FINAL PUBLISHABLE REPORT

Grant Agreement number	17SIP08
Project short name	NeWITT
Project full title	New Waveguide Interfaces for Terahertz Technologies

Project start date and duration:	01 September 2018, 18 months	
Coordinator: Karsten Kuhlmann, PTB Project website address: --	Tel: +49 531 592 2220	E-mail: karsten.kuhlmann@ptb.de
Primary Supporter: James Watts, Flann Microwave, 01 September 2018 to 20 February 2020 Ian Crane, Flann Microwave, 21 February 2020 to 29 February 2020		
Internal Funded Partners: 1. PTB, Germany 2. NPL, UK	External Funded Partners:	Unfunded Partners: 3. Flann, UK

TABLE OF CONTENTS

1 Overview

Several European industrial sectors require precise and reproducible measurements of high frequency signals which cannot be reproduced without standardised interfaces. Prominent uses are modern multi-sensor applications, including autonomous driving and smart cities, as well as more traditional areas such as security, radio astronomy, medical/healthcare technologies and remote sensing of climate change. Even next generation communication standard 5G uses frequencies up to 90 GHz, subsequent generations will reach even higher frequencies. Thus, current and future applications like Internet of Things (IoT) or Machine to Machine (M2M) communication, which rely on available infrastructures, will operate at frequencies above 100 GHz. The aim of this project was to maximise the uptake, by the end-user community, of a key output from the EMRP project SIB62 HFCircuits – in particular, the new IEEE 1785 series of standards ("Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above – Parts 1, 2 and 3"). Therefore, this project prepared a Good Practice Guide (GPG) and an open source software to promote the adoption and use of the new IEEE 1785 series of standards by the millimetre-wave and terahertz end-user communities. Additionally, feedback on the IEEE 1785 standards was sent to IEEE so that it can be taken into account in the revision of IEEE Std 1785.1-2012, which is scheduled for 2022.

2 Need

In Europe, typical applications of systems using frequencies of 100 GHz and above include autonomous vehicles and smart cities, as well as security, radio astronomy, medical/healthcare technologies and climate change monitoring. These applications represent both existing and emerging technologies and markets. It is important for the European industry that products and measurement results follow international standards that are compatible at the international level. This is especially important where signal level restrictions must be met, e.g. a signal at a certain frequency must be below a certain value to not interfere with other signals or to not endanger human health. To achieve all the above, a standardised measurement interface is a key component. Until recently, users have been advised to purchase their equipment from a single manufacturer, thus ensuring compatibility of the waveguide sizes and connections. However, this leads to problems if waveguide components are replaced, interchanged, or resold.

Before 2008 (the year in which the IEEE P1785 Working Group was established), measurement systems for frequencies up to 500 GHz were already commercially available. Since that time, the frequency region in which research and development is carried out has been extended to 1.5 THz and beyond. The end-users of millimetre-wave and terahertz systems require reliable and standardised waveguide sizes and interfaces. The dimensions of the waveguide apertures must be well defined as well as the frequency limits, and the interfaces must be compatible with older designs while also providing the necessary precision for millimetre-wave and terahertz electrical signals. The IEEE 1785 series of standards address all these issues, but many end-users were not aware of this or simply continued to use old methods (with their inherent old problems). To cope with extremely high frequencies (up to 3.3 THz), the interface designs are somewhat more complex than in the past, which also discouraged some end-users from adapting existing systems. These issues were addressed with user information (e.g. GPG), software tools and knowledge dissemination activities (e.g. European workshop).

3 Objectives

Precise and reproducible measurements of high frequency signals require standardised interfaces. The aim of this project was to maximise the uptake, by the end-user community, of the new IEEE 1785 series of standards. The primary objective of this project was:

- To promote the adoption and use of the new IEEE 1785 series of standards by the millimetre-wave and terahertz end-user communities to support wider dissemination and uptake by academic and industrial sectors.

4 Results

All work undertaken in the project was aiming to achieve the primary objective as described in Section 3. The work was split in four main subsections, as described below. The excellent collaboration between the partners contributed to the achievements of the project targets.

4.1 Good Practice Guide

The project produced a Good Practice Guide (GPG) on rectangular waveguide connections above 100 GHz, with the assistance of all project partners. PTB provided data from several test measurements and the rest of the project partners reviewed and improved the document with additional content. The measurement data can be accessed here:

https://oar.ptb.de/resources/show/10.7795/720.20200625

With this GPG, the end-user community can make reliable waveguide measurements with standardised flanges as shown in Figure 1.

