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Metrology for THz Communications

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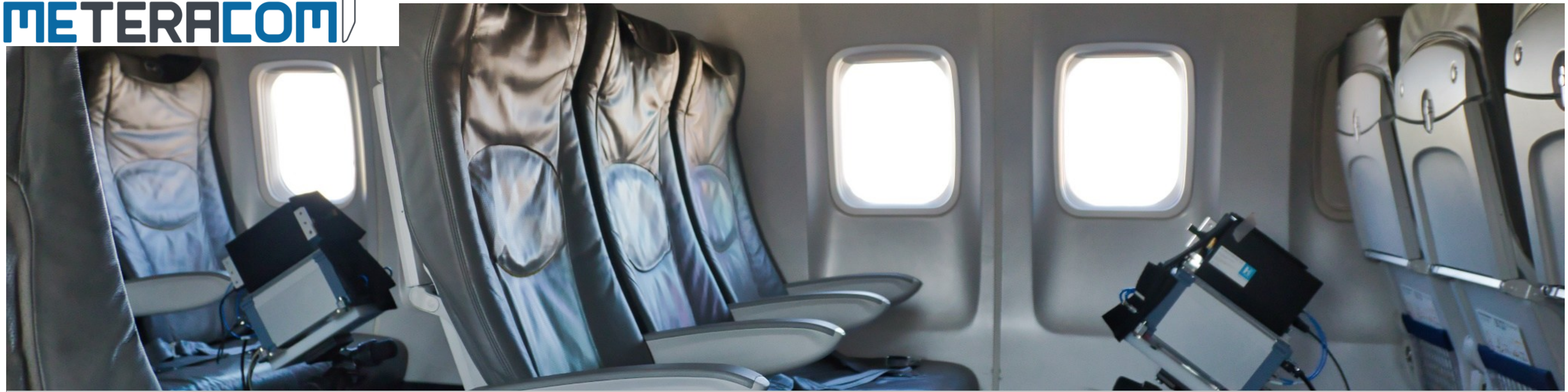

Measurement Techniques and Testbeds for Over-the-Air Sub-THz Channel Sounding Systems

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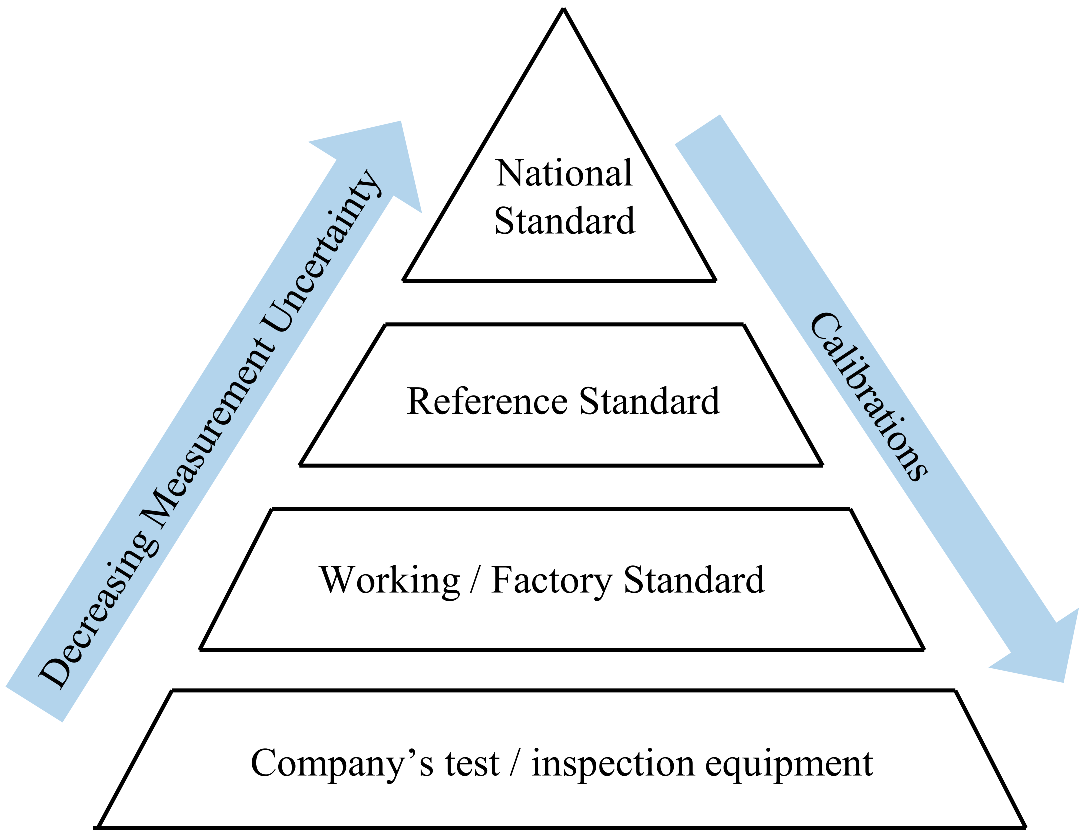
DFG FOR2863 Meteracom Final Workshop @ IRmmW-THz 2025, 20 August 2025

Introduction

- Measurement traceability is defined as "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties" [1].
- The VNA can be used as a reference measurement device to reach traceability via the calibration standards.
- Comparison into a reference device can rule out the environmental influences related to multi-path, and absorptions.
- Theoretical Calculations can also be used as a reference to verify the measured values.

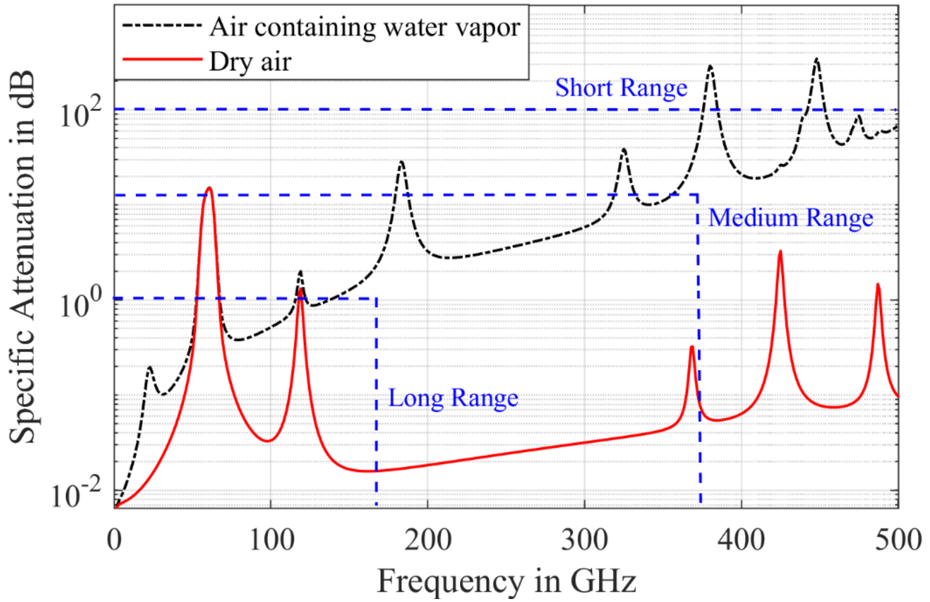


Measurement Traceability Steps.

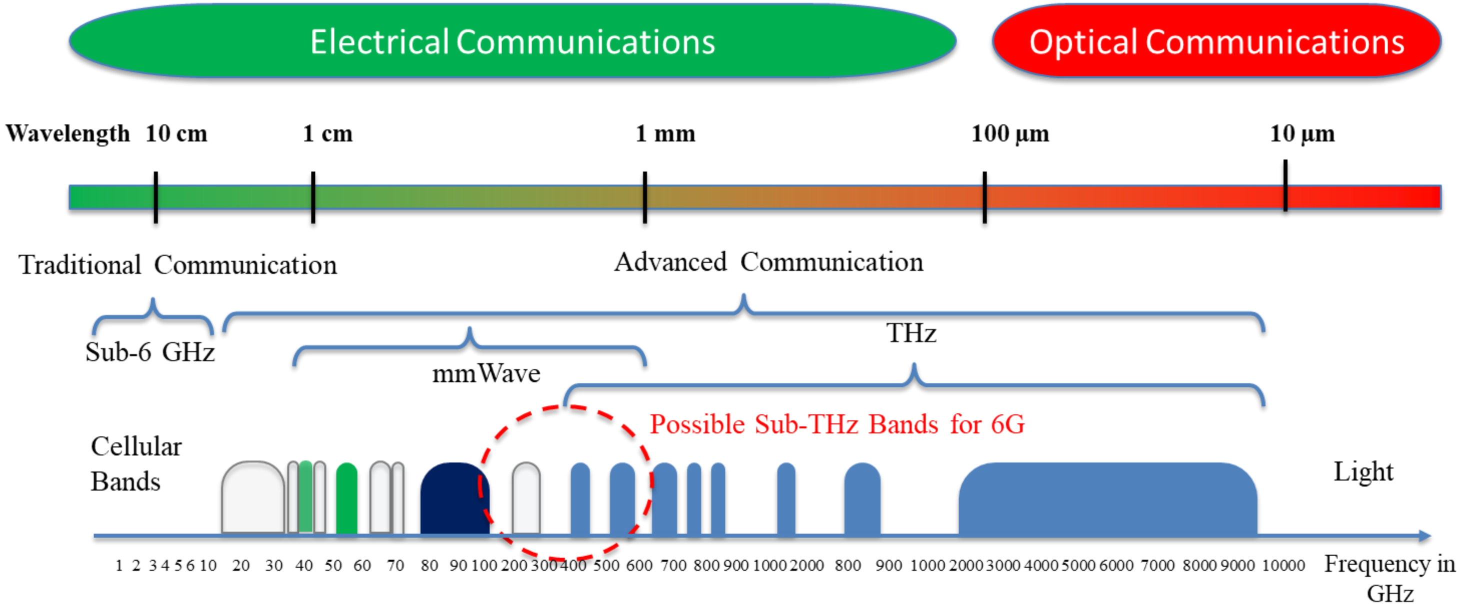
[1] International Organization for Standardization. International Vocabulary of Basic and General Terms in Metrology. 2. Geneva, Switzerland: ISO; 1993.

Introduction

Sub-THz Frequencies for Future Generations of Mobile Communications:



Average atmospheric absorption vs. frequency.



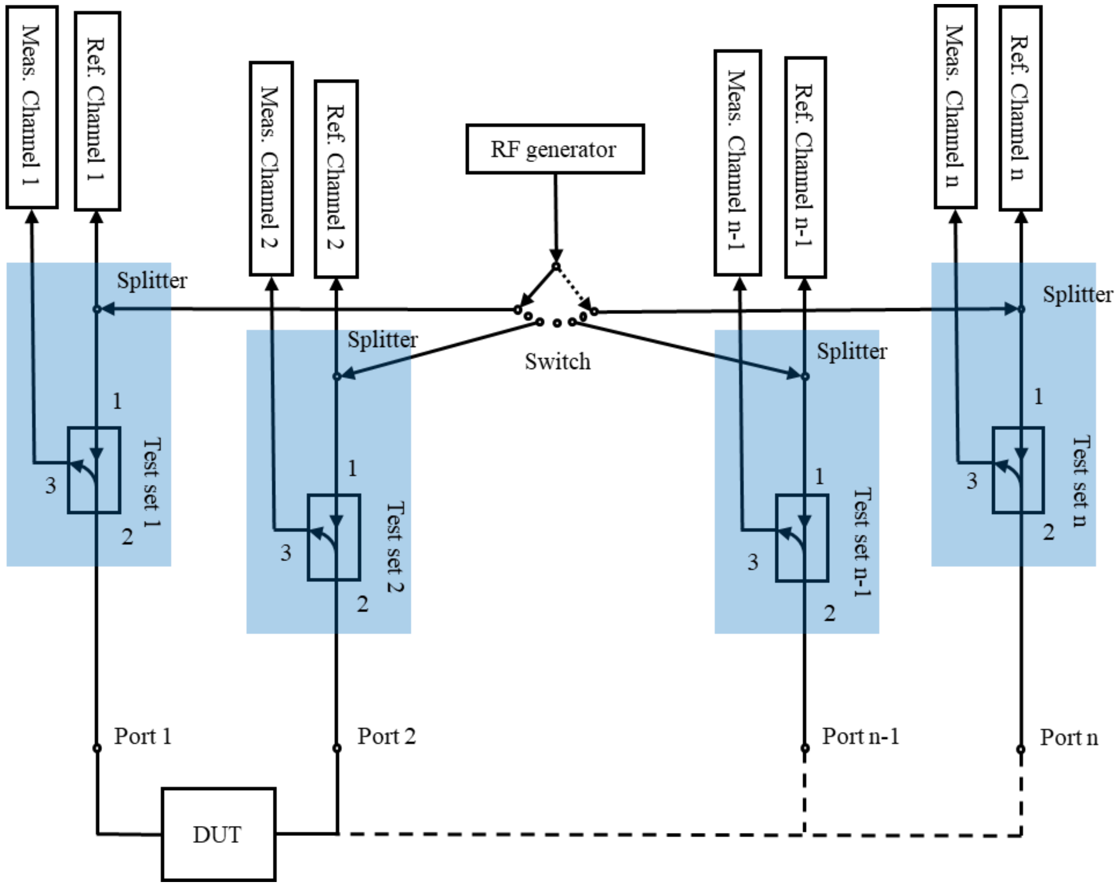
Frequency allocation of the radio spectrum [2].

