Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: IEEE P1785 Workgroup - Progress on the Standardization of THz Waveguides and Interfaces

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Abstract: The P1785 IEEE Workgroup is developing a standard to define waveguides used at frequencies above 110 GHz. The standard will define both the dimensions of the waveguides (and associated frequency bands) and their interfaces (that is flanges). The standard will also provide recommendations for summarizing the performance and the expected uncertainty of rectangular-waveguide interfaces for 110 GHz and above.

Purpose: Informing IG THz on recent developments towards standardization of THz waveguide.

IEEE P1785 Workgroup - Progress on the Standardization of THz Waveguides and Interfaces

J.L. Hesler (VDI) (Secretary P1785)
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IEEE P1785 Workgroup

- P1785 – "Waveguides for Millimeter and Sub-Millimeter Wavelengths"
  - Website: grouper.ieee.org/groups/1785
- Workgroup History
  - First meeting in June 2008 at IMS-Atlanta
    - DARPA THz Program "re-booted" the WG in May 2010
      - Albrecht, 2010 IMS Symp. Dig., pp. 1118-1121
  - Current membership level ~30
- Workgroup Goals
  - Develop an international standard to define waveguides at > 110 GHz

122 IEEE microwave magazine February 2009

MTT-S Society News

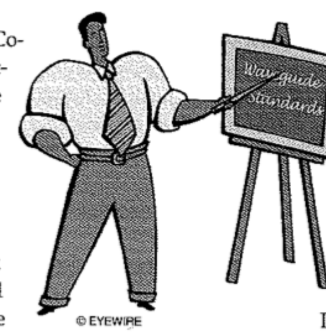
IEEE Begins Work on Waveguide Standards Above 110 GHz

■ **Nick Ridler**

The IEEE New Standards Committee (NesCom) has recently given the go-ahead for a new standard to be developed for waveguides that operate above 100 GHz: specifically, from 110 GHz to 1100 GHz (i.e. 1.1 THz). The standard will cover both waveguide aperture sizes and waveguide flanges.

Existing standards in this area only cover waveguide aperture sizes to 325 GHz and there is hardly any useful information about waveguide flanges above 110 GHz. This is what led the IEEE activity to start from 110 GHz and put in place a reliable source of information for both apertures and flanges in a single standard.

The Standards Coordinating Committee (SCC) of the Microwave Theory & Techniques Society (MTT-S) is sponsoring the development of the standard. The work has been assigned the project reference number P1785 and the official title of the standard, when published, will be:



IEEE Standard for Rectangular Waveguides and Flanges for Rectangular Waveguides for use at Millimeter and Sub-Millimeter Wavelengths.

The first meeting of the Working Group (WG) that is tasked with developing the standard took place during Microwave Week 2008, in Atlanta, Georgia. The second WG meeting took place during the ARFTG Conference in December 2008. A third meeting will be held during IMS week. A website has been set up that gives more information about this activity.

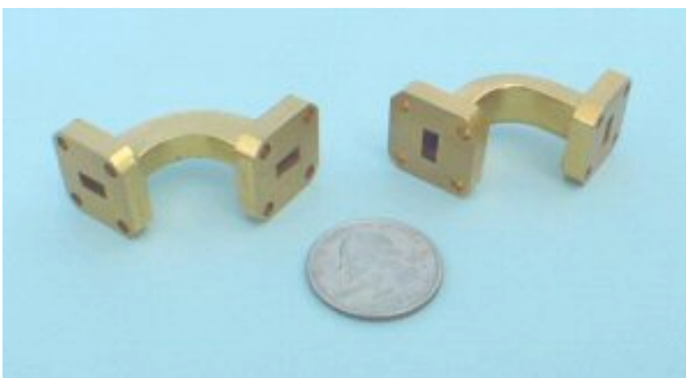
Nick Ridler (nick.ridler@ieee.org) serves as P1785 WG Chair Web site: grouper.ieee.org/groups/1785.

Digital Object Identifier 10.1109/MMM.2008.930695

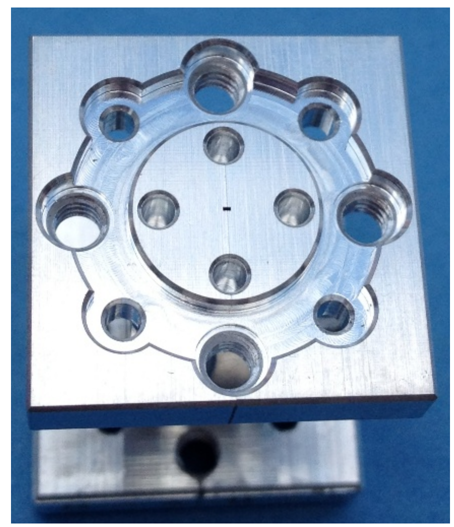
Rectangular Waveguide Components

Waveguide Taper

Waveguide Tripler



Waveguide Bends



Experimental Waveguide Interface (500-750 GHz)

Figures from www.microwaves101.com & www.vadiodes.com

Rectangular Waveguide

- Why rectangular guide?
  - Low loss guiding structure at THz
    - Microstrip ~ 1 dB/mm @ 600 GHz
    - Waveguide ~0.08 dB/mm @ 600 GHz
  - High power handling
  - Many techniques for integration of device with guide

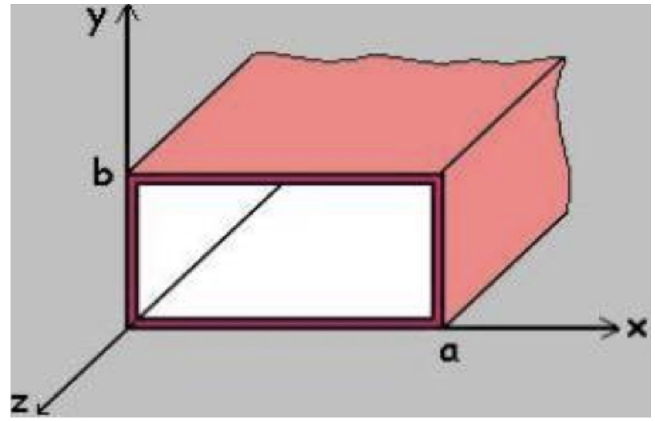
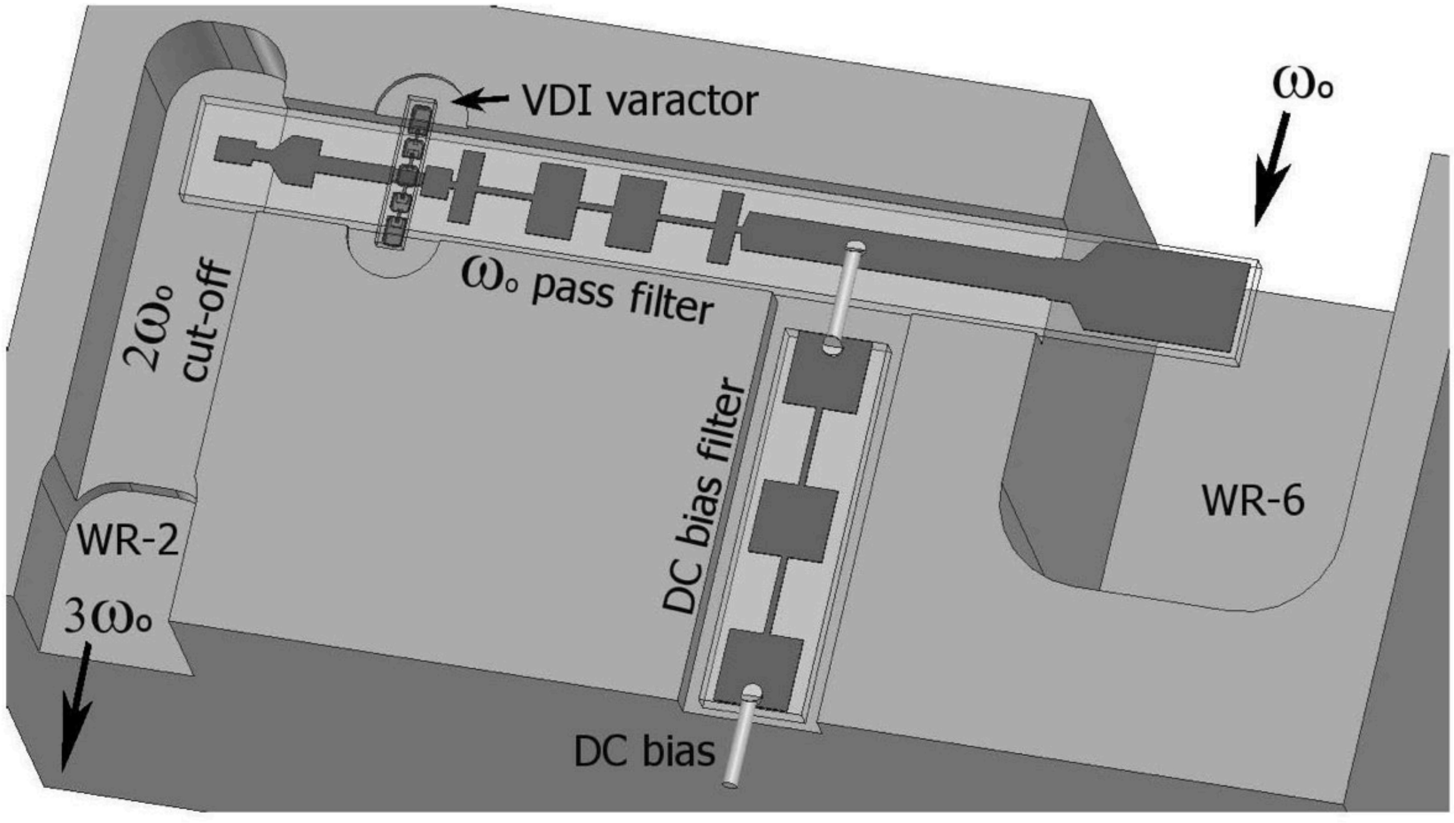