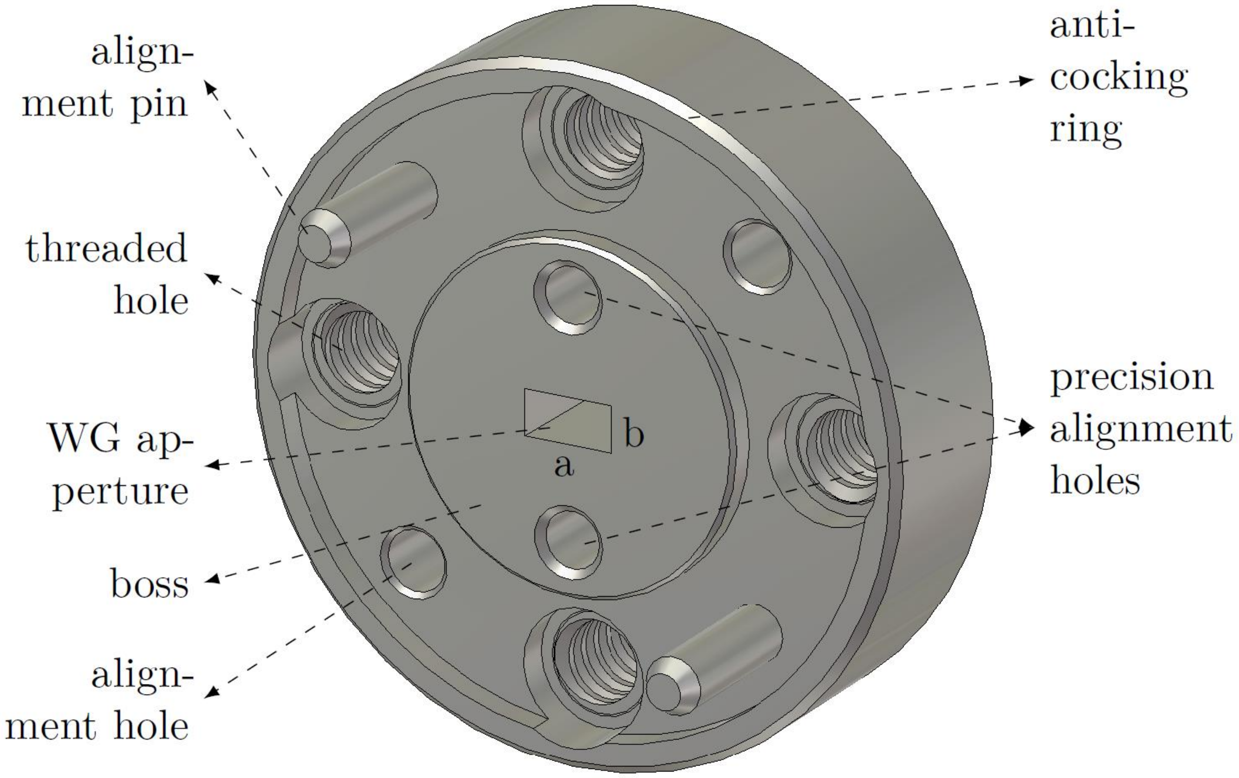

Figure 1: Example flange for rectangular waveguide.

The GPG consists of four chapters and is 26 pages long. Its main focus is on the right usage of the different existing flanges, as well as on performing the actual measurements. It also includes guidance on how to prepare measurements set-ups as well as the related documentation. Figure 2 shows exemplarily the difference in measurement repeatability, if different torques are applied to fasten the flange bolts.