[2] Huawei Technologies, "Terahertz Sensing and Communication: The Next Frontier," https://www.huawei.com/en/huaweitech/future-technologies/terahertz-sensing-communication, 2025, accessed: 27-Mar-2025.

Sub-THz Channel Measuring Systems

n-port VNA System Architecture:

- **Calibration:** VNAs possess a well-characterized calibration procedures using standardized procedures and known uncertainty contributions.
- **Flexibility:** Offers adjustable frequency range, step size, and resolution, suitable for comparing measurements with other systems like channel sounders.
- **High accuracy:** Through low noise floor and trace noise, controlled by IF bandwidth, dwell time, and averaging.
- **IFBW:** Can be as low as a few Hz, useful for enhancing signal detection and used extensively for calibration and time-varying signal analysis which will directly influence the sweep durations



n-port network analyzer architecture. The signal from an RF generator is distributed to active ports, which are switched on consecutively.

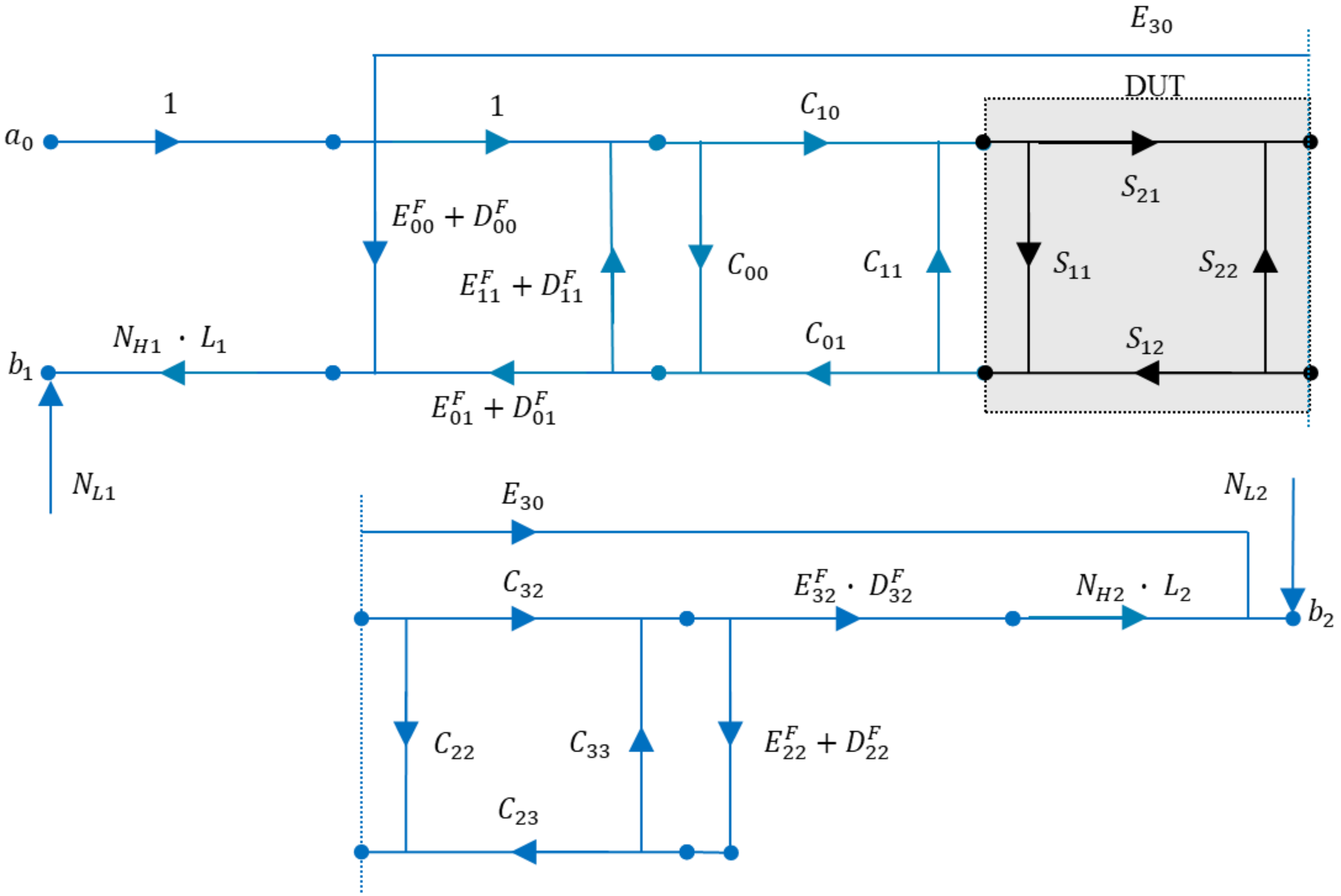
Sub-THz Channel Measuring Systems

VNA Measurement Model:

Uncertainty Contributions of the extended error terms in VNA Measurements [3].

Symbol	Description
NL	Noise Floor
NH	Trace Noise
L	Non-Linearity
D_{00}	Drift of Directivity
D_{01}	Drift of Reflection Tracking
D_{11}	Drift of Source Match
C_{00}, C_{11}	Reflection of Cable and Connector
C_{01}, C_{10}	Transmission of Cable and Connector

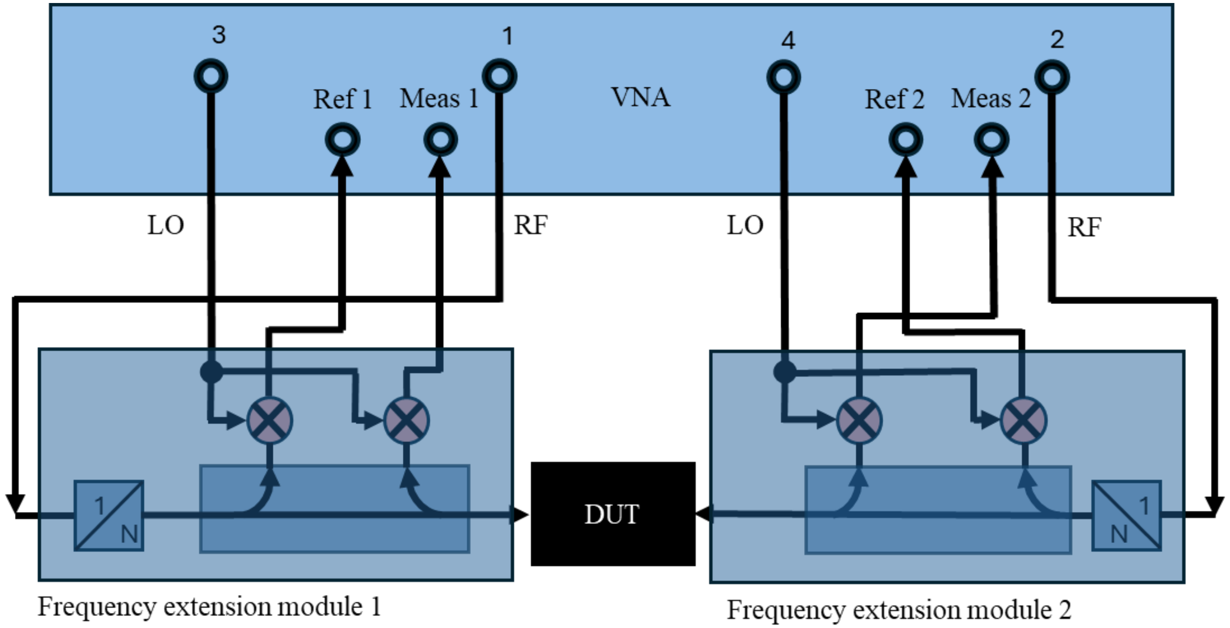
[3] M. Zeier, D. Allal, and R. Judaschke, "Guidelines on the evaluation of vector network analysers (VNA)," EURAMET Calibration Guide, 3(12), 507–521, 2018.



The signal flow graph represents a two-port VNA measurement model, extending the conventional 12-term forward VNA error model by incorporating additional terms that influence the measurement results. . (Adopted from [3])

Sub-THz Measurements using a VNA

VNA Measurement System With Frequency Extension Modules:

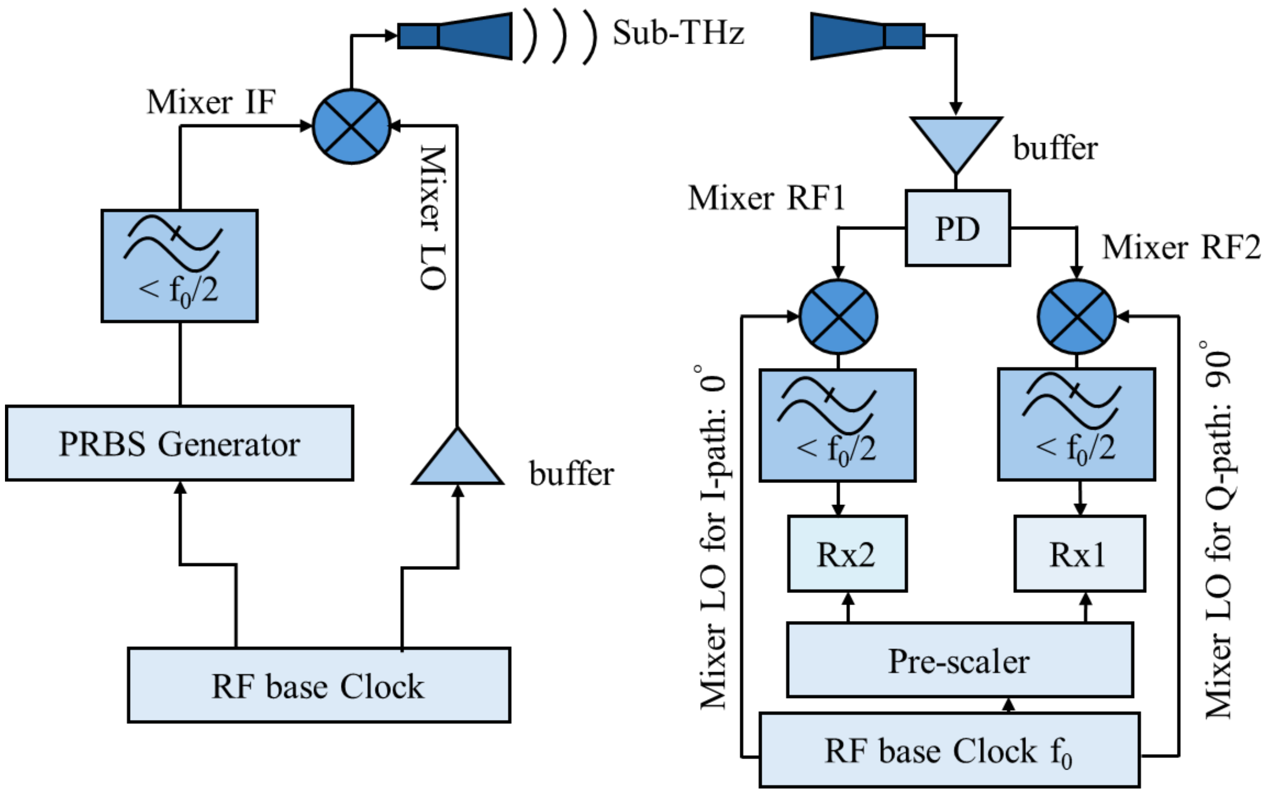


External frequency modules for waveguide bands. To operate the extension modules, a 4-port VNA with access to reference and measurement channels at two ports is necessary.

