using this waveguide as the calibration port and the theoretical frequency entered as the calibration cutoff frequency constant would have a significant error in its calibration matrix. More than 12 sections of new WR-03 waveguide showed this same oversize induced error. Marker 3 shows the S21 dynamic range achieved after the one path, two port 8 term calibration was completed.

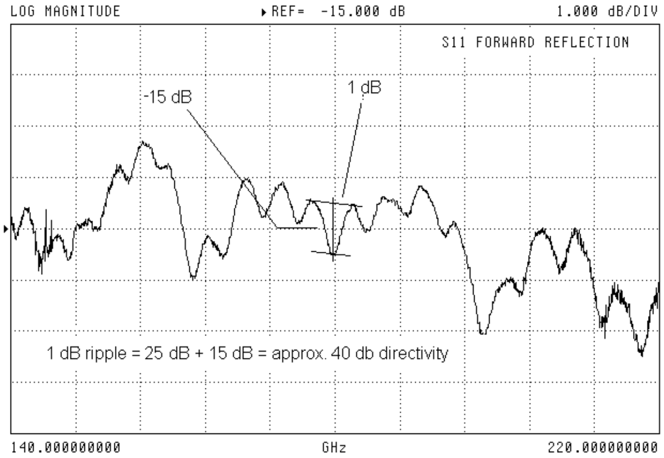


Fig. 19, Test set directivity.

C. The measurement of waveguide flange misalignment as allowed by MIL-L-3922-67B-xxx tolerances.

To measure potential misalignment errors that can be suffered when the 67B specifications are applied the WR-08 waveguide and smaller, an assembly of three new, 2 inch long, standard 67B WR-05 waveguide sections was created. As a comparison, a similar assembly of two new, 1 inch long, precision 67B WR-05 waveguide sections was likewise created. A time domain analysis of the three standard 67B section assembly is shown in Fig. 22. The Markers identify the following: 1) the interface of the test set output flange (the point of calibration) and the first 2 inch 67B waveguide section, 2) the interface of the first and second 67B waveguide section, 3) the interface of the second and third 67B waveguide section, 4) the interface of the third 67B waveguide section and the precision load and 5) the reflection of the load element within the precision load. Note that at Markers 2 and 3 there are double traces. These were intentionally created by recording to memory the first result and then loosening, moving and retightening the waveguide interface randomly for the most significant displacement of the measurement. Almost 10 dB of degradation was achieved. At Marker 3 the interface was taken apart, rotated 180 degrees, and reassembled. This resulted in an approximate improvement of 4 dB.

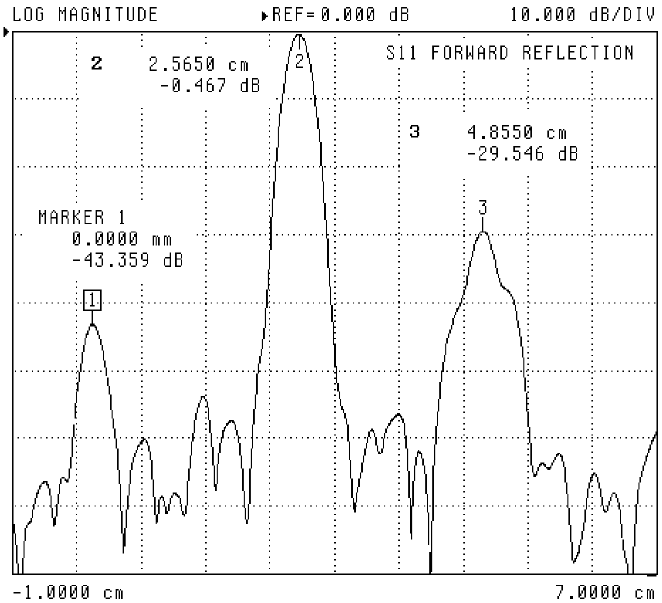


Fig. 20, Time domain of one inch precision waveguide section.

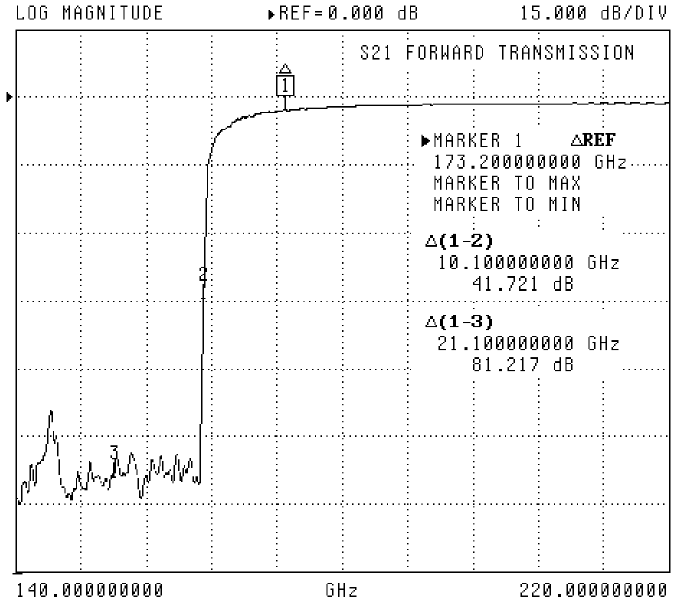


Fig. 21, Cutoff of oversize WR-03 waveguide.