Figure from www.ee.bilkent.edu.tr

Varactor Frequency Tripler



Porterfield, 2007 IMS Symp. Dig., pp. 337-340

Rectangular Waveguide – TE10 Mode

- Single-mode Operation
  - High pass filter
    - Blocks lower harmonics
  - Operate with only TE10 mode propagating
    - TE20 mode is next highest mode
    - Turns on at 2 times the TE10 cutoff frequency
  - Operating range approx. 1.25 to 1.9 times the TE10 cutoff frequency
    - To reduce the effect of dispersion on performance

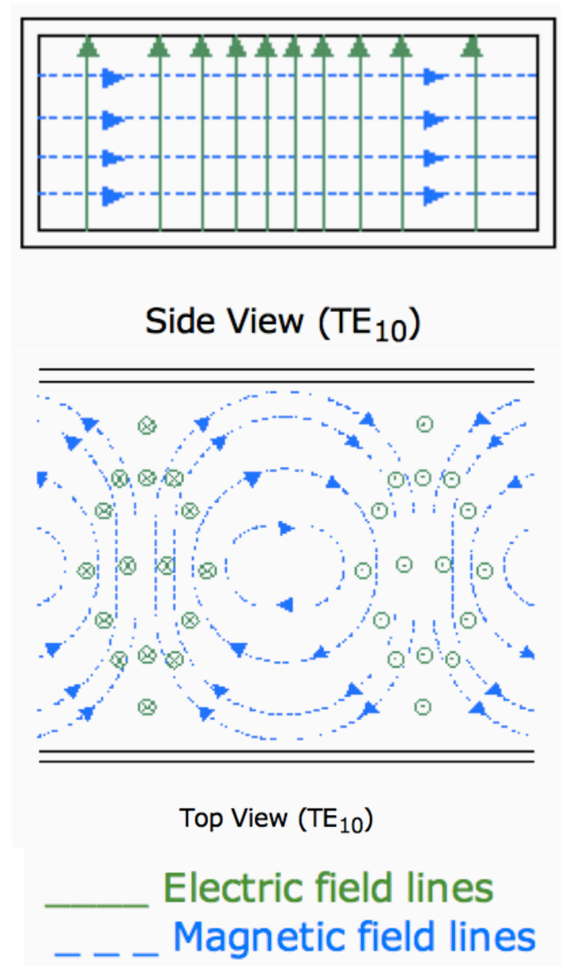


Figure from www.rfcafe.com

Previous Waveguide Standards

TABLE I: MIL Spec Flanges for Small Waveguides

WR-#	Frequency GHz	MIL-F-3922/74-( ) 0.373" dia. (TRG-714 type)	MIL-F-3922/67B-( ) 0.75" dia. (UG-387 type)	MIL-F-3922/67B-( ) 1.125" dia. (UG-383 type)	MIL-F-3922/54-( ) 0.75" sq. (UG-599)	MIL-F-3922/54-( ) 0.875" sq.
3	220-325	005	003M			
4	170-260	004	004M			
5	140-220	003	005M			
6	110-170	002	006M			
8	90-140	001	008M			
10	75-110		010			
12	60-90		009			
15	50-75		008			
19	40-60			007		
22	33-50			006		
28	26.5-40			005	003	
42	18-26.5			004		001

Kerr et al., ALMA Memo No. 278, 1999

Previous Waveguide Standards

- Waveguide Bands defined up to 325 GHz
- Standard UG387 Interface to 110 GHz
  - Marginal performance even at 110 GHz
    - Raised boss make repeatable connections challenging
  - Standard extended for use up to 325 GHz
    - Numerous variants, manufacturer dependent

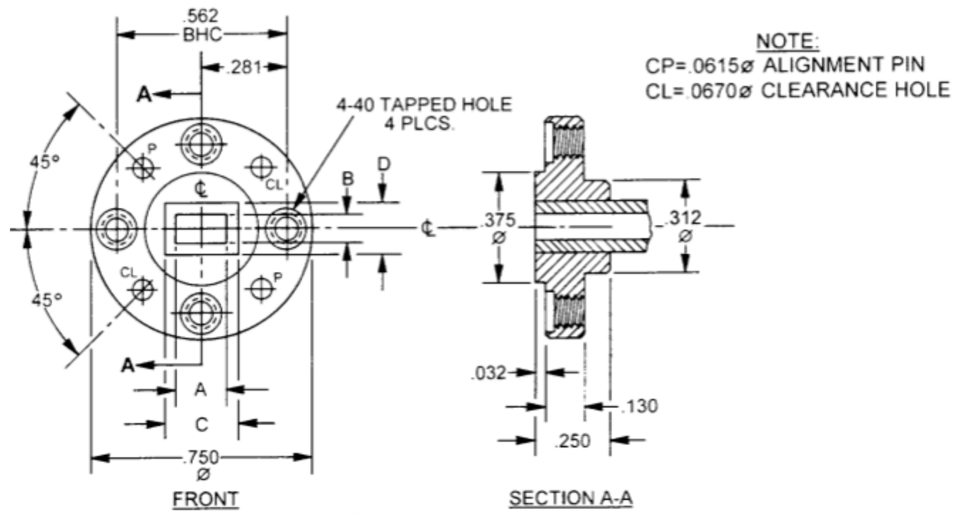
Previous Waveguide Standards

TABLE I: MIL Spec Flanges for Small Waveguides

WR-#	Frequency GHz	MIL-F-3922/74-( ) 0.373" dia. (TRG-714 type)	MIL-F-3922/67B-( ) 0.75" dia. (UG-387 type)	MIL-F-3922/67B-( ) 1.125" dia. (UG-383 type)	MIL-F-3922/54-( ) 0.75" sq. (UG-599)	MIL-F-3922/54-( ) 0.875" sq.
3	220-325	005	003M			
4	170-260	004	004M			
5	140-220	003	005M			
6	110-170	002	006M			
8	90-140	001	008M			
10	75-110		010			
12	60-90		009			
15	50-75		008			
19	40-60			007		
22	33-50			006		
28	26.5-40			005	003	
42	18-26.5			004		001

Kerr et al., ALMA Memo No. 278, 1999

UG387 “750-Round” Interface



	WR-15	WR-12	WR-10	WR-8	WR-6	WR-5	WR-4	WR-3
A	.148	.122	.100	.080	.065	.051	.043	.034
B	.074	.061	.050	.040	.0325	.0255	.0215	.017
C	.228	.202	.180	.160	.145	.131	.123	.094
D	.154	.141	.130	.120	.1125	.1055	.1015	.077
MIL-F-3922/67B-( )	008	009	010	008M	006M	005M	004M	003M
CATALOG NO.	R750-15	R750-12	R750-10	R750-8	R750-6	R750-5	R750-4	R750-3

NOTE:
M=MODIFIED

.750 DIA. ROUND COVER FLANGE

Fig. 1 The MIL Spec 0.75" round flange (UG-387 type) (from the Custom Microwave catalog). Dimensions in inches.

Kerr et al., ALMA Memo No. 278, 1999

Previous Waveguide Standards

TABLE I: MIL Spec Flanges for Small Waveguides

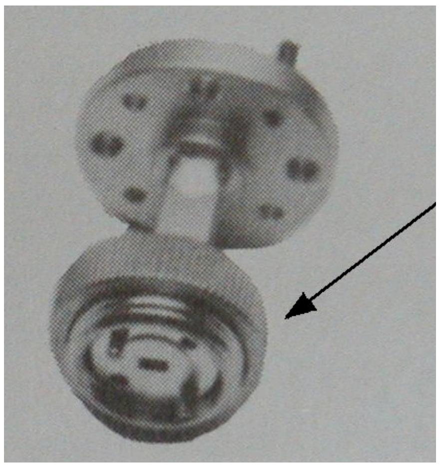
WR-#	Frequency GHz	MIL-F-3922/74-( ) 0.373" dia. (TRG-714 type)	MIL-F-3922/67B-( ) 0.75" dia. (UG-387 type)	MIL-F-3922/67B-( ) 1.125" dia. (UG-383 type)	MIL-F-3922/54-( ) 0.75" sq. (UG-599)	MIL-F-3922/54-( ) 0.875" sq.
3	220-325	005	003M			
4	170-260	004	004M			
5	140-220	003	005M			
6	110-170	002	006M			
8	90-140	001	008M			
10	75-110		010			
12	60-90		009			
15	50-75		008			
19	40-60			007		
22	33-50			006		
28	26.5-40			005	003	
42	18-26.5			004		001

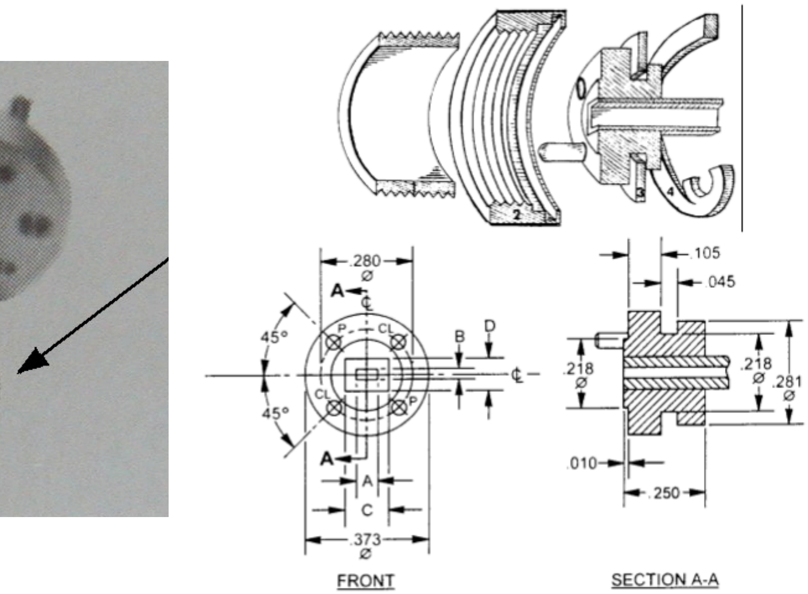
Kerr et al., ALMA Memo No. 278, 1999

Previous Waveguide Standards

- TRG-714 style was developed for higher frequency operation
  - Technical issues limited use of flange
    - Expensive to machine on components
    - No ability to view interface contact
- Not widely adopted by the industry

TRG-714 “Mini-Flange” Interface





	WR-8	WR-6	WR-5	WR-4	WR-3
A	.080	.065	.051	.043	.034
B	.040	.0325	.0255	.0215	.017
C	.160	.145	.131	.123	.094
D	.120	.1125	.1055	.1015	.077
MIL-F-3922/74-( )	001	002	003	004	005
CATALOG NO.	M-8	M-6	M-5	M-4	M-3

NOTE:
CP=.0465∅ ALIGNMENT PIN
CL=.0480∅ CLEARANCE HOLE

MINI-CONTACT FLANGE

Fig.2. The MIL Spec mini-contact flange (TRG-714 type) (from the Custom Microwave catalog). Dimensions in inches.