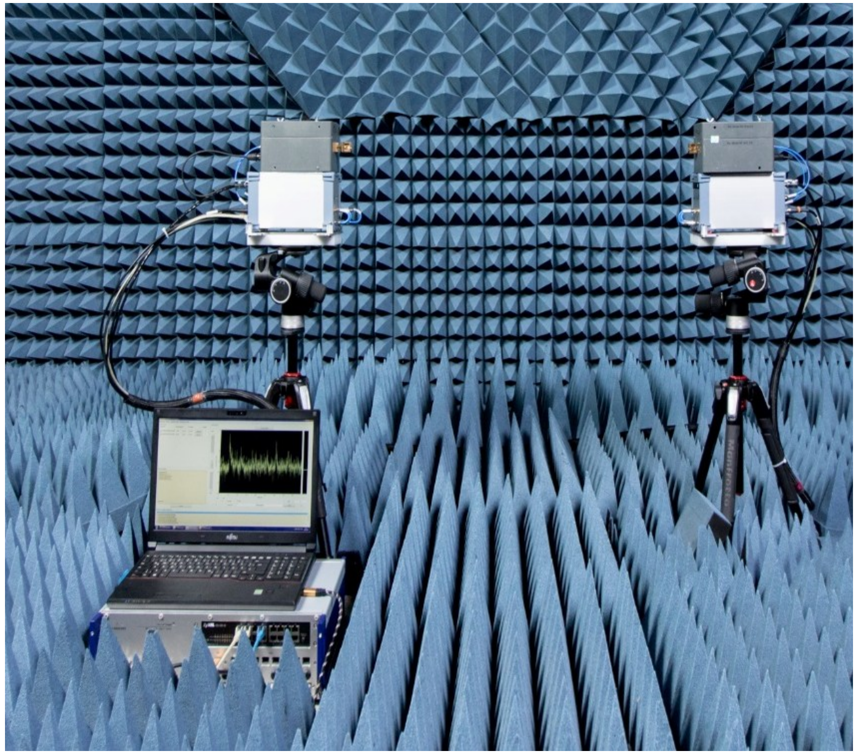
Vector Network Analyzer at WR05, and WR03 frequency bands at PTB from Rohde und Schwarz.

Sub-THz Measurements using a Channel Sounder

Time Domain Channel Sounder System Architecture:



Up- and down-conversion principle from extended UWB-band CS systems [4].

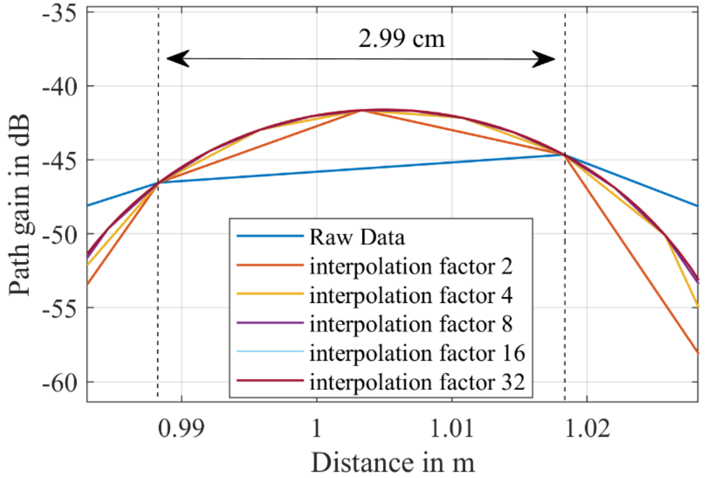


Channel Sounding System at 304 GHz, 9.2 GHz bandwidth at TU-Braunschweig

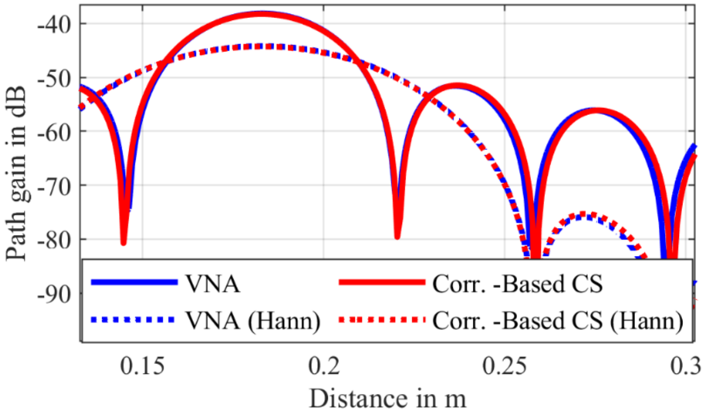
[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

Waveguide Component Characterization

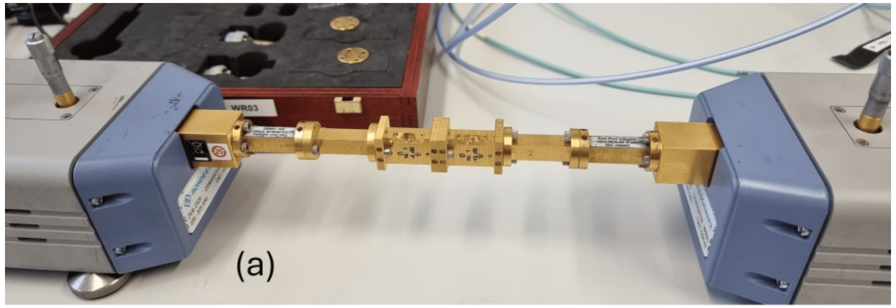
VNA and Channel Sounder Waveguide Components Characterization Using the PDP:



Raw data measurement and zero-padding grid-spacing for 1 m PDP [5].



Reference waveguide PDP measurement result consisting of two attenuators and two lines. The measurement used the VNA and the CS devices at the WR03 band.

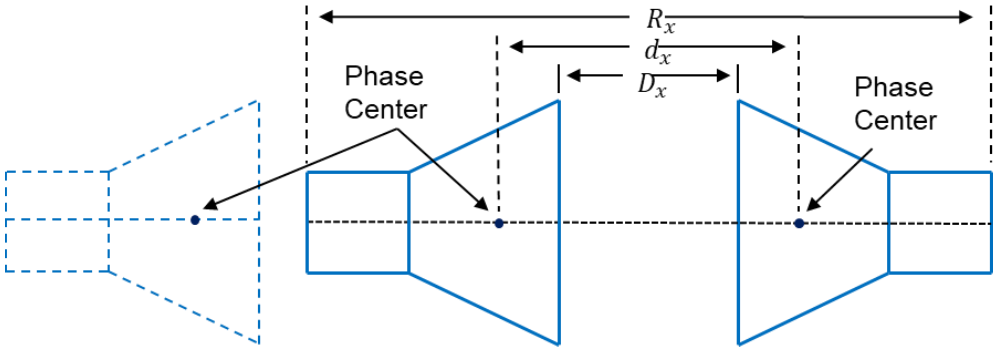


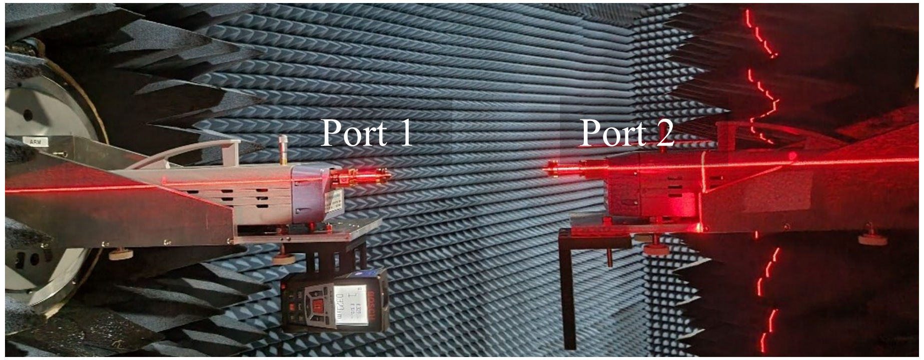
Component characterization, (a) Attenuators and lines cascaded in the WR03 band. (b) Waveguide artifact fabrication in the WR05 band.

[5] M. D. Al-Dabbagh, T. Kleine-Ostmann, and D. Humphreys, “Radiative Reference Plane Estimation and Uncertainty for THz Path Loss Measurements,” in 2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), pages1–2, IEEE, 2021

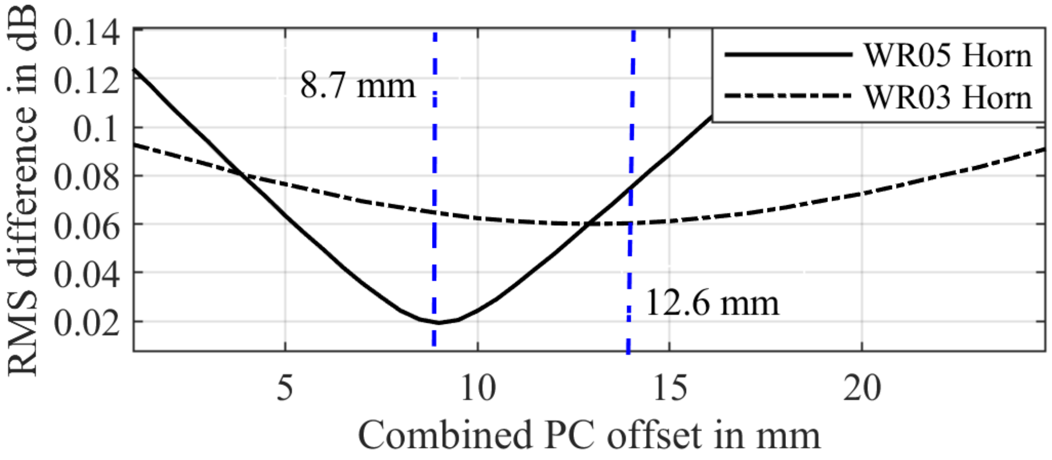
Distance Measurement Antenna Phase Center Calculation

Horn Antenna Phase Center Characterization Based on PDP Magnitude:





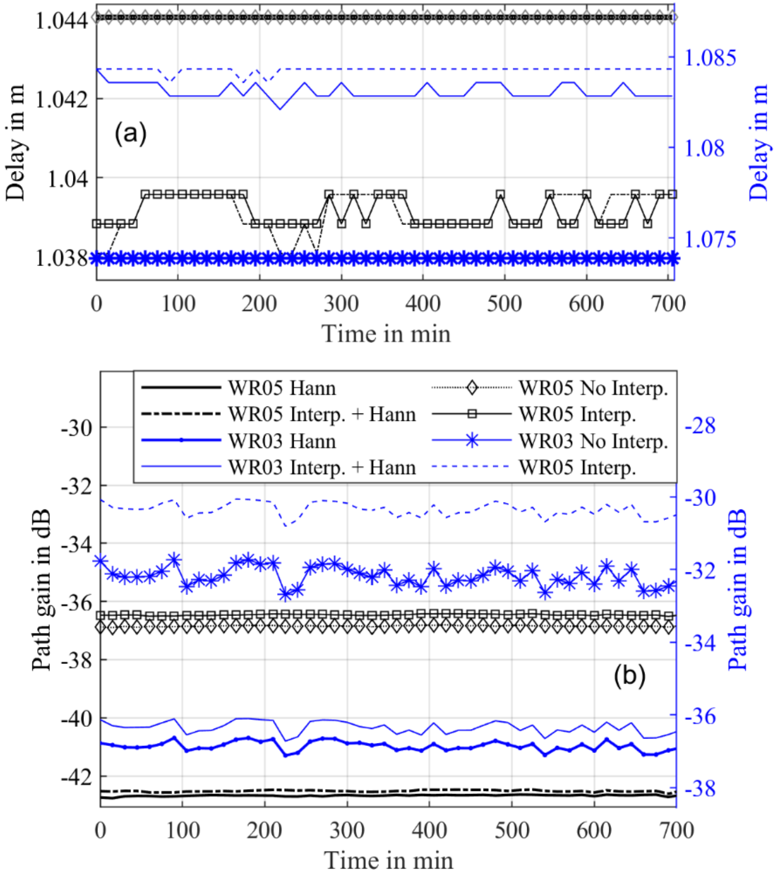
Far field measurement setup showing the VNA frequency converters positioned on motorized mounts. Port 2 moved successive steps of 10 cm away from port 1 to cover the total range between 10 cm –340 cm. The same setup was repeated for the CS systems [4].