The waveguide interface discontinuities represented by Marker 2 were isolated using time domain with distance gating. They were then examined using frequency domain with gating. The full waveguide band return loss of the original interface and the improved interface are shown in Figures 23 and 24, respectively.

The assembly of the two precision 67B waveguide sections was subjected to the same procedure as above. The results are shown in Fig. 25. Marker 1 again is the test port to first section interface. Marker 2 is the interface of the first and second precision 67B waveguide sections. Marker 3 is the interface of the second precision 67B waveguide section and the precision load and Marker 4 is the reflection of the load element within the precision load. Continued movement of the flange interface at Marker 2 did not result in observable change in return loss of the interface. It was only when the interface was disassembled and rotated 180 degrees that the approximate 2 dB change in interface return loss was recorded.

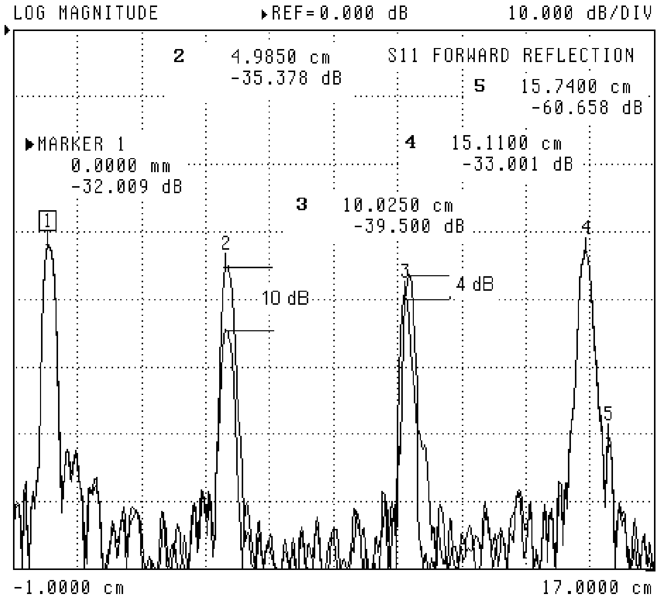


Fig. 22, Time domain of multiple 2 in WR-03 waveguides.

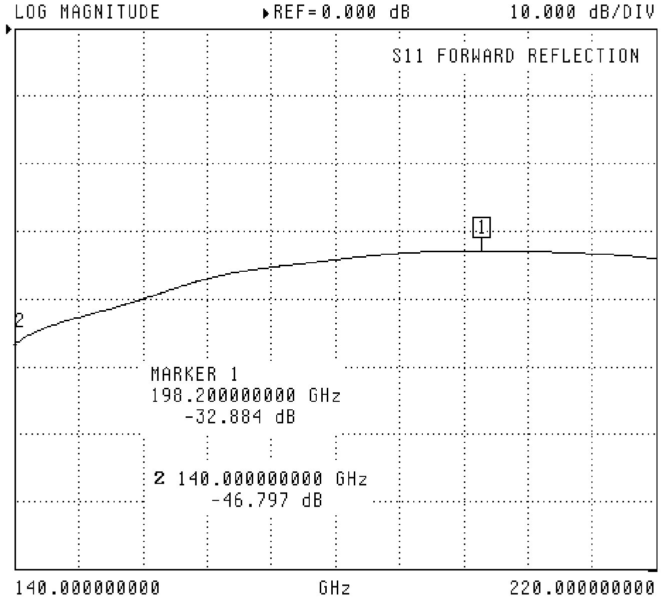


Fig. 23, Worst-case reflection, first waveguide interface.

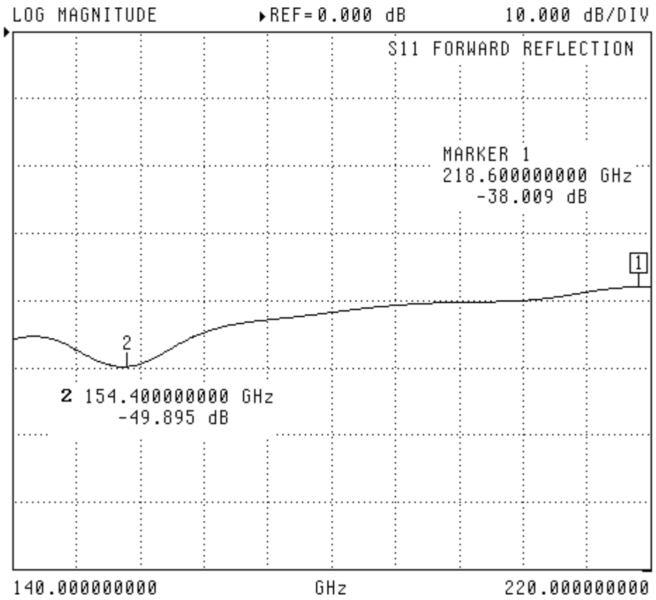


Fig. 24 Best-case reflection, first waveguide interface.