Kerr et al., ALMA Memo No. 278, 1999

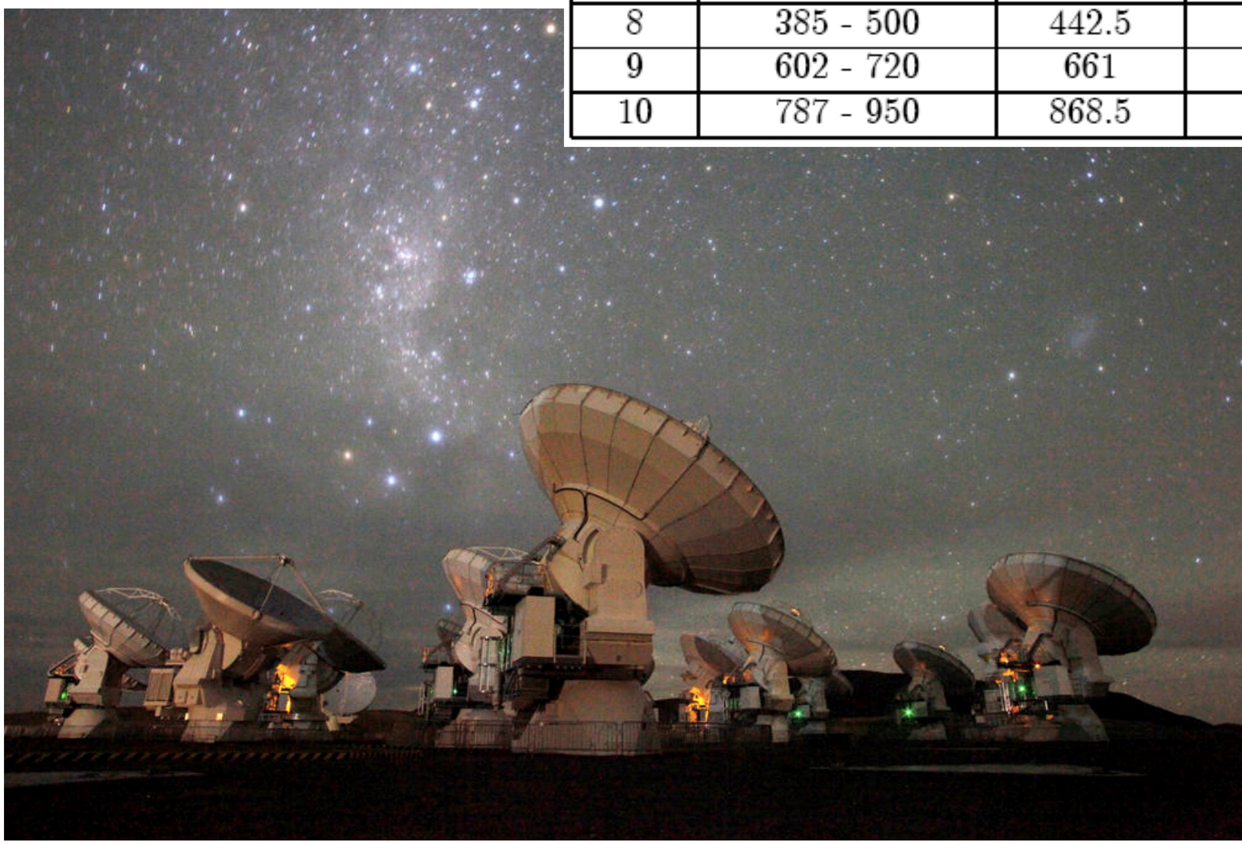
Waveguide at THz

- There has been a growing need for standardization of THz waveguide
  - The number of applications and systems at > 325 GHz has grown dramatically
- As one example, the ALMA Project
  - Atacama Large Millimeter-wave Array
    - almascience.nrao.edu/about-alma
  - International project
    - North America, Europe & Asia

- ALMA Coverage to 950 GHz
  - 66 Antennas
  - 2 Receivers for each band
- Components developed around the world

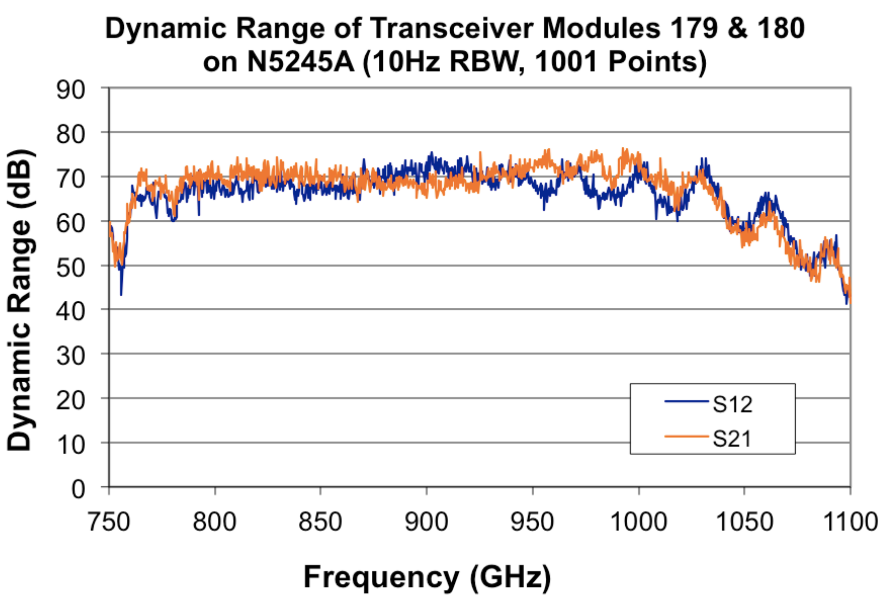
Table 1: Waveguides for ALMA bands

Band	from - to (GHz)	f_0 (GHz)	Δf (GHz)	$\frac{\Delta f}{f_0}$
3	84 - 116	100	32	32.0%
4	125 - 163	144	38	26.4%
5	163 - 211	187	48	25.7%
6	211 - 275	243	64	26.3%
7	275 - 370	322.5	95	29.5%
8	385 - 500	442.5	115	26.0%
9	602 - 720	661	118	17.9%
10	787 - 950	868.5	163	18.8%



VNA Extenders to 1.1 THz

- 750-1100 GHz with 60 dB dynamic range typical
- Waveguide calibrated measurements
  - Waveguide SOLT (TOSM) calibration
  - Also on-wafer TRL calibration (wafer probes at 850 GHz)
- Interface is a key factor limiting measurements



Examples of Problems Caused by Lack of a Standard

- Incompatibility of interfaces from different manufacturers
  - Loose fit, Different dowel sizes, Binding, Damage…
- Waveguide sizes and frequency bands undefined above 325 GHz
  - For operation at > 325 GHz what waveguide size and band should be used? How to decide??
- MIL-spec naming convention doesn't extend well to THz
  - 90-140 GHz → WR-8 (Width 0.080")
  - 220-325 GHz → WR-3 (Width 0.034")
  - 500-750 GHz → WR-? (Width 0.015")
    - "WR-2" name conflicts with 330-500 GHz band
    - "WR-1" name conflicts with 600-900 GHz band

Goals of a Waveguide Interface Standard

- The main reason for developing a waveguide interface standard is to ensure compatibility of components from different groups
- The following features and goals are desirable:
  - Metric
  - Repeatable operation to at least 1 THz with low reflection.
  - Backward compatiblility with existing interfaces and waveguides below 325 GHz
    - Cost benefits of backward compatibility (not having to replace existing equipment) must be weighed against the potential performance advantages of a new but incompatible interface
  - Ease of machining.
  - Asexual, to avoid the need for male and female flanges.
  - Anticocking

IEEE P1785: A New Standard for Waveguide Above 110 GHz

The Microwave Theory and Techniques Society (MTT-S) of the IEEE has recently launched an activity to develop an international standard to define waveguides used at frequencies of 110 GHz and above—specifically, rectangular metallic waveguides. The standard's Working Group (P1785) has already met several times and is looking to define both the dimensions of the waveguides (and associated frequency bands) and their interfaces (that is flanges).

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Cables & Connectors Supplement

TABLE III

EXTENDED FREQUENCY BANDS AND WAVEGUIDE DIMENSIONS FOR THE IEEE STANDARD

Waveguide Name	Aperture Width (μm)	Aperture Height (μm)	Cut-off Frequency (GHz)	Minimum Frequency (GHz)	Maximum Frequency (GHz)
WM-71	71	35.5	2111.2	2900	4000
WM-57	57	28.5	2629.7	3300	5000

Fig. 1 A precision version of the so-called "UG-387" flange, showing the two additional dowel holes, immediately above and below the rectangular waveguide aperture.