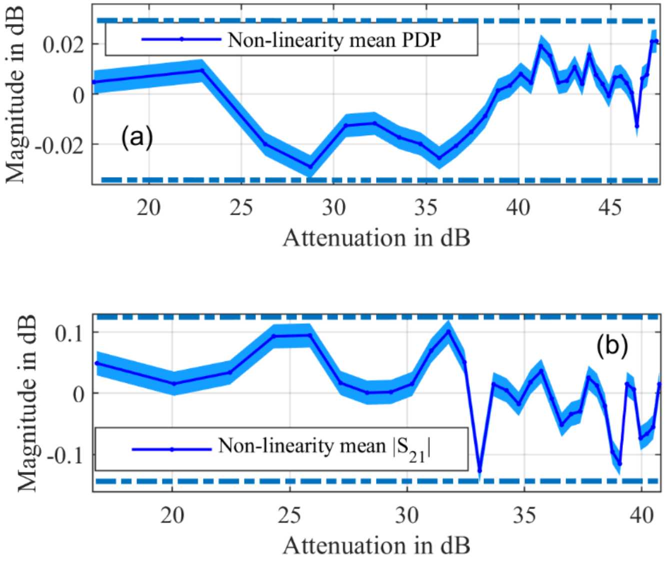
RMS difference in decibels between the PDP and measurement distance versus successive combined PC offset comparison for WR05 and WR03 horn antennas [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

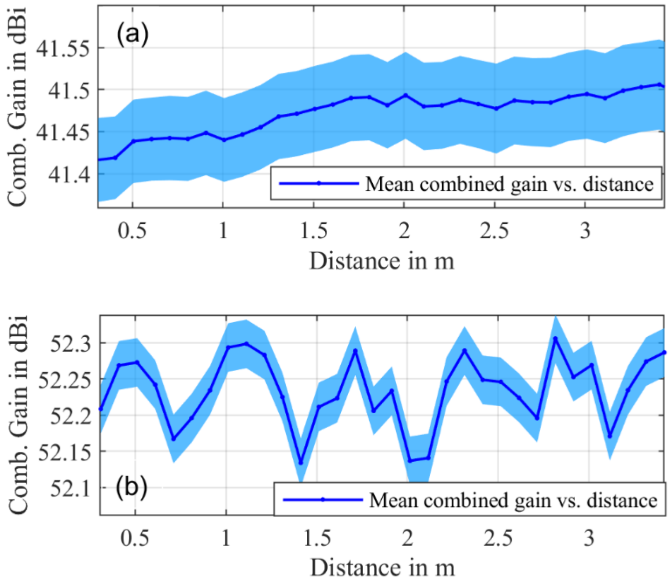
VNA OTA Measurement Characterization



VNA S_{21} PDP peak drift for WR05 and WR03 in terms of (a) delay and (b) path gain [4].



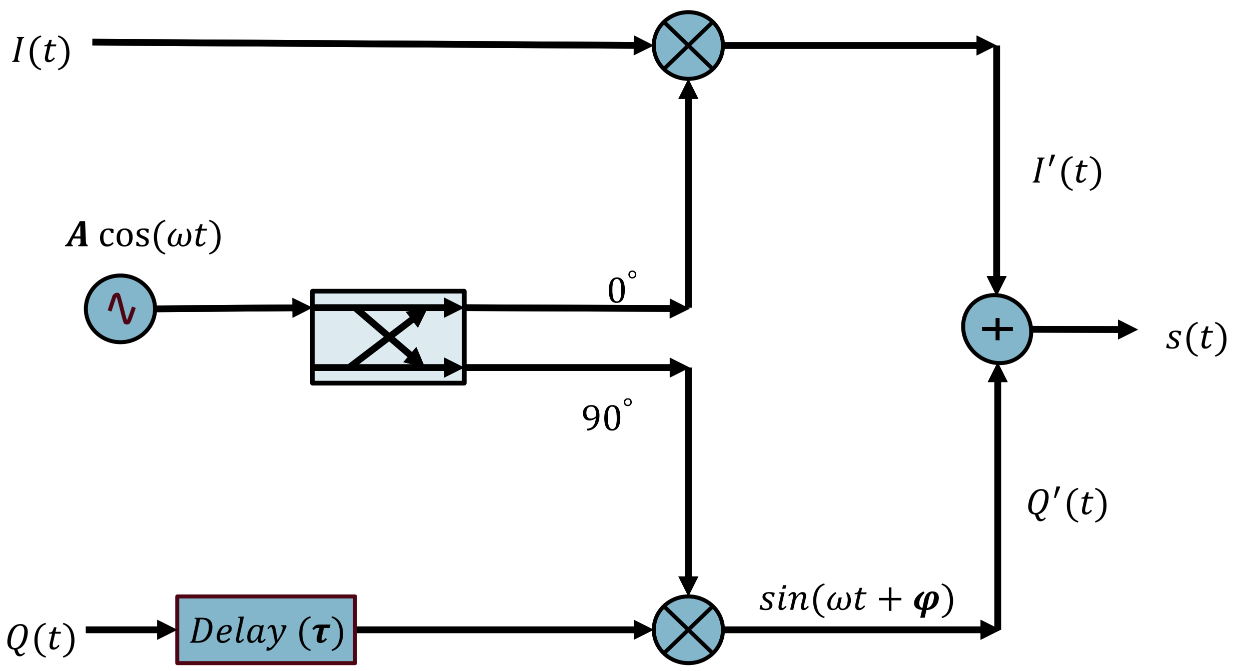
RMS difference in dB between the PDP and measurement distance versus successive combined PC offset comparison for (a) WR05 and (b) WR03 horn antennas [4].



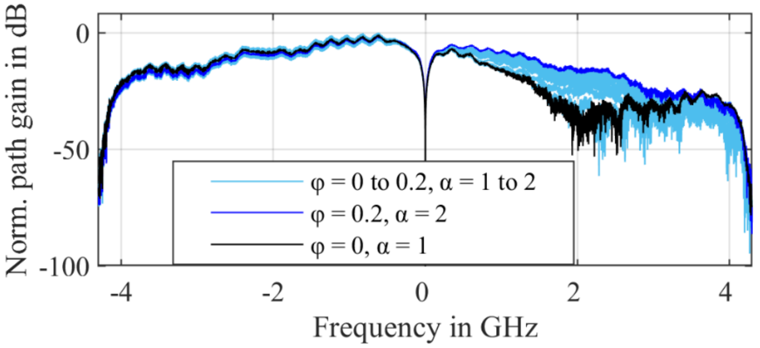
Combined antenna gain versus separation distances. (a) WR05. (b) WR03 [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

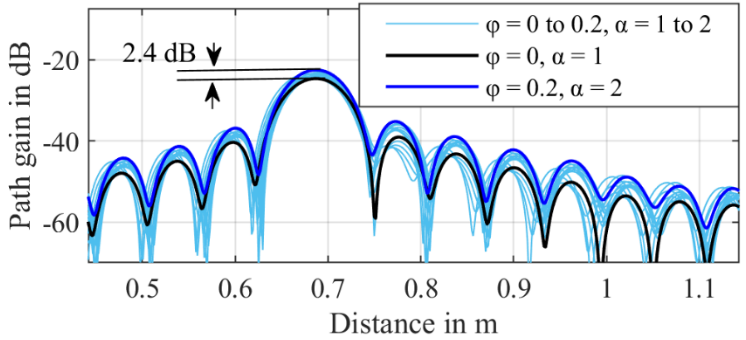
IQ impairment of a Channel Sounding system



IQ impairment of a CS system representing the possibilities of gain and timing imbalance.



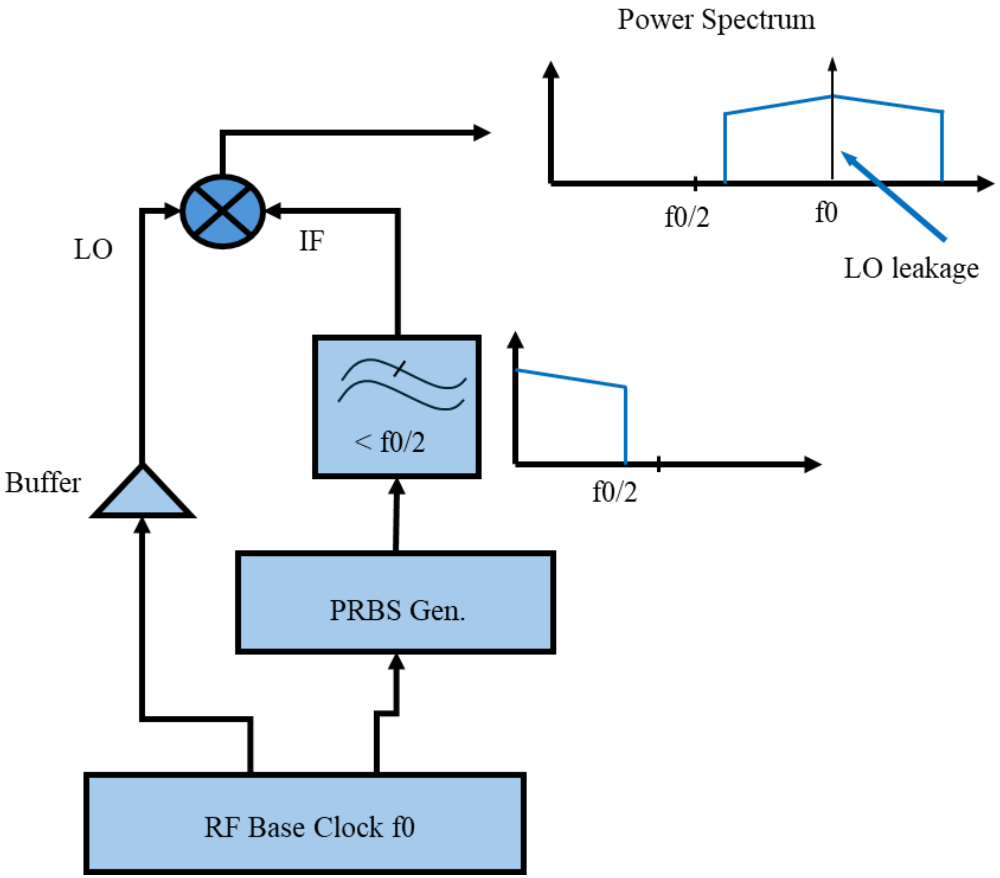
WR03 CS received spectrum at a 60 cm distance with different IQ corrections applied [4].



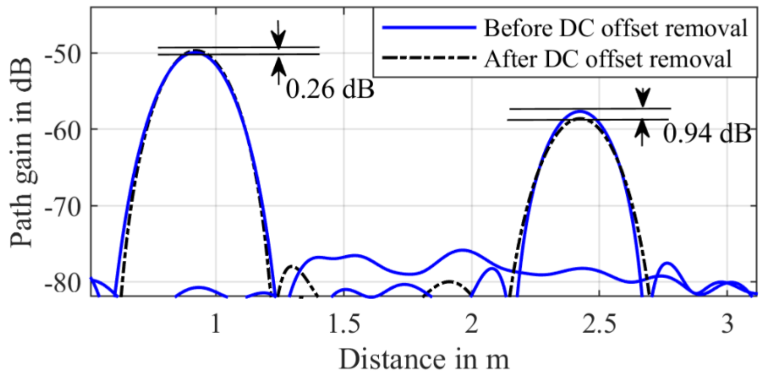
WR03 CS PDP for a 5 GHz bandwidth at a 60 cm distance under various IQ corrections [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.

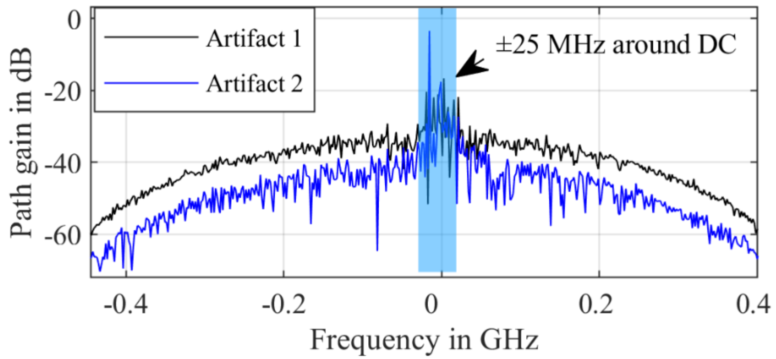
DC Offset of the Channel Sounding System



LO leakage and DC offset in the CS transmitter [4].



PDP of two measurement artifacts before and after DC removal [4].



WR05 CS DC offset influence on two measurement artifacts [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.