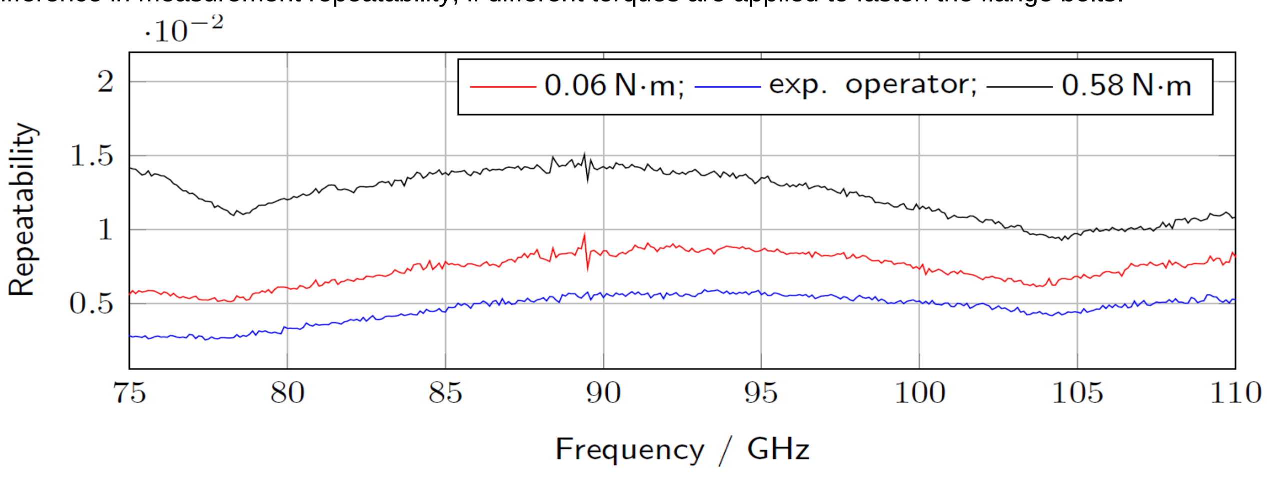

Figure 2: Repeatability measurements for different torques.

The GPG was submitted for publication to the convenor of the EURAMET Subcommittee Radiofrequency and Microwave (SC RF and MW), which is part of the Technical Committee for Electricity and Magnetism (TC-EM). The GPG will be reviewed on a regular basis. As a similar document did not exist before, the writing, reviewing, and publishing of the GPG is considered as progress beyond the state of the art. The GPG is published on the PTB OAR (Open Access Repository) and can be accessed here:

https://doi.org/10.7795/530.20190805

4.2 Software

The project also created and published a documented open source software for calculating the electrical performance of connected waveguides. PTB wrote the software while the other project partners tested it and gave feedback for further improvements. It is based on mechanical dimensions and tolerance data of the involved flanges (as depicted in Figure 1) and follows the procedures of part 3 of the IEEE 1785 series of standards. To be capable of propagating uncertainties through nonlinear systems, a Monte Carlo approach was used. The software functions cover the basic physical effects for mated waveguides to calculate repeatability. This includes:

- lateral displaced rectangular waveguides
- corner rounding
- angular displaced rectangular waveguides
- steps in waveguide height and width

When all input parameters are entered correctly, a documentation helps with this, repeatability and return loss results are calculated and plotted as shown in Figure 3.