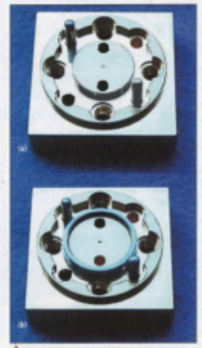

Fig. 2 Ring-centered waveguide flange: (a) with dowel holes and pins and (b) with the coupling ring in place.

"flanges". The Working Group is keen to ensure that it considered all flange designs that are used regularly at these frequencies (that is at 110 GHz and above). Therefore, a subgroup is being set up to investigate this matter further. Advice is also being sought from the entire millimeter- and submillimeter-wave communities to help identify any such candidate flange designs. *If you are aware of any flange design that you consider should be included in this standard, please contact the authors of this article.* The plan is that the standard, when published, will contain all appropriate flanges that will be used routinely in this frequency region.

For example, one such flange that is likely to be considered for inclusion in the standard is a precision version of the MIL-F-3922-67D flange (often called UG-387) that has been described[5] and is shown in **Figure 1**. Compared to the conventional UG-387 flange,[6] this precision version contains two additional alignment dowel holes immediately above and below the waveguide aperture. These additional holes (and the associated dowel pins) are specified to a tighter dimensional tolerance than the dowel holes and pins found on the conventional UG-387 flange. This leads to better mechanical alignment of the waveguide interfaces and hence lower electrical reflection from a mated pair of flanges.

Another type of flange that is likely to be considered for inclusion in the standard is a newer design—a ring-centered flange,[7] as shown in **Figure 2**. This design is compatible with both the UG-387 and precision UG-387 flange designs, but also uses a coupling ring to significantly improve the alignment of the flange interfaces.

It is expected that the IEEE standard, when published, will contain several flange designs, allowing end-users (such as customers, suppliers, etc.) to chose a design that best meets their given requirements. The role of the standard, in this context, is to provide the information needed for this choice to be made reliably.

CONCLUSION

The IEEE is well on its way to publishing a standard for defining rectangular metallic waveguides for use at frequencies above 110 GHz. Already, there are many applications emerging for the use of this part of the electromagnetic spectrum—millimetre-wave, submillimeter-wave, terahertz, etc.[8] Therefore, the publication of this standard is timely, and should serve our industry well for many years to come. ■

Nick Ridler and Ron Ginley are chair and vice-chair, respectively, of the IEEE P1785 working group (http://grouper.ieee.org/groups/1785).

References

1. N.M. Ridler, R.A. Ginley, J.L. Hesler, A.R. Kerr, R.D. Pollard and D.F. Williams, "Towards Standardized Waveguide Sizes and Interfaces for Submillimeter Wavelengths," *Proceedings of the 21st International Symposium on Space THz Technology*, Oxford, UK, 23-25 March 2010.
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3. IEC 60153-2, "Hollow Metallic Waveguides, Part 2: Relevant Specifications for Ordinary Rectangular Waveguides," Second Edition, 1974.
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7. H. Li, A.R. Kerr, J.L. Hesler, G. Wu, Q. Yu, N.S. Barker and R.M. Weikle II, "An Improved Ring-centered Waveguide Flange for Millimeter- and Submillimeter-wave Applications," *76th ARFTG Microwave Measurement Conference Digest*, December 2010, pp. 108-111.
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Ridler et al., Microwave Journal Cables & Connectors Supplement, Mar. 2011, pp. 20-24.

IEEE P1785 Workgroup

- Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above
  - Develop an international standard to define waveguides at > 110 GHz
- Three proposed parts to the standard
  - Part 1: Define waveguide dimensions and associated frequency bands
  - Part 2: Define waveguide interfaces (i.e. flanges)
  - Part 3: Recommendations for Interface Performance and Uncertainty Specifications

Part 1: IEEE P1785.1

IEEE P1785.1™/D3
Draft Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above. Part 1: Frequency Bands and Waveguide Dimensions

IEEE P1785.1™/D3
grouper.ieee.org/groups/1785

- P1785.1: Define a series of waveguide widths to cover the THz frequency range
  - Waveguide height defined to be half the width
- Define a series of frequency bands related to the waveguide widths

Key Design Criteria

- A. Frequency bands
  - The frequency bands (i.e. the suggested lower and upper frequencies of each waveguide band) should:
    - Be memorable (i.e. use whole numbers)
    - Be easily extendable from lower frequencies to higher frequencies (i.e. mapping from one decade to the next)
    - Agree with the existing values for WR-10 to WR-03, as given in the MIL standard
    - Form two contiguous interleaved series (i.e. should not contain gaps or overlaps in the frequencies covered by each series)

Ridler et al., Proc. ISSTT, 2010

Contiguous Interleaved Series

WR-#	Frequency GHz
3	220-325
4	170-260
5	140-220
6	110-170
8	90-140
10	75-110
12	60-90
15	50-75
19	40-60
22	33-50
28	26.5-40

Key Design Criteria

- B. Waveguide dimensions
  - It was soon agreed that a ratio of 2:1 would be used to describe the relationship between the waveguide aperture width and height (i.e. the ratio of the broad- to narrow-wall dimensions). Therefore, it was only necessary to define the waveguide broad-wall dimension (called the ‘width’, by convention). The waveguide widths should:
    - Where appropriate, be effectively identical (within stated tolerances) to sizes WR-10 to WR-03, as given in the MIL standard)
    - Avoid fractional micron values (i.e. x.y microns)
    - Where appropriate, be very similar to sizes WR-2.8 to WR-1.0, as given in Hesler (ISSTT Proc., 2007, pp. 100-103)

Ridler et al., Proc. ISSTT, 2010

- Waveguide sizes & bands described in Hesler et al.
  - Used by variety of groups, including the ALMA project, VDI, and other THz manufacturers

TABLE 2: CURRENT AND PROPOSED WAVEGUIDE BANDS

Proposed Band Designation	EIA Band Designation	Internal Dimensions (mils)	Internal Dimensions (mm)	Frequency Range (GHz)	TE(10) Cutoff (GHz)
WR- 10	WR- 10	100 x 50	2.540 x 1.270	75.0 - 110.0	59.0
WR- 8	WR- 8	80 x 40	2.032 x 1.016	90.0 - 140.0	73.8
WR- 6.5	WR- 6	65 x 32.5	1.651 x 0.826	110.0 - 170.0	90.8
WR- 5.1	WR- 5	51 x 25.5	1.295 x 0.648	140.0 - 220.0	116
WR- 4.3	WR- 4	43 x 21.5	1.092 x 0.546	170.0 - 265.0	137
WR- 3.4	WR- 3	34 x 17	0.864 x 0.432	220.0 - 330.0	174
WR- 2.8	n/a	28 x 14	0.711 x 0.356	265.0 - 400.0	211
WR- 2.2	n/a	22 x 11	0.559 x 0.279	330.0 - 500.0	268
WR- 1.9	n/a	19 x 9.5	0.483 x 0.241	400.0 - 600.0	311
WR- 1.5	n/a	15 x 7.5	0.381 x 0.191	500.0 - 750.0	393
WR- 1.2	n/a	12 x 6	0.305 x 0.152	600.0 - 900.0	492
WR- 1.0	n/a	10 x 5	0.254 x 0.127	750.0 - 1100.0	590

Hesler et al., ISSTT Proc., 2007, pp. 100-103

Key Design Criteria

- C. Related quantities
  - In addition to the above, the waveguide scheme should provide, for all bands:
    - Relatively uniform fractional bandwidths
    - Approximately constant k-factors (where k1 ≈ 1.25 and k2 ≈ 1.90)
      - The k-factors relate the band edges to the TE10 cutoff frequency
    - Similar ratios of cut-off frequencies (or, equivalently, waveguide widths) for adjacent bands

Ridler et al., Proc. ISSTT, 2010

Design Trade-offs

- There is a key design trade-off between either:
  - memorable sizes and bands
    or
  - uniform bandwidth and k-factors (geometric based)
- For example look at 1 THz waveguide
  - "Memorable" WM-250 band
    - Width 250 um, Band 750-1100 GHz
    - k1=1.25, k2=1.834
    - Bandwidth 1.47 (compared with up to 1.57 for other bands)
  - "Geometric" WM-254 band
    - Width 254 um, Band 735-1115 GHz
    - k1=1.25, k2=1.89
    - Bandwidth 1.52 (similar to other bands in series)
- Workgroup tried to find best compromise
  - Kept example of earlier IEC 60153-2 standard in mind
    - IEC 60153-2 followed strict geometric approach

IEC 60153-2 Standard

Relevant Specifications for ordinary rectangular waveguides

- Frequency range based upon strict k-factors
  - k1=1.25 and k2=1.9
- Waveguide bands not memorable
  - Also not contiguous
- Not widely adopted by community

Waveguide size determines frequency range (using k1=1.25, k2=1.9)

Frequency Range (Ghz)	Waveguide Designation			Internal Dimensions (mm)
	British WG	IEC R	EIA WR	
73.8 - 112.0	27	900	10	2.540 x 1.270
92.3 - 140.0	28	1200	8	2.032 x 1.016
114.0 - 173.0	29	1400	6	1.651 x 0.826
145.0 - 220.0	30	1800	5	1.295 x 0.648
172.0 - 261.0	31	2200	4	1.092 x 0.546
217.0 - 330.0	32	2600	3	0.864 x 0.432

Flann Catalog

IEEE P1785.1^{TM}/D3

Table 1—Waveguide sizes and frequency ranges

Name	Width (µm)	Height (µm)	Cut-off frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)
WM-2540	2540	1270	59.014	75	110
WM-2032	2032	1016	73.768	90	140
WM-1651	1651	825.5	90.791	110	170
WM-1295	1295	647.5	115.75	140	220
WM-1092	1092	546	137.27	170	260
WM-864	864	432	173.49	220	330
WM-710	710	355	211.12	260	400
WM-570	570	285	262.98	330	500
WM-470	470	235	318.93	400	600
WM-380	380	190	394.46	500	750
WM-310	310	155	483.54	600	900
WM-250	250	125	599.58	750	1100