Channel Sounders Distance Measurement Characterization

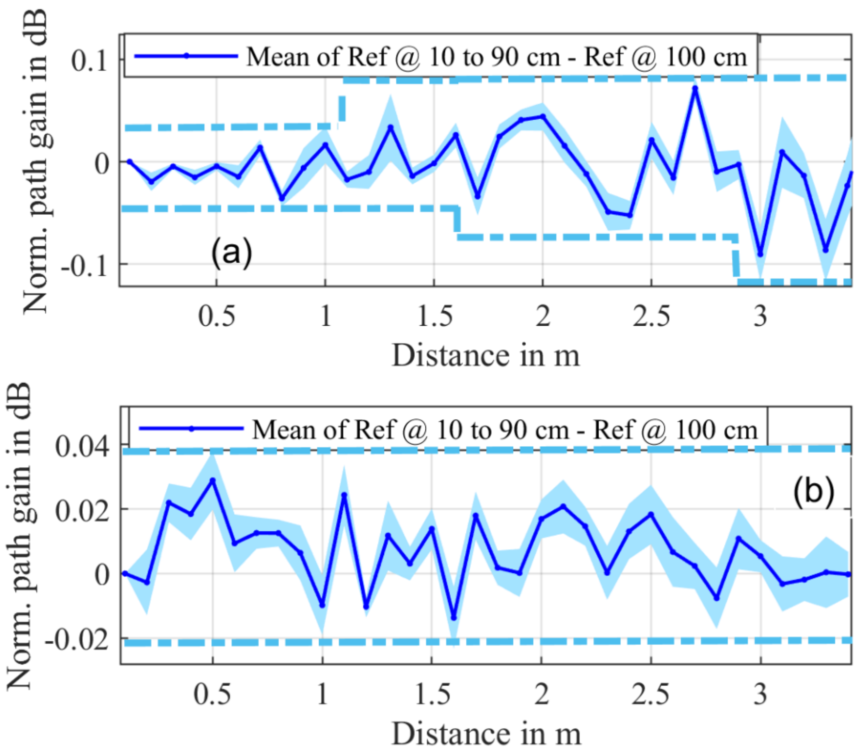
Channel Sounders Reference Measurement Influence on the Measurement Uncertainties:

- Correlational-based CSs require a well-characterized reference measurement.

- Small reference magnitude or phase deviations will propagate errors and increase measurement uncertainty.

- Theoretical and VNA-verified distance measurement serve as a valuable testbed as each distance can be used as a reference.

- The mean values of all distances are calculated when 10 cm – 90 cm distances are used as references in comparison with 100 cm reference.



PDP path gain differences using measurement distances between 10 cm and 90 cm as reference measurements, compared to a 100 cm reference for the CS systems at (a) WR05 and (b) WR03 [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

Combined CS and VNA Measurement Uncertainties

VNA PDP Magnitude Uncertainties At WR05 And WR03 Bands [4].

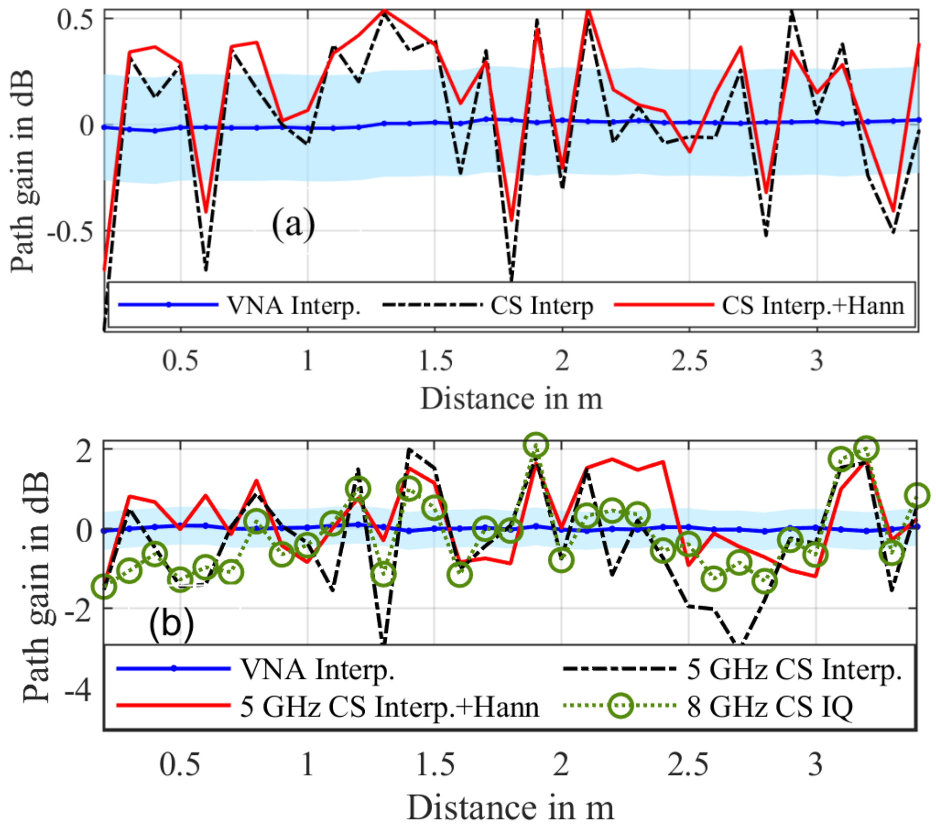
Parameter	WR05 (dB)	WR03 (dB)
Calibration	0.01	0.02
Trace Noise	$3.2 \cdot 10^{-3}$	$10 \cdot 10^{-3}$
Drift	0.2	0.45
Antenna Gain	0.05	0.1
Non-Linearity	0.06	0.22

$$u_{\text{Combin}} = \sqrt{u_{\text{cal}}^2 + u_{\text{noise}}^2 + u_{\text{drift}}^2 + u_{\text{ant}}^2 + u_{\text{n-linear}}^2}$$

WR05 band (185–190 GHz):
- VNA: 0.01 dB std. dev., ±0.22 dB combined uncertainty.
- CS: 0.4 dB std. dev. after DC removal, 0.34 dB with Hann-window.

WR03 band (300–305 GHz):
- VNA: 0.04 dB std. dev., ±0.51 dB combined uncertainty.

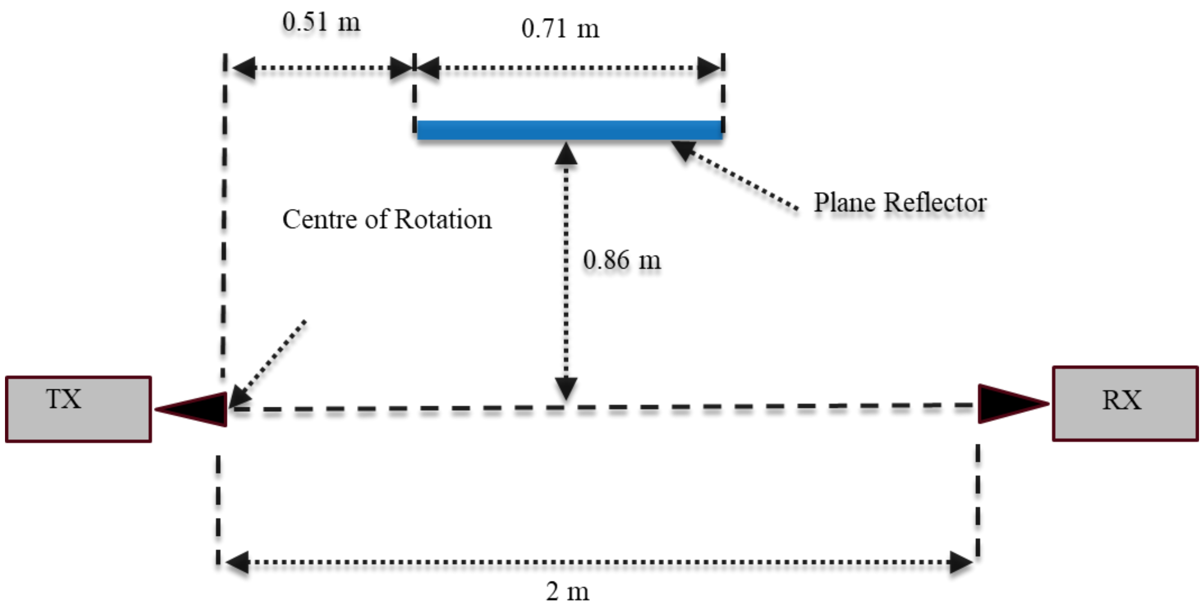
CS: 1.4 dB, reduced to 1.0 dB with Hann-window.

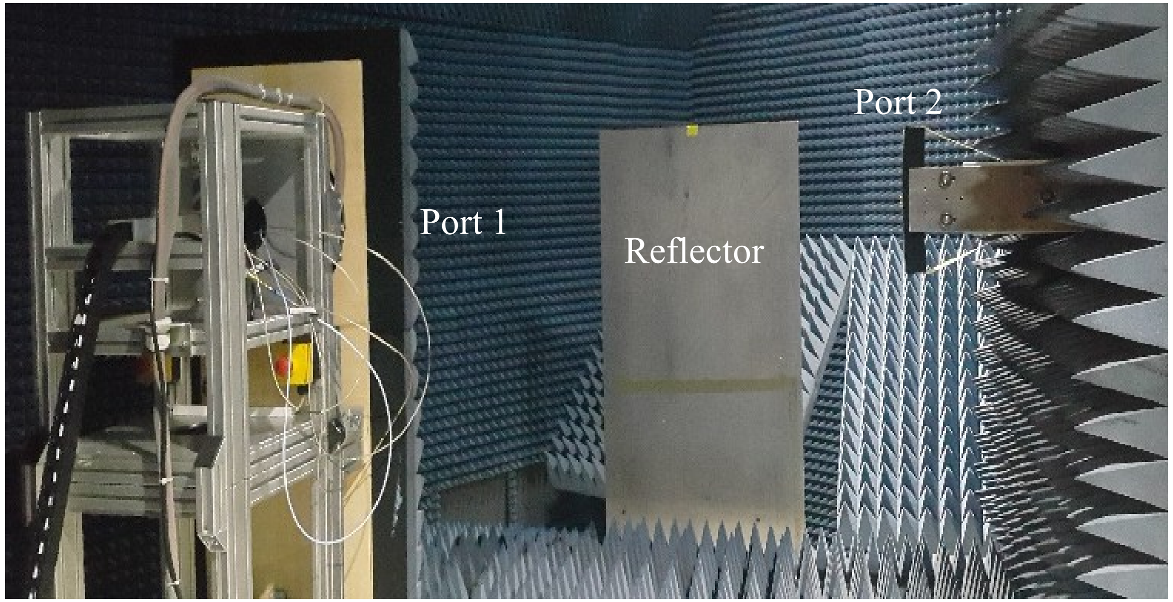


Distance measurement deviations from the theoretical path gain for (a) WR05 and (b) WR03 CS systems [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

Plane Reflector Measurement

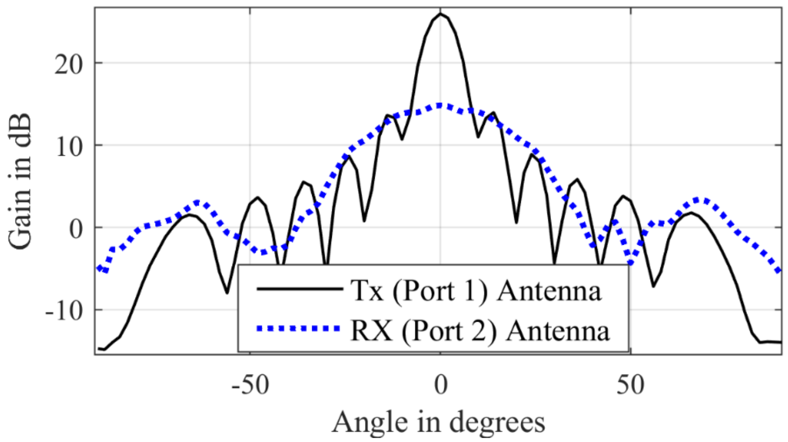




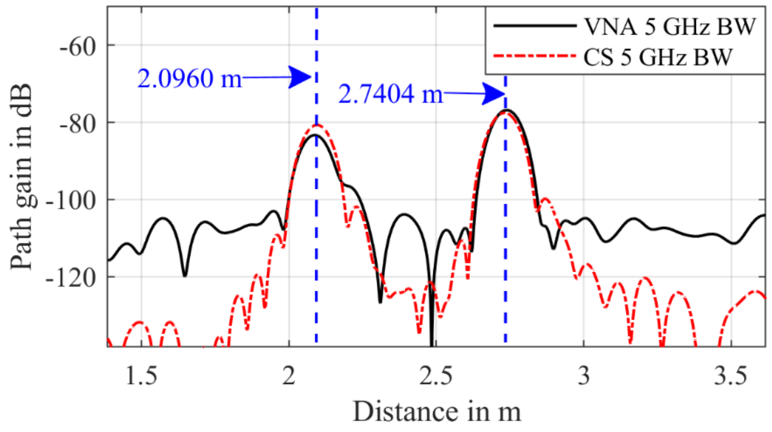
Plane reflector measurement setup. (a) Schematic of the measurement setup. (b) Photograph of the measurement setup [6].

[6] M. D. Al-Dabbagh, T. Doeker, T. Kleine-Ostmann, T. Kürner, et al., “THz chan-nel sounder and VNA verification measurement based over-the-air multipath artifact,”in 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves(IRMMW-THz), pages 1–2, IEEE, 2022.