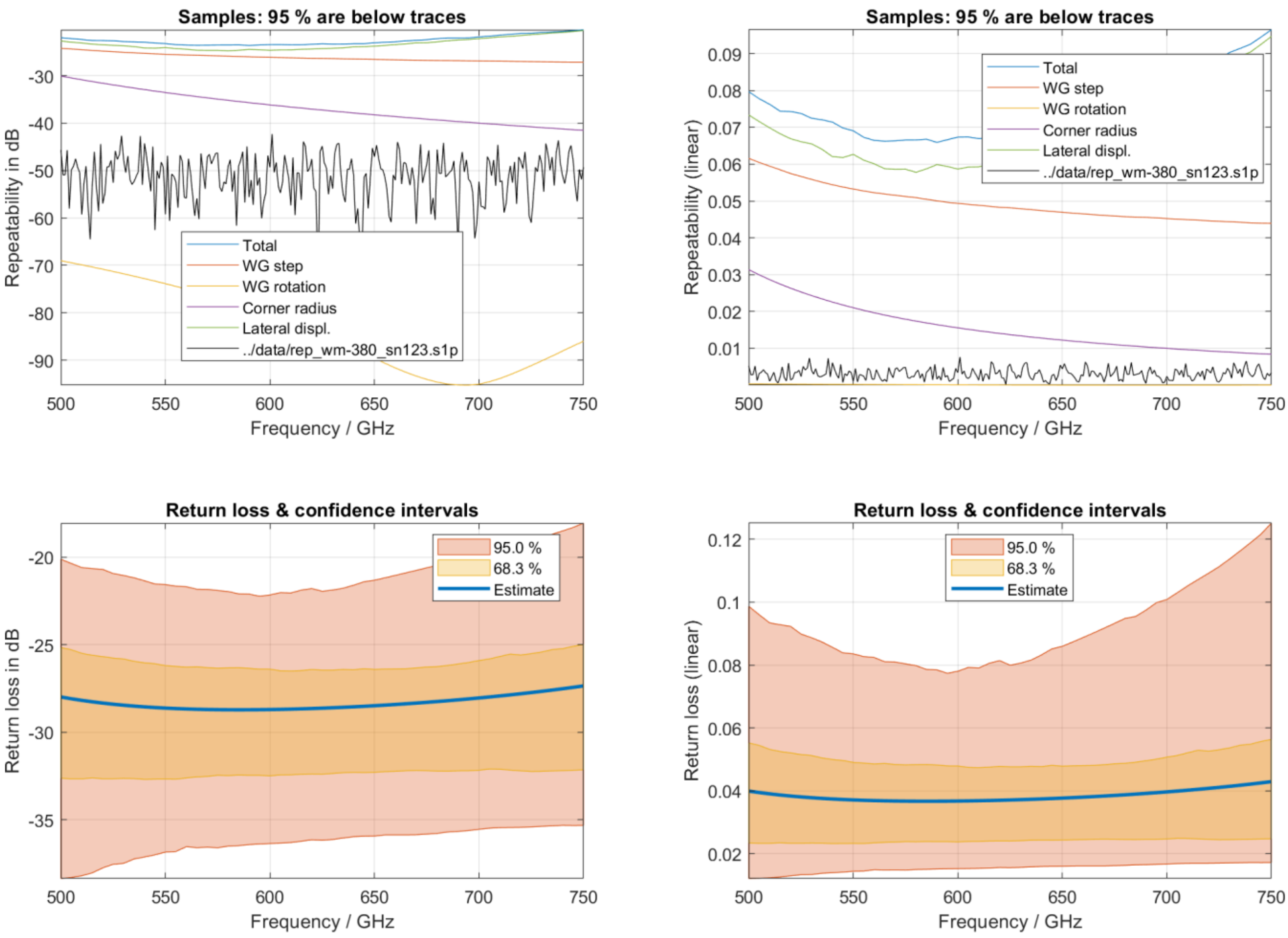

Figure 3: Simulated repeatability and return loss and measured repeatability.

A detailed and frequency depended analysis of each physical effect can be performed on logarithmic and linear scales. And, if available, measurement data can be plotted together with the simulation result.
Though a similar software has been published by NIST (USA) shortly after the publishing of the IEEE 1785

series of standards, this work is considered as progress beyond the state of the art, because it is open source. The software is written in MATLAB and can accessed here:
https://doi.org/10.24433/CO.2045615.v1

4.3 Workshop

The GPG and software that were described in Sections 4.1 and 4.2 have been disseminated in detail at an international full day workshop with the title “Measurements and Waveguides for Millimetre-wave and Terahertz Frequencies”. The workshop was organised by NPL, while contributions from the other project partners who gave presentations. The workshop took place during the European Microwave Week (EuMW), in Paris, France, on 4th October 2019. The workshop reviewed the latest developments of waveguide technology and focussed on both the new waveguide sizes and interfaces. It included activities by both IEEE and IEC standardisation bodies. The workshop also presented the current state of the art of the measurements – both using waveguide and quasi-optical techniques – that are available at millimetre-wave through to terahertz frequencies (i.e. from 30 GHz to at least 1.5 THz). One of the main topics that were discussed, was related to the table shown below (Figure 4) by Hans Ulrich Nickel as presented with the title DESIGN CONSIDERATIONS FOR AN IMPROVED INTERFACE FOR MILLIMETER WAVEGUIDES.

Interface Requirements for Current Interfaces

Interface designation	hermaphroditic	0° and 180°	cross sections R, C, …	R 740	R 900	R 2.6k	R 26k	toler. scale with w/g	free E plane	free H plane	flange-to-flange	flange-to-blind	blind-to-blind	captive alignment el.	captive clamping el.	diameter < 19 mm	length < 6.35 mm	easily repairable	interface apparent	O-ring seal	compatible to IEEE1785-2a
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
Philips Claw-Fl.	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	N	N	Y	N	N	Y	Y	N	Y	N
M3922/67	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	Y
“UG-387mod”	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	Y
M3922/66	Y	Y	Y	Y	Y	N	N	N	N	N	Y	N	N	Y	N	Y	Y	N	Y	N	N
M3922/74	Y	Y	Y	N	N	Y	N	N	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	N	N
IEEE1785-2a = 60154 IEC-UFC	Y	Y	Y	N	Y	Y	Y	N	N	N	Y	Y	N	N	Y	N	Y	N	N	N	Y
IEEE1785-2b	Y	Y	Y	N	Y	Y	Y	N	N	N	Y	Y	N	N	Y	N	Y	N	N	N	Y
IEEE1785-2c	N	Y	Y	N	Y	Y	Y	N	N	N	Y	Y	N	Y	Y	N	Y	N	N	N	Y
60154 IEC-UGC	Y	Y	Y	N	Y	Y	Y	N	N	N	Y	Y	N	N	Y	N	Y	N	N	N	Y
GuideLock	?	Y	Y	Y	Y	Y	N	N	N	N	Y	?	N	Y	N	N	N	N	Y	N	Y
ГОСТ 13317-89	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y	?	N	Y	?	Y	?	N	N	?	N
HRC Mini	Y	Y	Y	?	Y	Y	?	?	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	?	N
NRAO Mini	Y	N	Y	?	Y	Y	?	?	Y	N	Y	Y	N	Y	Y	Y	?	N	N	?	N

Figure 4: Table with current waveguide flange standards (interface designations) vs. 21 different requirements.