TABLE III
COMPARISON BETWEEN NEW IEEE AND EXISTING MIL WAVEGUIDE NAMES

MIL name	New IEEE Name	f_{min} (GHz)	f_{max} (GHz)
WR-10	WM-2540	75	110
WR-08	WM-2032	90	140
WR-06	WM-1651	110	170
WR-05	WM-1295	140	220
WR-04	WM-1092	170	260
WR-03	WM-864	220	330

TABLE IV
COMPARISON BETWEEN NEW IEEE AND 'EXTENDED MIL' WAVEGUIDE NAMES

'Extended MIL' name	New IEEE Name	f_{min} (GHz)	f_{max} (GHz)
WR-2.8	WM-710	260	400
WR-2.2	WM-570	330	500
WR-1.9	WM-470	400	600
WR-1.5	WM-380	500	750
WR-1.2	WM-310	600	900
WR-1.0	WM-250	750	1100

Ridler et al., Proc. ISSTT, 2010

Name	Width (µm)	Height (µm)	Cut-off frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)
WM-2540	2540	1270	59.014	75	110
WM-2032	2032	1016	73.768	90	140
WM-1651	1651	825.5	90.791	110	170
WM-1295	1295	647.5	115.75	140	220
WM-1092	1092	546	137.27	170	260
WM-864	864	432	173.49	220	330
WM-710	710	355	211.12	260	400
WM-570	570	285	262.98	330	500
WM-470	470	235	318.93	400	600
WM-380	380	190	394.46	500	750
WM-310	310	155	483.54	600	900
WM-250	250	125	599.58	750	1100
WM-200	200	100	749.48	900	1400
WM-164	164	82	914.00	1100	1700
WM-130	130	65	1153.0	1400	2200
WM-106	106	53	1414.1	1700	2600
WM-86	86	43	1743.0	2200	3300

Extend to higher frequency bands by scaling lower bands by factors of 10

Name	Width (µm)	Height (µm)	Cut-off frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)
WM-71	71	35.5	2111.2	2600	4000
WM-57	57	28.5	2629.8	3300	5000

IEEE P1785.1^{TM}/D3
grouper.ieee.org/groups/1785

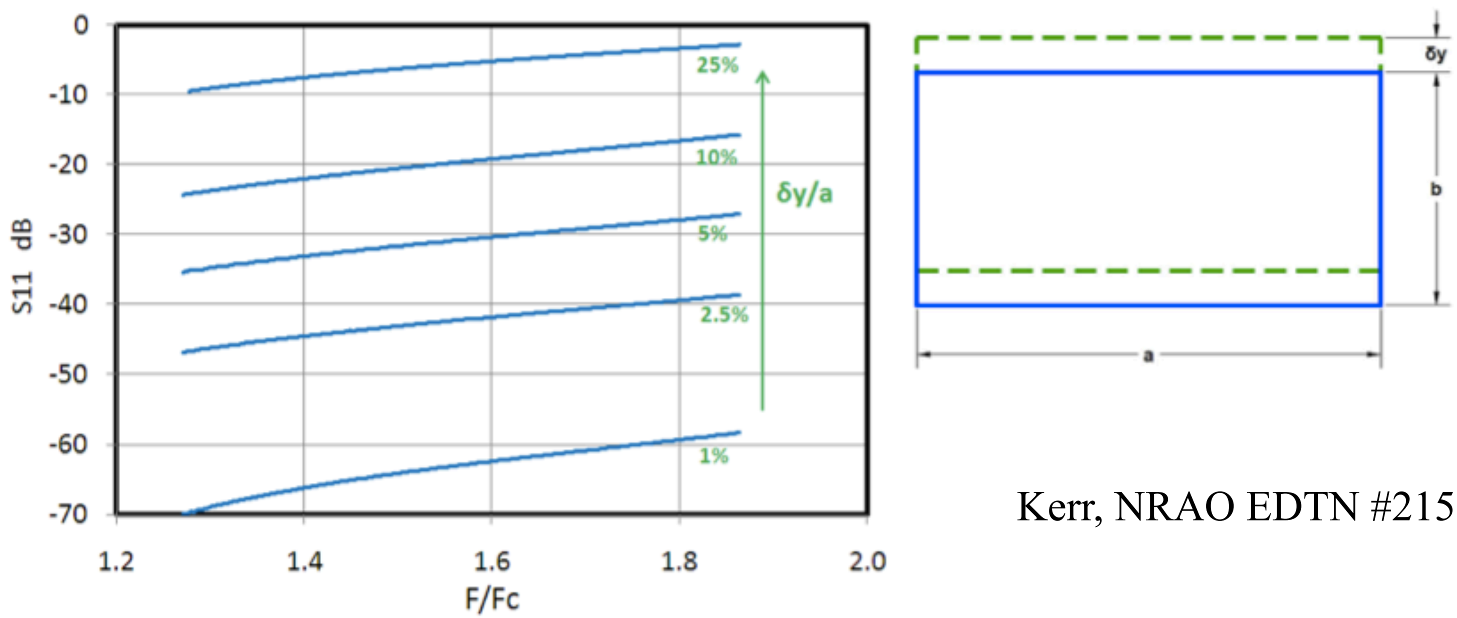
IEEE P1785.1^{TM}/D3 Current Status

- IEEE P1785.1^{TM}/D3 has passed the first sponsor ballot in the IEEE standards committee
  - Near unanimous decision
  - 19 Comments
    - Most related to formatting or grammar
    - 3 relatively minor technical comments
- P1785.1 is heading back for recirculation vote
  - Should occur in the next month

Part 2: IEEE P1785.2

- P1785.2: Define one or more THz waveguide interfaces for use in the standard
- Key Design Criteria
  - Backward compatibility with existing interfaces and waveguides
  - Ease of machining.
  - Asexual, to avoid the need for male and female flanges.
  - Anticocking
  - Repeatable operation to >1 THz with low reflection

Mismatch Caused by Flange Misalignment



Kerr, NRAO EDTN #215, 2009

Fig. 4. Effect of flange misalignment of rectangular waveguides with 2:1 nominal aspect ratio. Only misalignment in the *b* direction is considered because misalignment in other directions has a smaller effect.

- E-plane offsets are dominant
- Rotation is not a significant effect and can be ignored for the flanges under consideration

Mismatch for Several Waveguide Bands

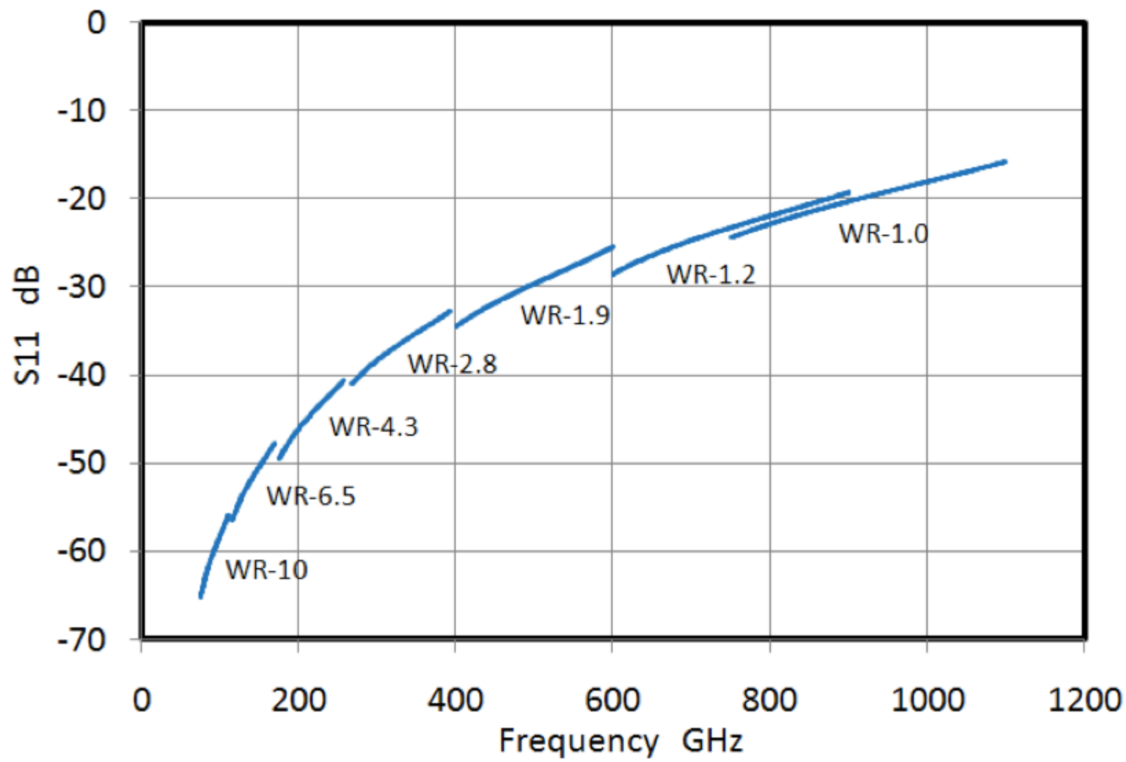


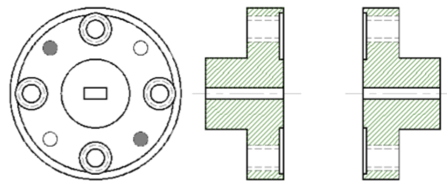
Fig. 4. Reflection at a waveguide joint with a 0.001" (25 μm) misalignment in the *b* direction, for several waveguide bands (simulated [7]).