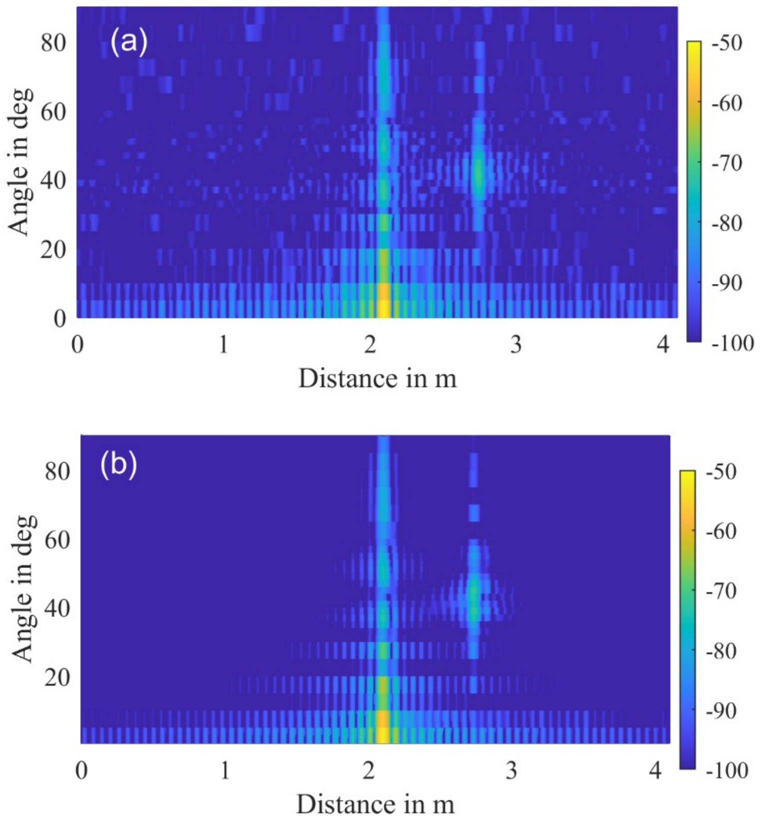
Plane Reflector Measurement



Transmitting and receiving antennas' RMS gain measured using the three-antenna method [6].



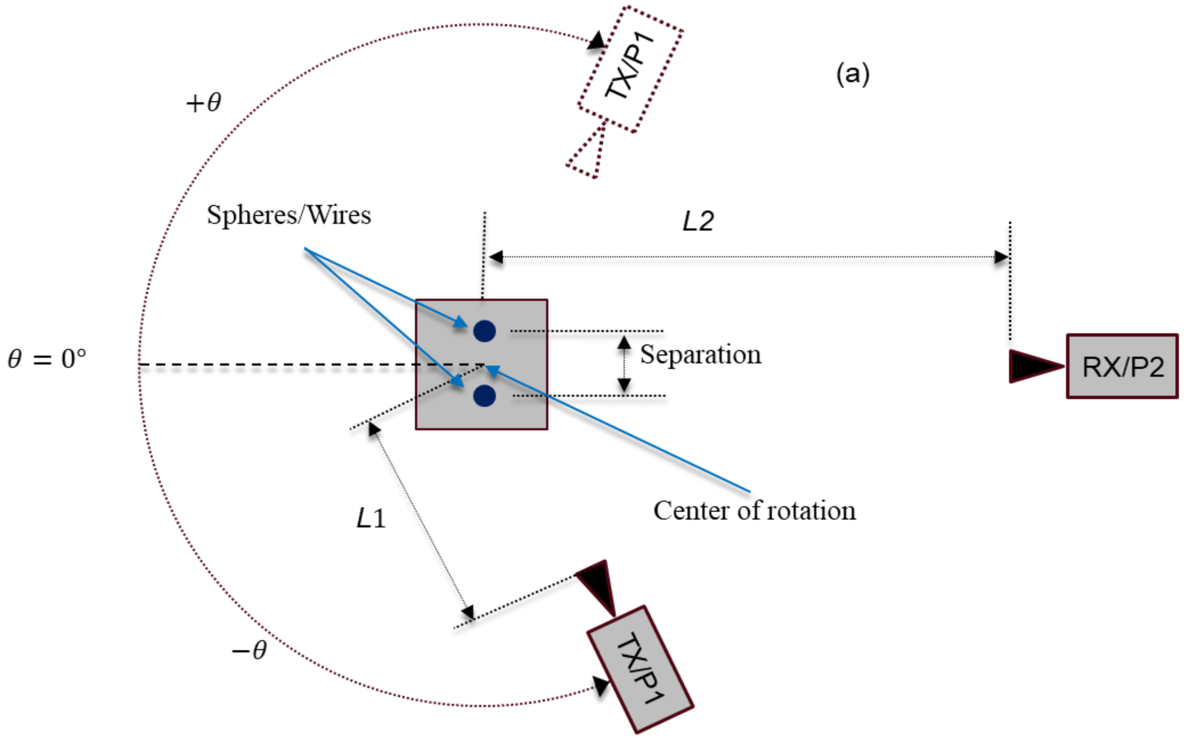
Measured PDP at different rotation angles. VNA and CS measured path gain based on PDP LoS and reflection peaks [6].

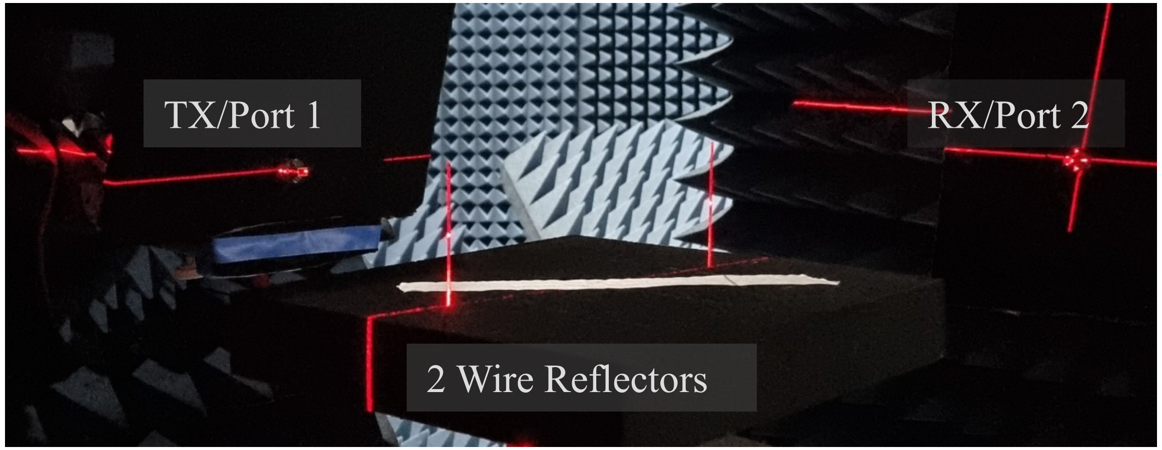


Measured LoS and reflection at different rotational angles concerning distance and path gain.(a)VNA (b) CS [6].

[6] M. D. Al-Dabbagh, T. Doeker, T. Kleine-Ostmann, T. Kürner, et al., "THz chan-nel sounder and VNA verification measurement based over-the-air multipath artifact,"in 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves(IRMMW-THz), pages 1–2, IEEE, 2022.

Multiple Reflectors Rotational Stage



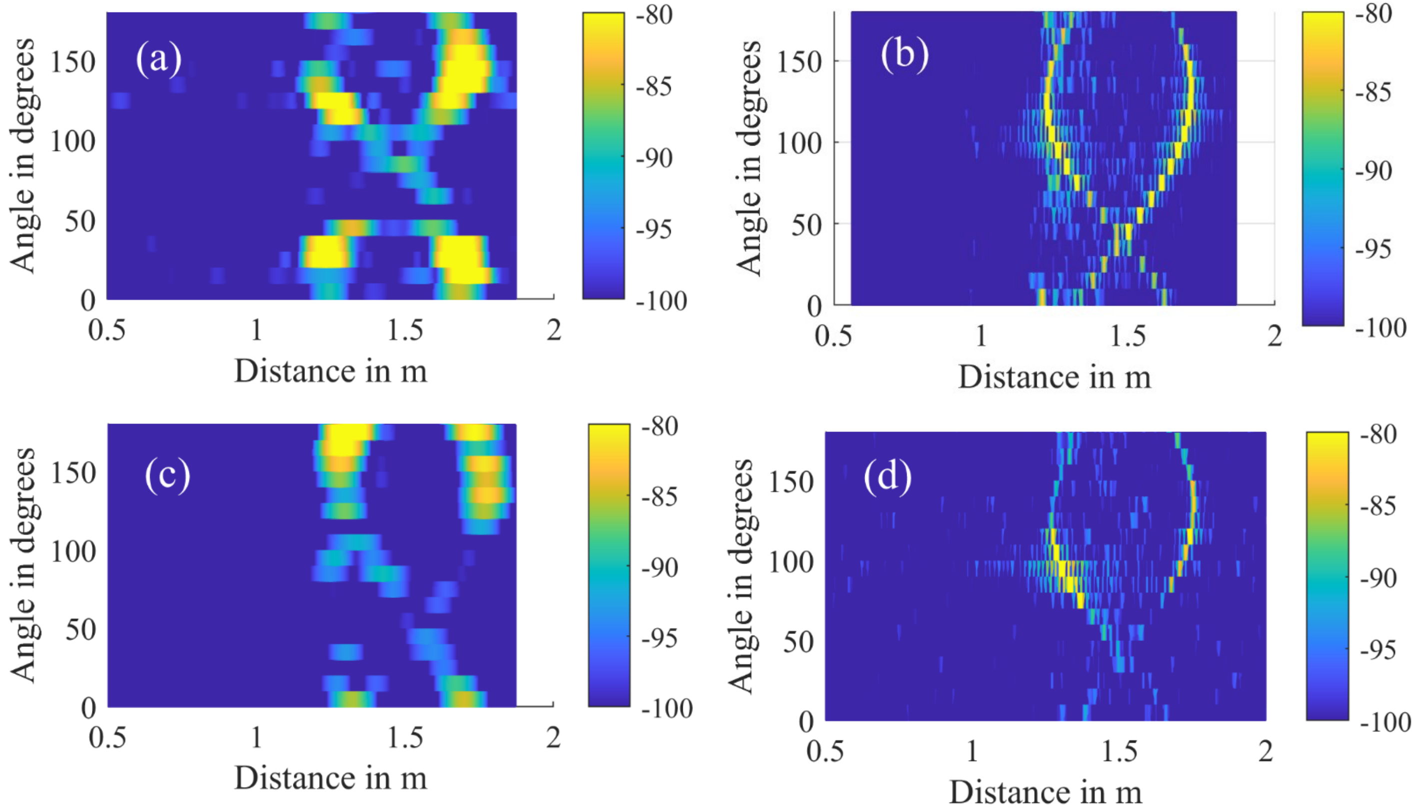


Far-field multi-reflector measurement setup. (a) Schematic representation of the measurement setup. (b) Measurement setup showing the frequency converters placed on motorized mounts, where Port 1rotates in 10◦ steps around the center of rotation [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.

Multiple Reflectors Rotational Stage

- **Objective**: Use spheres and thin wires as reference artifacts to verify THz channel sounder performance and evaluate 2D free-space multipath scattering.
- **Goal**: Compare measured reflective path loss (via PDP) with theoretical predictions to quantify measurement uncertainty.
- **Test objects**: Stainless steel spheres (10–6 mm) and a 1.5 mm × 8 mm thin wire.
- Known geometries allow for calculable radiation patterns.
- **Outcome**: Enables accurate uncertainty estimation, guides optimal THz measurement resolution strategies, and validates theoretical scattering models.
-



CIR of a two-wire artifact with 300 mm separation: (a) WR05 CS at 5 GHz bandwidth with Hann window applied. (b) WR05 VNA at 20 GHz bandwidth. (c) WR03 CS at 5 GHz bandwidth with Hann window applied. (d) WR03 VNA at 20 GHz bandwidth [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

Conclusion

- Two correlation-based CS systems at ~200 GHz (WR05) and ~300 GHz (WR03) verified using a VNA as reference.
- DC Offset and IQ imbalance affects path loss non-linearly based on reference.
- Friis-based comparison enabled estimation of antenna gains and phase centers.
- Precise calibration and OTA alignment are critical for sub-THz system verification.
- Results validate the use of well-characterized reflectors for metrological evaluation of CS performance.
- The investigation continued for Time-varying signal propagation using a the VNA and data transmission using a photonic-assisted measurement testbed.