This discussion led to new ideas on how the existing IEEE flange standards can be further improved, with the suggestion that this should be considered in the next review round from standardisation bodies.
The documented feedback from the end-users who attended the workshop on rectangular waveguide interfaces for connections above 100 GHz can be accessed here:
https://doi.org/10.7795/EMPIR.17SIP08.CA.20200324

4.4 Feedback to standardisation body

Based on the results as described in Sections 4.1-4.3, a report was submitted to the IEEE related to the project outputs as well as to errors and problems identified in the IEEE 1785 standards. The report was written by NPL and reviewed by the project partners. Future changes to the IEEE 1785 series of standards may include, but will not be limited to, three important points:

- Improvement of the technical drawings, e.g. the change of the datum, improvement of automated manufacturing and measuring of the main flange dimension.

- Change of tolerance definition for some flange dimensions to allow more cost-efficient manufacturing processes at lower frequencies.
- Including of one or more new flange designs based on the requirements table shown and discussed during the workshop

It is envisaged that this contact with the IEEE standards committee will continue beyond the end of this project and is likely to lead to the revision and update of these IEEE standards when the time comes for such an activity to be initiated. IEEE standards are routinely reviewed every 10 years to ensure the contents of the standards are still relevant and up to date. The first of the IEEE waveguide standards (IEEE Std 1785.1-2012) is due for such a review in 2022.

In conclusion, the project objective has been fully met. The adoption and use of the new IEEE 1785 series of standards by the millimetre-wave and terahertz end-user communities was promoted and a wider dissemination and uptake by academic and industrial sectors was supported. This is also an ongoing process. The GPG will be reviewed on a regular basis beyond the end of this project and will be extended and further improved. The same applies for the developed software, which, together with the open source approach, should lead to a continuously updated and improved software.

5 Impact

A one-day workshop, describing the work from this project, has been organised and took place at EuMW, which is Europe's largest microwave event and attracted more than 5,000 attendees in 2019. The funded partners in the consortium (PTB and NPL) chaired the workshop and gave several presentations. The keynote presentation at the workshop was given by the unfunded partner in the consortium (Flann Microwave Ltd). Other presentations have been from organisations in Germany (Spinner), USA (Anritsu and VDI) and Japan (NMIJ). The workshop was very successful, as presenters and attendees engaged in detailed discussion, and new connections and networks have been formed.

Waveguide interfaces based on the new IEEE 1785 series of standards are now available and offered by more manufacturers. The GPG and the software from this project, together with the workshop facilitated the adoption of the standards, leading to other manufacturers adapting their products faster and more efficiently. Thus, soon, incompatibility problems should be limited to a minimum, which in turn should save the Primary Supporter, Flann Microwave Ltd, and other European companies' costs and manpower. These companies and their subcontractors will profit greatly from a consistent standardisation, as their products will be compatible and competitive on an international level and new business opportunities may be created, not only in Europe but also in the USA and Asia.

In 2017, the frequency range of waveguides described in the standard IEC 60154-2 has been increased to 3.3 THz, but the interface itself is based on the IEEE 1785 standards. Thus, there are no compatibility issues between interfaces in accordance with either of both standardisation bodies, and a good acceptance and wide distribution of the IEEE 1785 standards will also be beneficial for users of IEC 60154-2.

6 List of publications

Kuhlmann, K., Probst, T., Ridler, N., Watts, J., *Good Practice Guide on Making Rectangular Waveguide Connections at Frequencies above 100 GHz*, https://oar.ptb.de/resources/show/10.7795/530.20190805, 2019.

Kuhlmann, K., Probst, T., *Software EMPIR 17SIP08 NeWITT v1 [Source Code]*, https://doi.org/10.24433/CO.2045615.v1, 2019.

Kuhlmann, K., Ridler, N., Watts, J., *Documented feedback from the end-users who attended the workshop on rectangular waveguide interfaces for connections above 100 GHz*, https://doi.org/10.7795/EMPIR.17SIP08.CA.20200324, 2020.