Kerr, Proc. ISSTT, 2009

Candidate THz Waveguide Interfaces - Examples

Hesler et al. modified UG-387 type

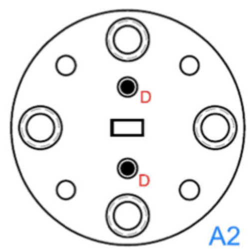
- Anti-cocking version of UG-387 with tighter tolerances
- Used for ALMA project, VDI Components



Hesler et al, Proc. ISSTT, 2007.

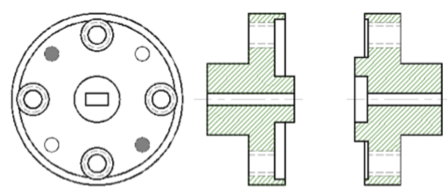
Modified UG-387 with Inner Dowels

- Commonly used in industry



Lau & Denning boss and socket interface

- Potentially has the most precise alignment
- Sexed interfaces
- New unpublished variant is stated to be compatible with UG-387 (no RF testing)

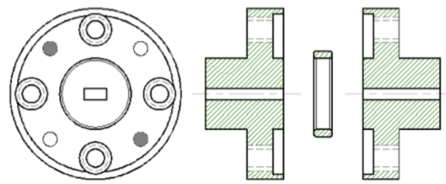


Lau et al, 69th ARFTG, 2007.

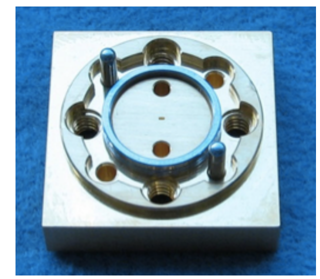
Candidate THz Waveguide Interfaces

Kerr et al. Ring-Centered Interface

- Compatible with UG-387



Kerr, Proc. ISSTT, 2009



Horibe et al. modified Oshima type

- Similar to ring flange, but alignment using outer ring

Horibe, 79th ARFTG, Montreal, 2012

Measurements of Waveguide Repeatability

- Perform a one-port calibration, with the last standard being a load
- Before disconnection the trace will show the system noise floor
  - Calibration corrects for load & interface imperfections
- Disconnecting and reconnecting the load will randomizes the interface alignment
  - Allows a direct measurement of load repeatability
- Disconnect and reconnect the load multiple times to gather statistics

Interface Repeatability at WM-380

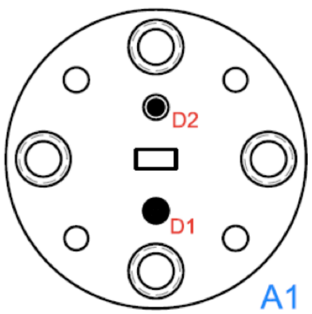
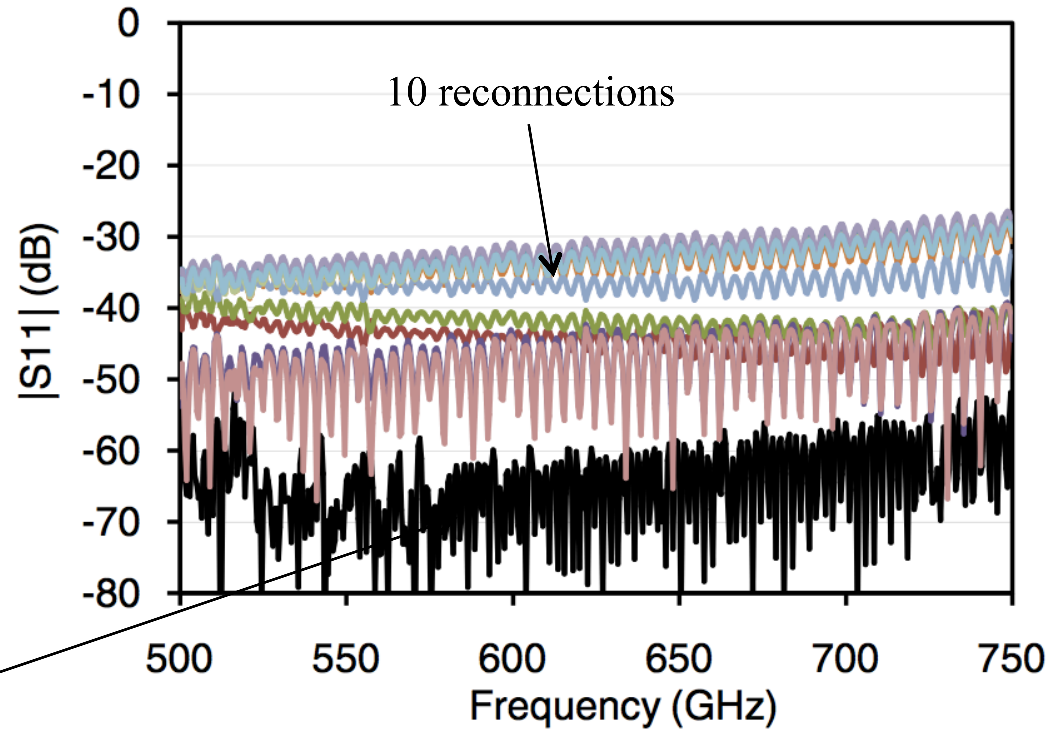


Fig. 1. Interface A1. Two unequal inner dowels.



System Noise Floor

(a). |S11| measured for ten disconnection/reconnection cycles.

Li, 79th ARFTG, Montreal, 2012

Interface Repeatability at WM-380

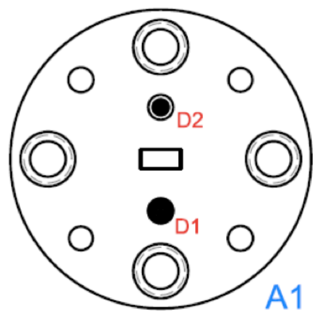
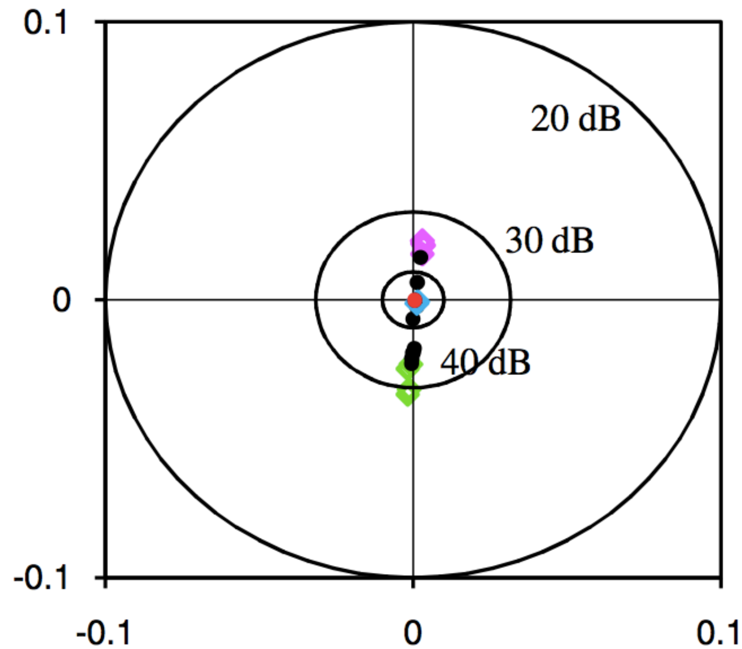


Fig. 1. Interface A1. Two unequal inner dowels.

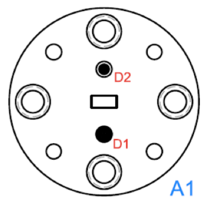


(c). Complex S11 on a Smith Chart at 625 GHz. The pink, green, and light blue empty diamonds are measurements with the flanges pushed in the *H*- and *E*-planes, and in rotation, respectively, while tightening the screws. The ten black dots represent the disconnection/re-connection data. And the red dot is the initial measurement before disconnection of the load.

Li, 79th ARFTG, Montreal, 2012

Interface Repeatability at WM-380

"A1" Design



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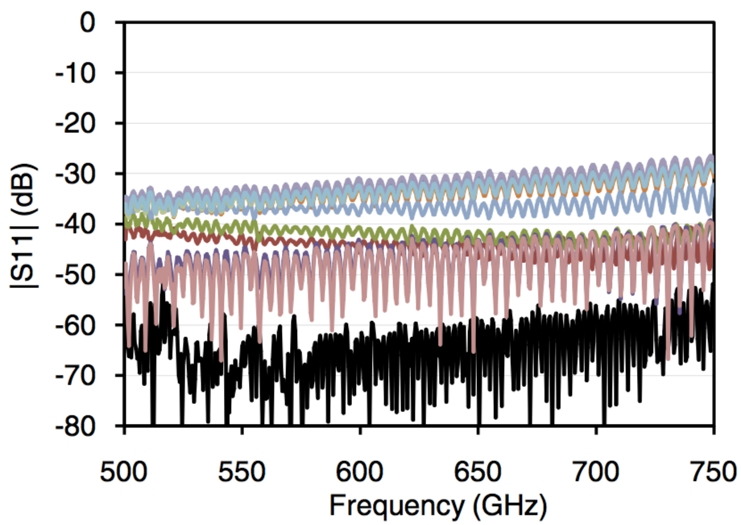


(a). |S11| measured for ten disconnection/reconnection cycles.