Thank you very much for your Attention

Funded by

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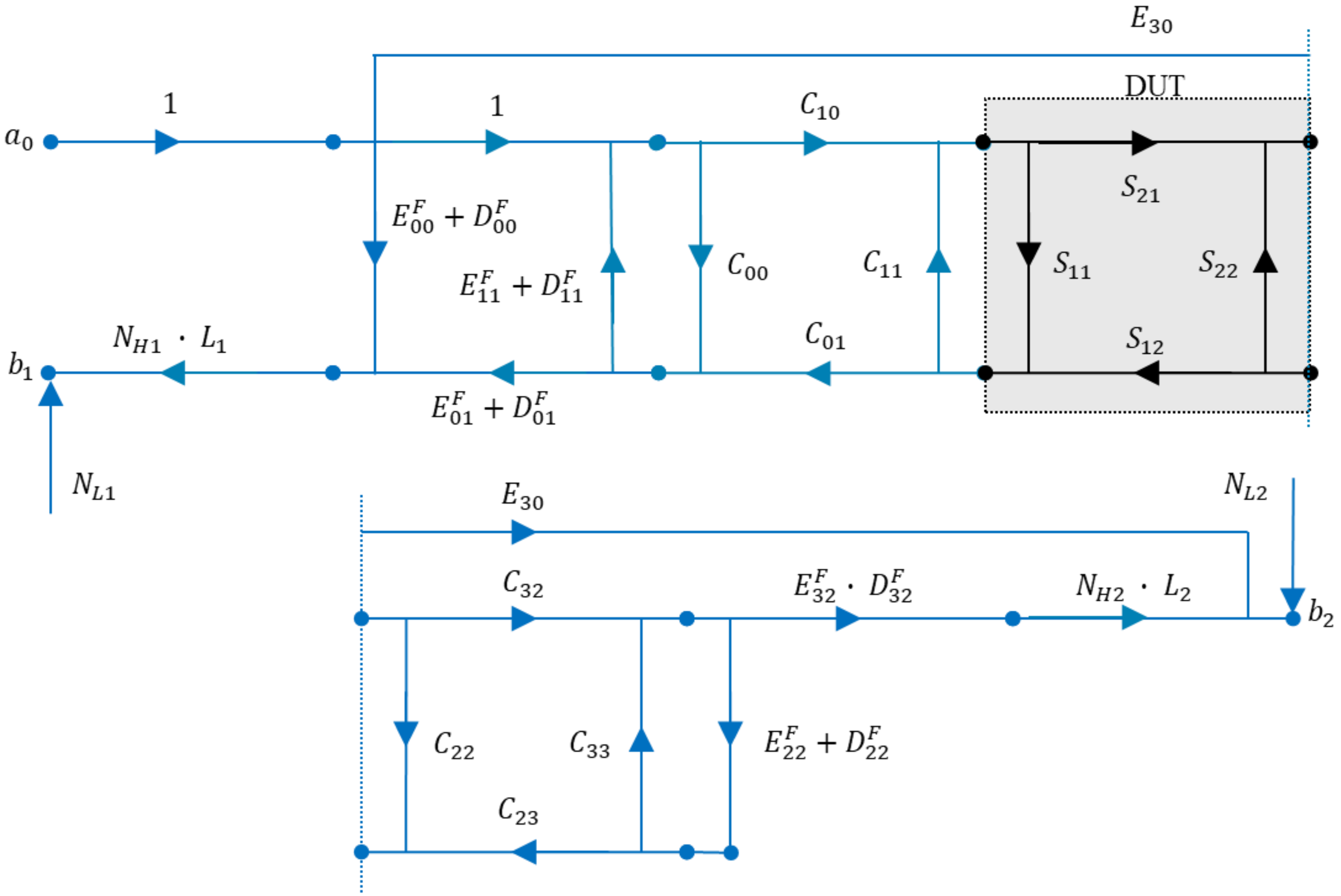
VNA Measurement Model:

Systematic Error Coefficients of the Seven-Term Error Model in VNA Measurements [3].

Symbol Forward	Symbol Reverse	Error Coefficient
E_{00}	E_{33}	Directivity
E_{01}	$E_{32}E_{23}$	Reflection tracking
E_{11}	E_{22}	Source match
E_{30}	E_{03}	Isolation

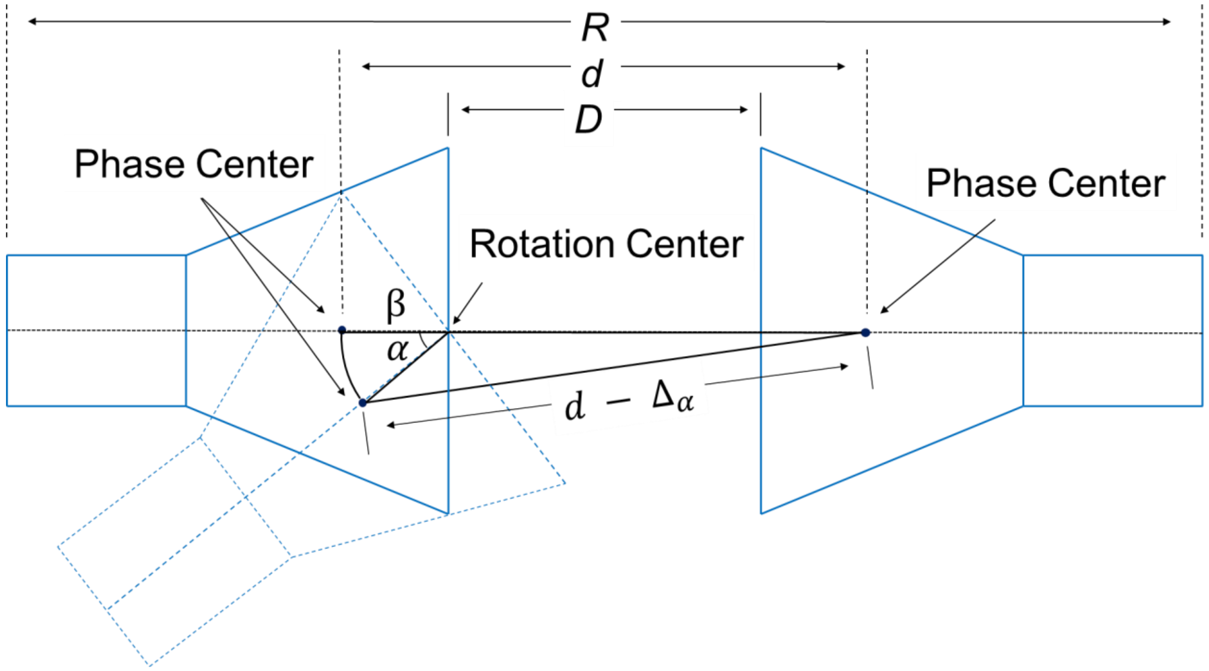


[3] M. Zeier, D. Allal, and R. Judaschke, "Guidelines on the evaluation of vector network analysers (VNA)," EURAMET Calibration Guide, 3(12), 507–521, 2018.

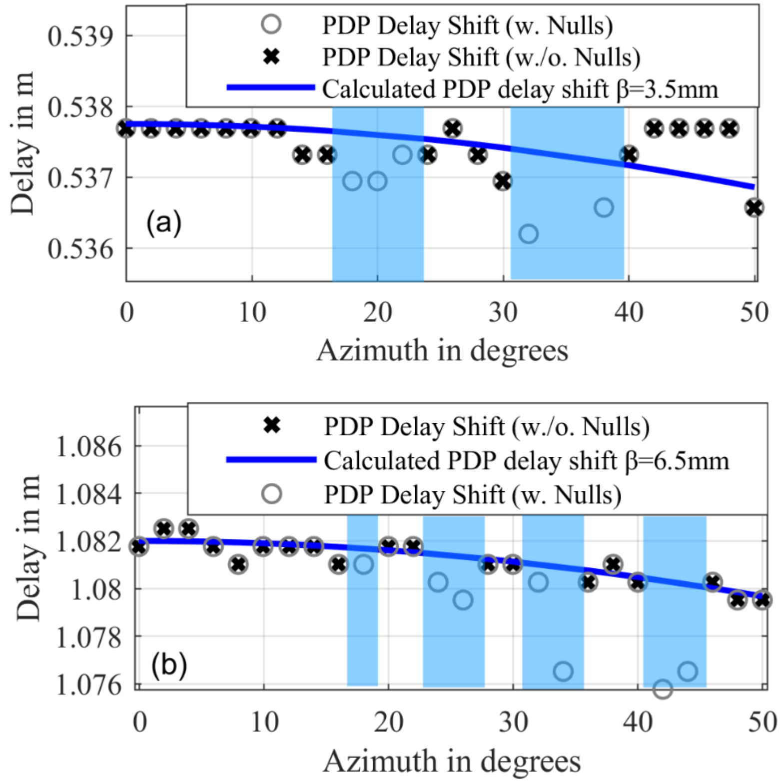
The signal flow graph represents a two-port VNA measurement model, extending the conventional 12-term forward VNA error model by incorporating additional terms that influence the measurement results. . (Adopted from [3])

Rotational Antenna Measurement Phase Center Calculation

Horn Antenna Phase Center Characterization Based on PDP Delay:



Measurement setup for antenna rotation, where D is the physical separation between the antenna apertures, d is the phase center separation at 0°, and β is the targeted phase center distance from the aperture [6].

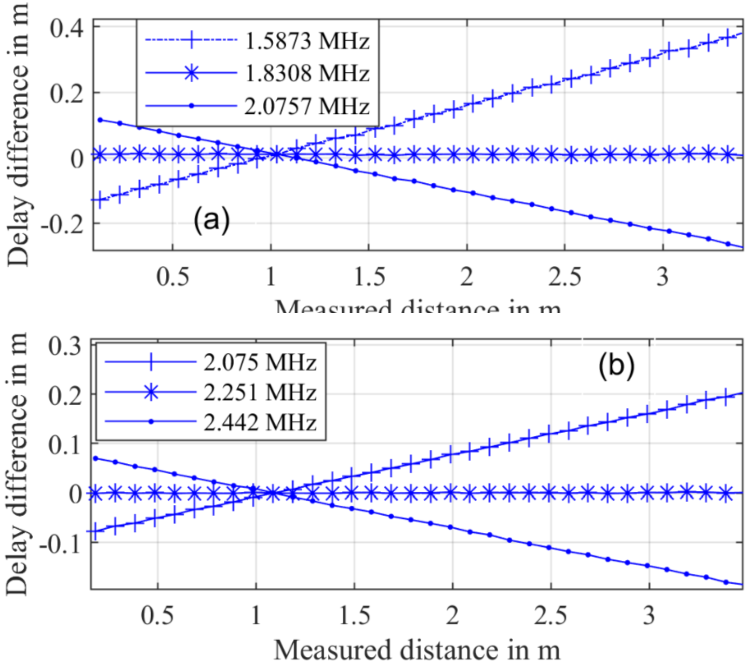


Phase center (PC) delay shift for WR05 and WR03 horn antennas across rotational angles from 0° to 50°. (a) WR05 horn delay shift; (b) WR03 horn delay shift [6].

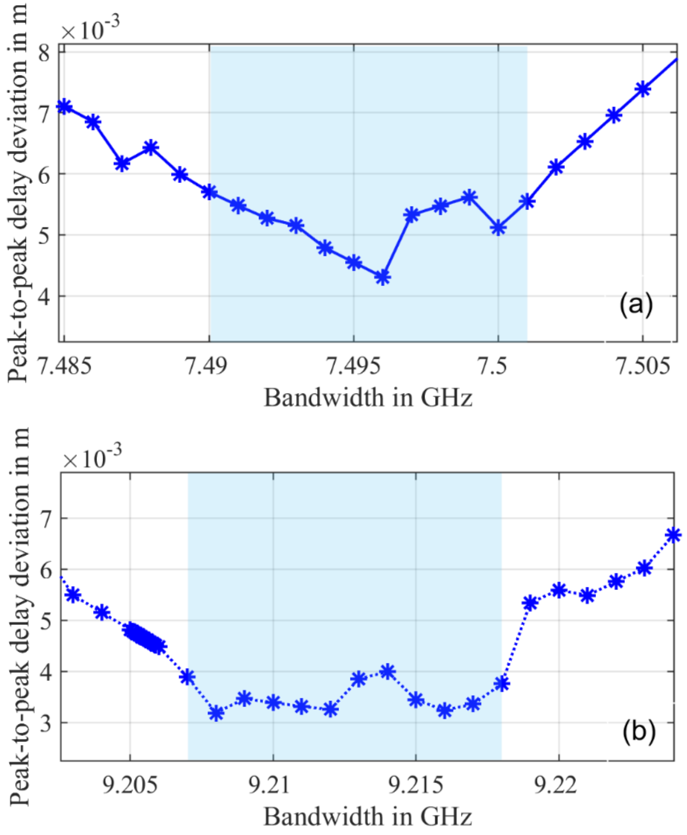
[6] M. D. Al-Dabbagh, D. Ulm, T. Kleine-Ostmann, and D. Humphreys, “Horn AntennaPhase Center Position Influence on Sub-THz Measurements Uncertainties,” in 2024 18thEuropean Conference on Antennas and Propagation (EuCAP), pages 1–5, IEEE, 2024.