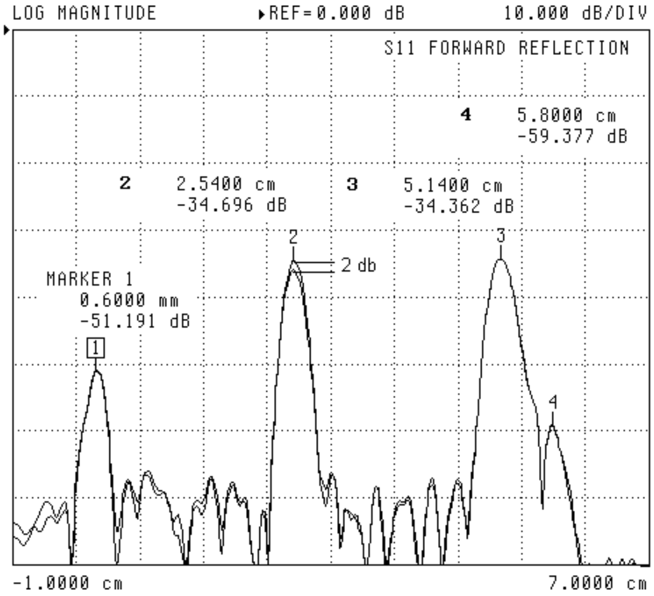


Fig. 25, Effect of flange rotation at precision waveguide interface.

IV. VNA measurement and calibration problems

The impacts of the three types of waveguide irregularities presented will vary depending on the type of device being tuned or analyzed. The position the irregular waveguide occupies in the test setup will also have specific effects. If the irregular waveguide forms a component or all of the components in a calibration standards kit, there will be one set of errors introduced. However, if an irregular section of waveguide is used as the “test port adapter” and is left in place as the test port after calibration with a precision set of components, a different set of effects occurs. There are even impacts for using an irregular waveguide section as a convenient interconnection to, or as part of the device under test. Because of the magnitude of errors that can be introduced into the VNA calibration by these irregularities, the entire measurement setup should be well thought out before even starting calibration.

The oversize waveguide component, when used as a component of a calibration kit, will cause the VNA dispersion correction and the waveguide loss model to be incorrect. This is especially problematical if the waveguide theoretical cutoff frequency, rather than the waveguide's actual cutoff frequency, is entered during the calibration data entry. This will cause the test data to have phase and magnitude errors as well as time domain errors. The use of an oversize waveguide section as a test port adapter, attached to the VNA RF head test port, will cause errors much in the same manner as trying to calibrate an SMA coaxial system with a 3.5 mm calibration kit. These same types of SMA vs 3.5 problems will be encountered in system measurements where waveguides of different internal dimensions are intermixed, i.e. precision and standard, etc.

An offset, such as those allowed by the 67B specification tolerances, between waveguide interfaces during calibration will introduce an unexpected ripple component in the test data that will impact the quality of the measurements, particularly in the high return loss measurements made in metrology. A standard flange section of waveguide could induce destructive ripple when looking at return losses of 30 dB or more. The lack of repeatability allowed by the 67B tolerances can be very disruptive to an orderly calibration organization.

The presence of a rounded aperture leading edge in the waveguide flange can affect both the precision and standard 67B flanges, WR-08 and smaller. The effects would most likely exacerbate the degradation caused by any offset in the flange interfaces. The inability to predict the relative offset of the two flanges in a 67B interface, coupled with the possibility of waveguide leading edge rounding, has potential impact for any meaningful VNA measurements above 90 GHz with the possible exception of low return loss characterization such as wafer probing.

V. Conclusions

Given that much of the 90 GHz and above waveguide currently in laboratory inventories is left over from previous programs, it is likely that these components have not been mechanically or electrically characterized. New waveguide is similarly suspect. The state of the art in waveguide manufacturing is presently limited by the tolerances attainable in drawing waveguide and cost-effective geometric techniques for identifying the “true center“ of the waveguide aperture in order to locate the waveguide flange hole pattern and associated locater pins. Much work needs to be done in advancing manufacturing science for waveguide and waveguide flanged components.

Before use in any rigorous testing program, all of the waveguide to be used should be fully characterized for its electrical properties and mechanical compatibility. It is recommended that as many waveguide flange interfaces be eliminated as possible. The use of a specifically designed single-piece waveguide run that includes all of the necessary bends, twists and other convolutions is highly recommended.

Vector Network Analysis measurements have shown that the anomalies of the waveguide itself, which can be handled in the process of calibration data entry, are less destructive than the imperfections inherent in the alignment uncertainty in the flange interface.

The use of dedicated waveguide test setups, which are not tampered with once assembled, should be considered mandatory. It is even more important for the prudent technician to fully understand and qualify his test set when working at these at these frequencies.

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Reference

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