Ring-Centered Design

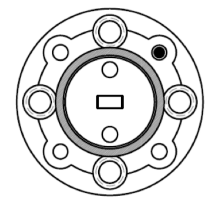
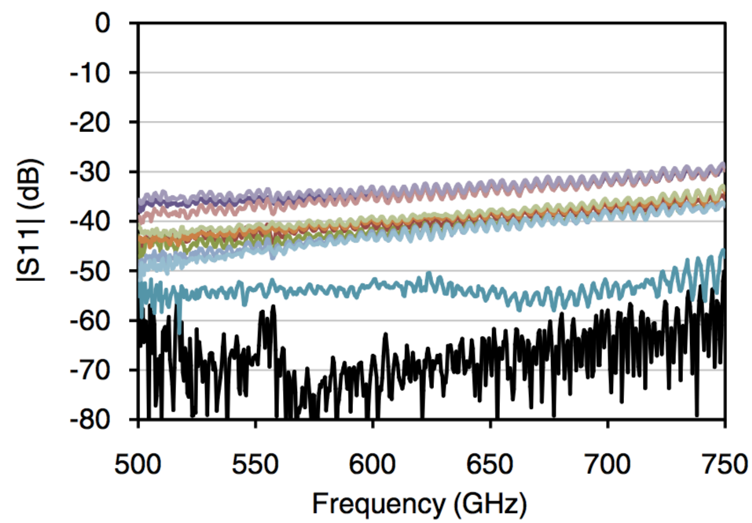


Fig. 4. Ring-centered flange. Close fitting coupling ring and loose pin P.

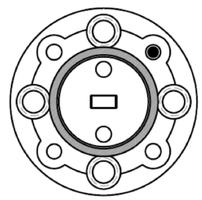


(a). |S11| measured for ten disconnection/reconnection cycles.

Li, 79th ARFTG, Montreal, 2012

Interface Repeatability at WM-380

Ring-Centered Design



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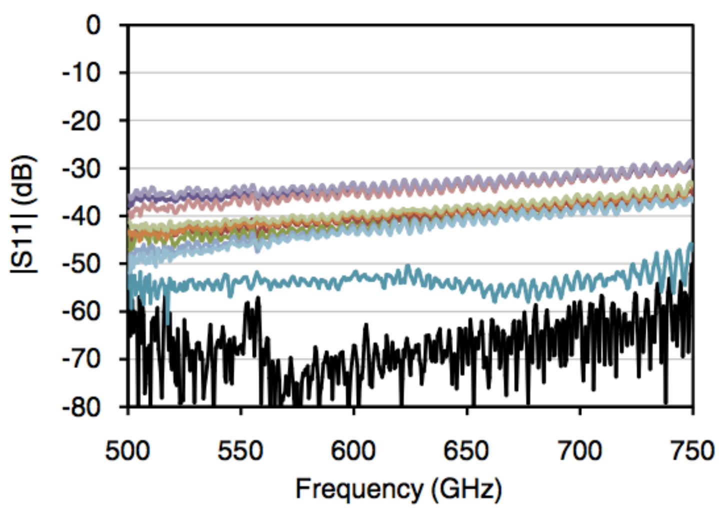
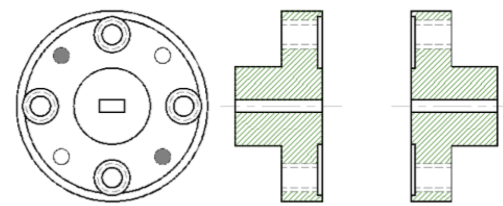
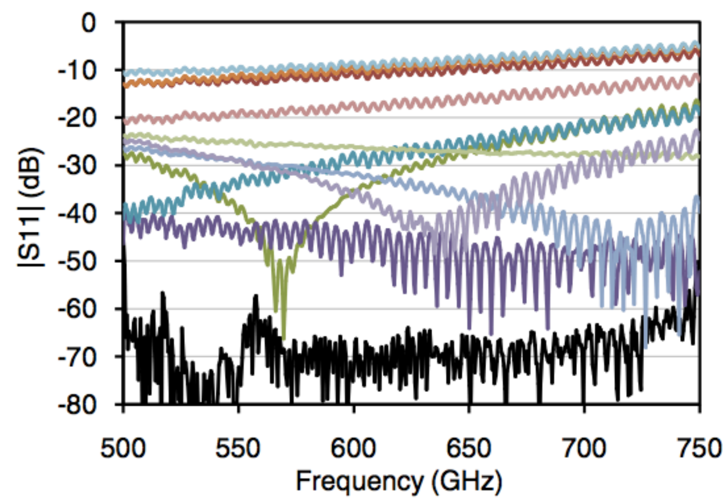


(a). |S11| measured for ten disconnection/reconnection cycles.

Standard UG-387

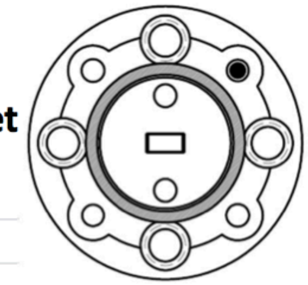




(a). |S11| measured for ten disconnection/reconnection cycles.

Li, 79th ARFTG, Montreal, 2012

Analysis of Interface Misalignment



Example of Alignment Analysis Spreadsheet

Ring-centered interface -- using UG-387 outer pins

	Metric		Nominal (mm)	Tolerance (mm) +	Tolerance (mm) -	Min (mm)	Max (mm)	Position tolerance zone diameter (mm)	
1	Boss diameter	Db	9.525	0.000	0.005	9.520	9.525	Z1 =	0.005
2	Ring diameter	Dr	9.528	0.003	0.000	9.528	9.530		--
3	Outer pin hole diameter	Dh	1.702	0.025	0.000	1.702	1.727	Z2 =	0.051
4	Pin diameter	Dp	1.562	0.000	0.013	1.549	1.562	Z3 =	0.076
5	Pin hole PC diam	PCD	14.288	--	--	--	--		--

6 **Interference test** -- Want (Dr,min - Db,max) + (Dh,min - Dp,max) - (Z1 + Z2/2 + Z3/2) > = 0

7 (Dr,min - Db,max) + (Dh,min - Dp,max) - (Z1 + Z2/2 + Z3/2) = 0.0740

				% of *a* for WM250		Approx |S11| for WM250 (dB)
8	Max misalignment in the a direction*	**0.015**	mm	**6.0**	%	-28
9	Max misalignment in the b direction*	**0.015**	mm	**6.0**	%	-24
10	Maximum angular misalignment	**2.1**	deg	--		-55

* Approximate dB values from Figs. 4-7 of NRAO EDTN215: Link

Presented by A.R. Kerr at the June 2012 P1785 Meeting

Analysis of Interface Misalignment

- Look at maximum interface offset and mismatch at WM-250 Band for various interface designs
- Work is still underway to reconcile predicted S11 with measurements

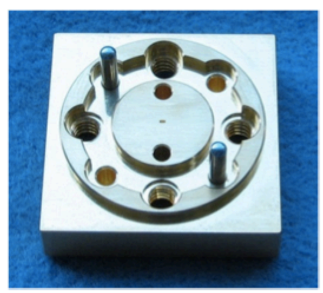
	a - misalignment microns	*b* - misalignment microns	|S11|max in WM-250 dB*
Candidate A1 (unequal dowels)	19	14	-25
Ring-centered (+ UG-387 outer pins)	15	15	-24
Hesler et al. (improved UG-387)	60	60	~ -3
UG-387	152	152	large
* Approximate dB values from Figs. 4-7 of NRAO EDTN-215			
In all cases, min dowel-to-hole clearance is 3 microns (in diameter)			

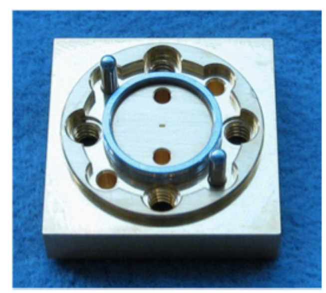
Presented by A.R. Kerr at the June 2012 P1785 Meeting

Analysis of Interface Misalignment

Pros and Cons of Candidate-A1 and Ring-Centered Interfaces

	Candidate-A1	Ring-Centered
Compatibility with UG-387 and variants	Compatible with all, except ring-centered	Compatible with all including Candidate-A
Ease of use	Requires two dowels of slightly different size -- the wrong choice will cause damage, or poor alignment.	Uses a single standard ring
E-plane split-block components	Maintaining dowel hole tolerance requires very tight alignment between block halves during assembly	Ring provides 3-axis alignment during assembly
Wear and tear	Dowel holes enlarge by a few microns after a lot of use	Have not seen significant wear on bosses (much larger contact area than dowels)
Through shims for TRL cal	OK	Need two-piece shims





Presented by A.R. Kerr at the June 2012 P1785 Meeting

IEEE P1785.2 Current Status

- P1785 Meeting at IMS (Montreal 2012) was predominately focused in the interface issue
- The Workgroup voted unanimously to continue work on a single interface encompassing the "A1" and Ring-Flange designs
  - A subcommittee will continue work on the interface details before the next P1785 meeting in November 2012
- The Lau-Denning Interface was also approved for further study
  - A new variant of the interface was presented at the Workgroup
    - RF test results and further analysis are needed