Channel Sounders Distance Measurement Characterization

Characterizing the Channel Sounders Frequency Step Size and Total Spectrum Based on Measured and Calculated PDP delay Differences:



Characterization of the frequency step size based on distance separations and delay differences from the VNA reference delay [4].

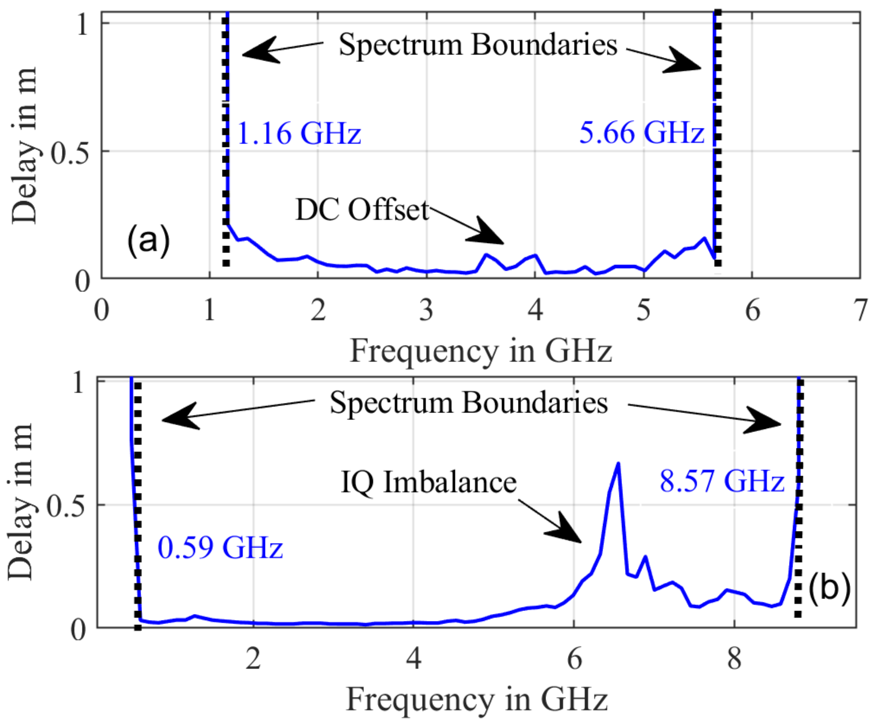


Total CS spectrum showing the combined peak-to-peak delay deviation across all measured distances (a) WR05. (b) WR03 [4].

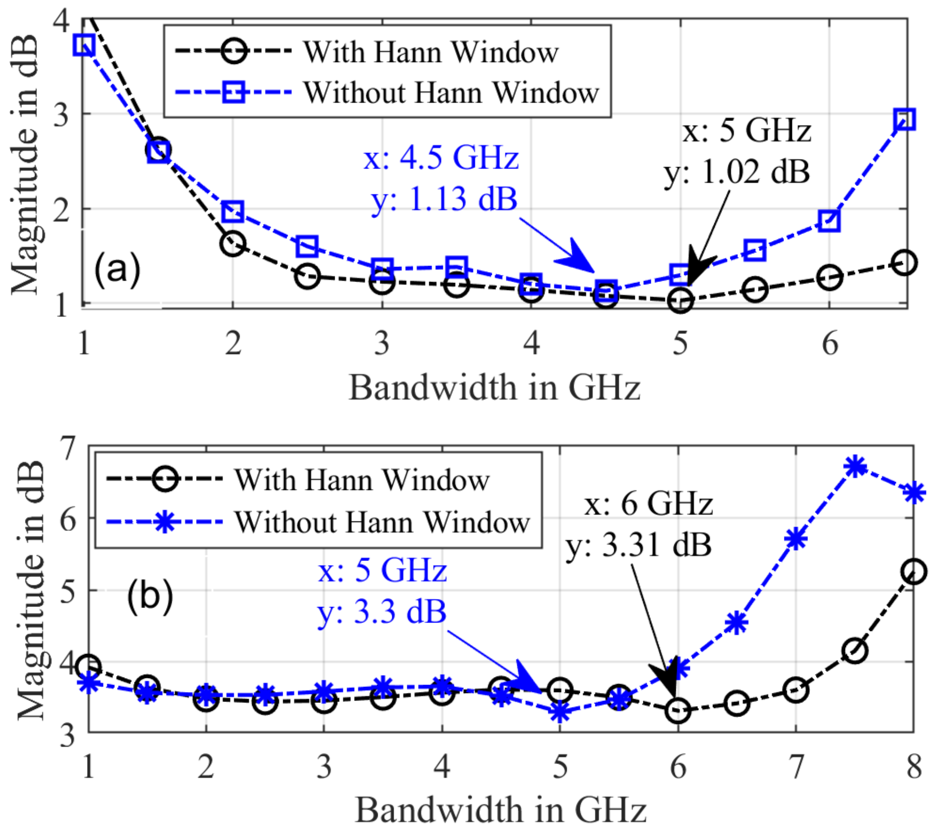
[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.

Channel Sounders Distance Measurement Characterization

Channel Sounders Spectrum Boundaries and BW Feasibility:



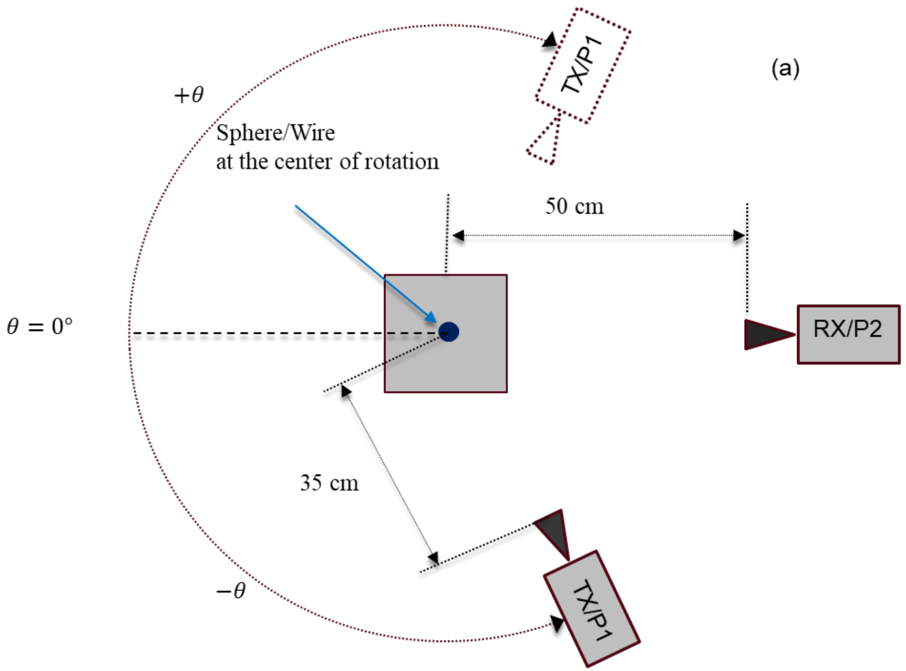
CS spectrum boundaries investigation using a 500 MHz spectral window swept across the complete spectrum of both CS systems in 100 MHz increments. (a) WR05. (b) WR03 [4].

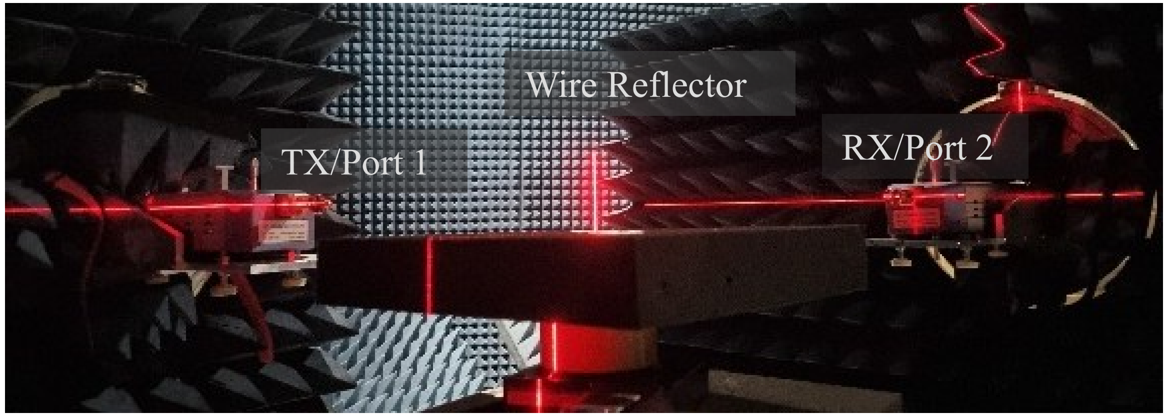


CS peak-to-peak magnitude deviation across different measurement bandwidths. (a) WR05. (b) WR03 [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.

Single Reflector Rotational Stage





Far-field single reflector measurement setup. (a) Sketch of the measurement setup. (b) Measurement setup showing the frequency converters placed on motorized mounts. Port 1 rotates in 10° steps around the wire at the rotation's center [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., "Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer," IEEE Transactions on Antennas and Propagation, 2025.

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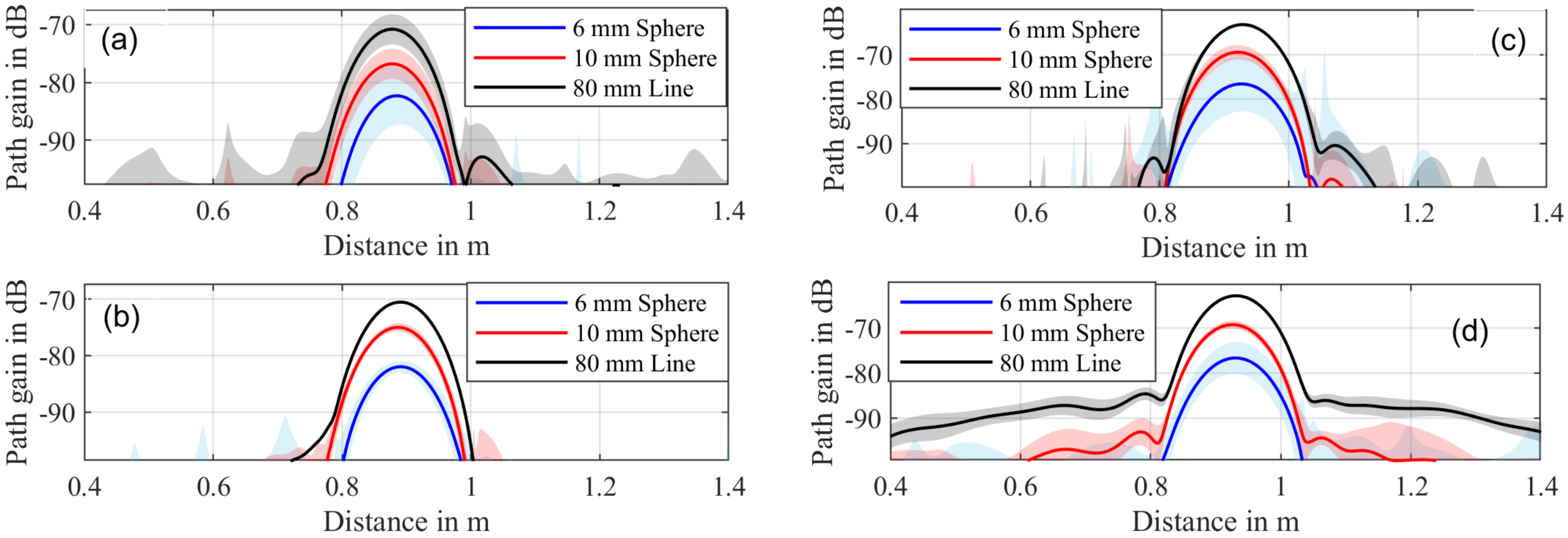

5 GHz measurement bandwidth PDP of the different reflectors at rotational angles of -110° to -70° for the WR05 band and 110° to 70° for the WR03 band placed at the center of the rotational stage. (a) WR05 CS. (b) WR05 VNA. (c) WR03 CS. (d) WR03 VNA [4].

[4] M. D. Al-Dabbagh, D. Ulm, T. Doeker, D. Dupleich, et al., “Characterization of Sub-THz Channel Sounding Systems in OTA Measurement Scenarios Using a Vector Network Analyzer,” IEEE Transactions on Antennas and Propagation, 2025.