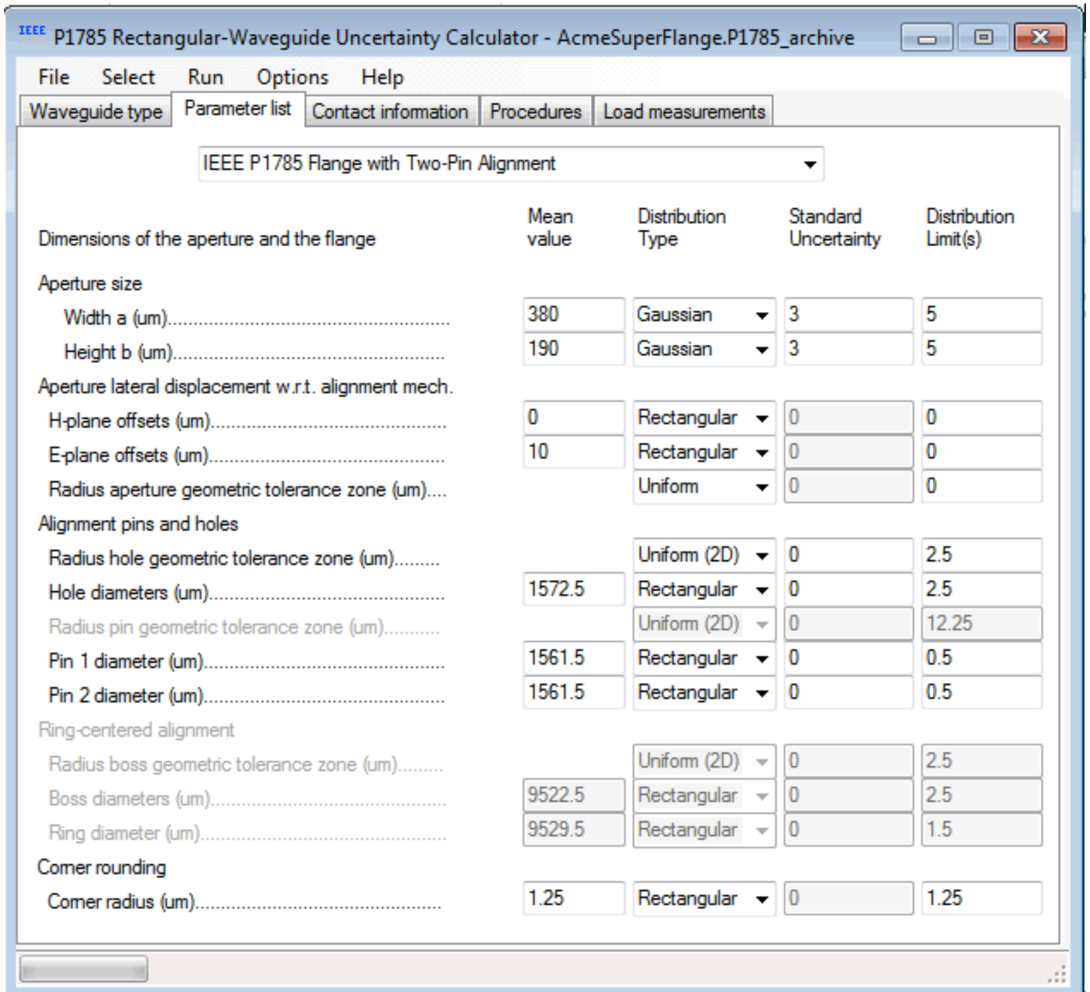
Part 3: IEEE P1785.3

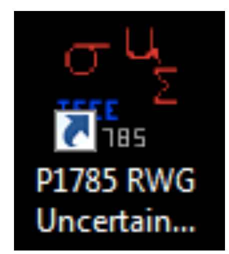
- P1785.3: Recommendations for Interface Performance and Uncertainty Specifications
  - Part 3 was added relatively recently
    - Based upon experience gained during analysis of the different interface designs

Part 3: IEEE P1785.3

- The goal of Part 3 is to provide a minimum amount of information that should be provided by a manufacturer so that the End User can perform a complete uncertainty analysis of a measurement
- Dylan Williams (NIST-Boulder) has been developing a waveguide interface calculator
  - To eventually appear on the web at:
    - www.boulder.nist.gov/dylan

Rectangular-Waveguide Uncertainty Calculator





www.boulder.nist.gov/dylan

IEEE P1785 Rectangular-Waveguide Uncertainty Report

Waveguide type: WM 380 (WR 1.5)
Flange type: IEEE P1785 Flange with Two-Pin Alignment
Model: Acme Super-Strength Flange
Serial or lot numbers: SN 1006-1178

Contact Information

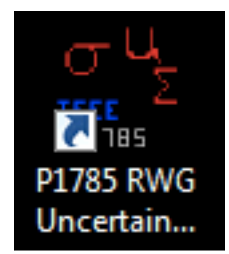
Manufacturer or test laboratory	Acme Flange Company
Address	101 Acme Lane
	Boulder, CO
	80305
Telephone	(303) 447-9863
E-Mail	flanges@acme.com
Test engineer	Bo Jangles

Flange Description and Markings

Triangle points up on this design.

Recommended Cleaning and Connection Procedures

Clean well before use.
Connect gently.



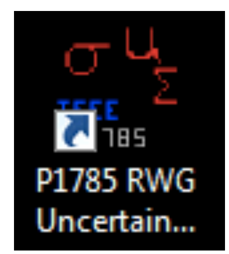
www.boulder.nist.gov/dylan

Standard-Uncertainty Summary Table (From Sensitivity Analysis at 625 GHz)[2]

Component	Standard uncertainty in the reflection coefficient of a flange-to-flange connection	
	Linear	Decibels
Aperture size		
Width a	.0025	-51.9
Height b	.0078	-42.1
Lateral displacement		
Lateral displacement repeatability[3]	.0025	-51.9
Lateral displacement reproduceability[4]	.0327	-29.7
Total lateral displacement	.0328	-29.7
Corner rounding		
Corner radius	.0000	-100.8
Total	.0338	-29.4

Summary Table From Monte-Carlo Analysis at 625 GHz[5]

Totals	Uncertainty in the reflection coefficient[6]	
	Linear	Decibels
68 % confidence level	.0262	-31.6
95 % confidence level	.0606	-24.3



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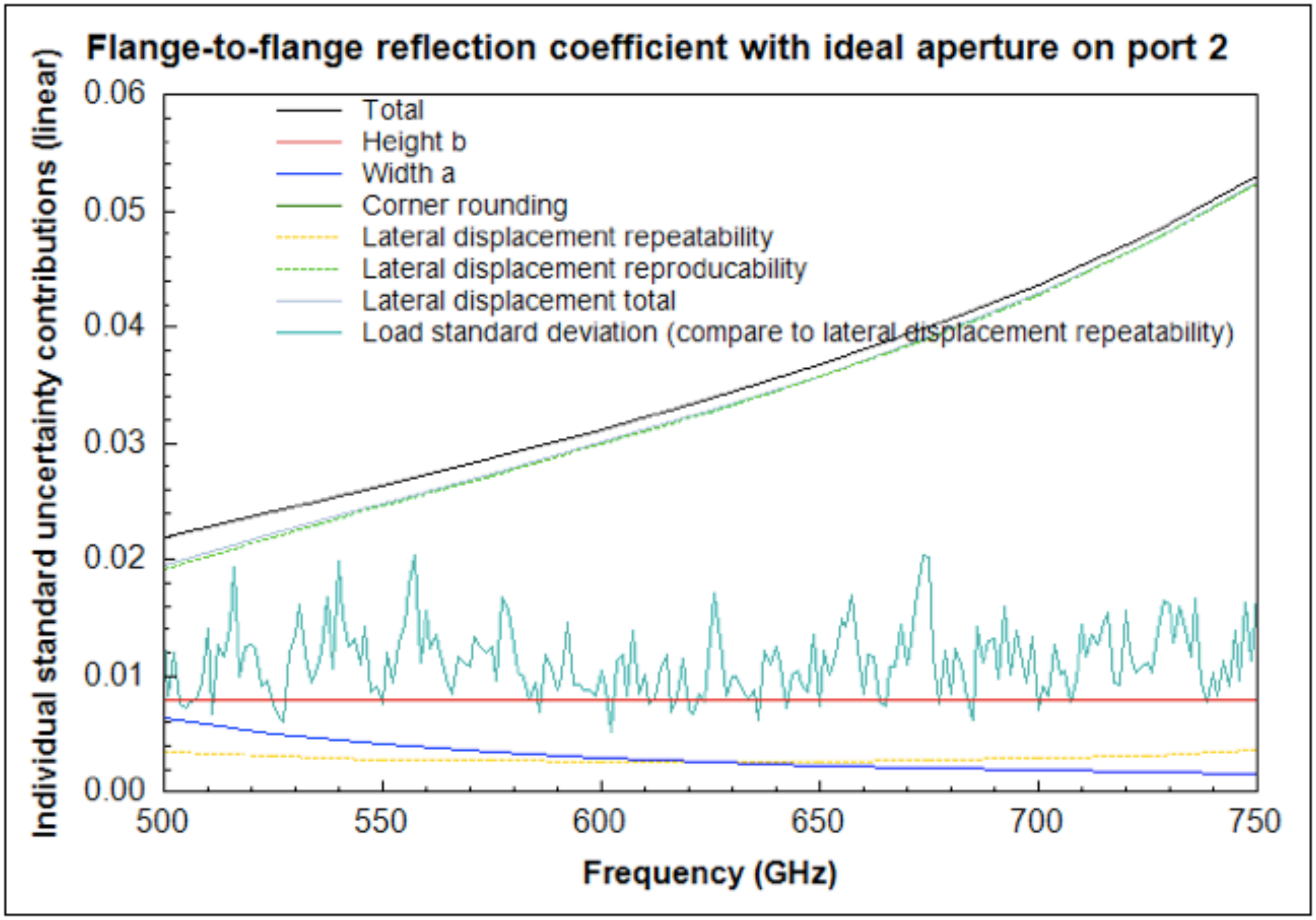

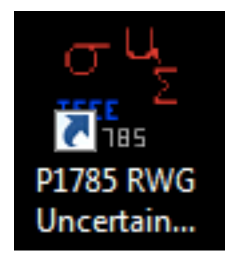

www.boulder.nist.gov/dylan

IEEE P1785 Workgroup

- Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above
- Part 1: Define waveguide dimensions and associated frequency bands
  - Passed sponsor ballot, recirculation vote next
- Part 2: Define waveguide interfaces (i.e. flanges)
  - The detailed design of two interfaces are being worked on for potential inclusion in the standard
- Part 3: Recommendations for Interface Performance and Uncertainty Specifications
  - In relatively early stages

Future Research

- Improved interfaces for use at > 1 THz
  - Current interfaces have usable performance at 1 THz performance
    - However, interface is still a limiting factor
  - What about measurements at (e.g.) 2 THz?
- Current interface designs are large compared with waveguide
  - Options for ultra-miniature interface
- Manufacturing – reduced cost