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Title: Sub-THz emission measurement guidance
Short Title: Sub-THz guidance

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Keyword/Subject: Spectrum Horizons, Sub-THz, millimeter-wave, mmW, decimillimetric-wave, above 95 GHz.

Question: What FCC guidance is available for manufacturers and test laboratories for radiated emission test procedures for devices operating above 95 GHz?

Answer: See attachment 800303 D01 Sub-THz emission measurement guidance v01 below/

Attachment List:

800303 D01 Sub-THz emission measurement guidance v01

800303 D01 Sub-THz emission measurement guidance v01

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SUB-THZ EMISSION MEASUREMENT GUIDANCE

DATE OF PUBLICATION

1. INTRODUCTION

On March 21, 2019, the Commission released a Spectrum Horizons Report and Order[1] (R&O) focused on developing new communication and material imaging applications to expedite the deployment of enhanced experimental licensing and unlicensed applications within their designated communication frequency bands. This R&O brought about significant impacts on test and measurement procedures due to the requirement of performing electromagnetic compatibility (EMC) emission testing up to 750 GHz for devices above 95 GHz,[2] and the associated challenges of making accurate and repeatable sub-THz[3] radiated emission measurements in this expanded frequency spectrum.

This publication is designed to provide guidance to manufacturers and test laboratories regarding millimeter-wave (mmW) and sub-THz (decimillimetric wave[4] range) radiated emission measurement for devices operating above 95 GHz. The sub-THz radiated emission measurement guidance, contained herein, can be used to augment the mmW radiated emission measurement procedures found in ANSI C63.10-2020 Clause 9 and in KDB Publication 842590 (Upper Microwave Flexible Use Service) for determining the lowest and highest frequency emission to be scanned.
Accordingly, this publication addresses the following topics:

- Extension of the present mmW measurement procedures to 300 GHz.
- Introduction of mechanical constraints in the required sub-THz test setup.
- Usage of specialized sub-THz test tables and test equipment.
- Accounting for propagation path losses in sub-THz test setups.
- Accounting for water vapor and molecular oxygen attenuation in the test results
- Need for identification of the highest capable test frequency in the accreditation scope assessment of a test laboratory.

[1] *Spectrum* Horizons, ET Docket No. 18-2, First Report and Order, 34 FCC Rcd 1605 (2019) (*Spectrum Horizons First R&O*).

[2] The *Spectrum Horizons First R&O* acknowledges that devices operating above 95 GHz will likely not have detachable antenna or ports that could be used for conducted emissions measurements: thus, making such measurements difficult with standard waveguides used for compliance measurements, respectfully. *Spectrum Horizons First R&O* at paras. 44-45 and n.119.

[3] This publication refers to "sub-THz" as the frequency range between 300-750 GHz.

[4] *See* 47 CFR § 2.101(b) at Table 1 (designating wavelength band 11 as "EHF" (Extremely High Frequency) covering the frequency range 30 to 300 GHz and corresponding to the millimetric wave metric subdivision,), and designating band 12 as covering the 300 to 3000 GHz frequency range and corresponding to the decimillimetric wave metric subdivision.

2. MILLIMETRIC-WAVE EMISSION TEST GUIDANCE

At present, there are well established sub-231 GHz mmW radiated emissions test procedures for evaluating licensed, unlicensed, and ISM devices for compliance with their respective emission limits. For devices operating above 30 GHz, mmW test guidance can be found in KDB Publication 842590[5] for licensed devices and in ANSI C63.10[6] for unlicensed devices.

However, mmW radiated emission test procedures end at 200 GHz for licensed devices and at 231 GHz for unlicensed devices, leaving a procedure gap for mmW between 200-300 GHz. In this publication, the ANSI C63.10 sub-231 GHz mmW EMC test procedures provide the foundations for extending the radiated emissions measurement guidance up to 300 GHz.

3. SUB-THZ (UP TO 750 GHZ) -WAVE EMISSION TEST GUIDANCE

For radiated emission test procedures between 300-750 GHz (or sub-THz, in the decimillimetric[7] wave range), the following test-related issues must be considered:

- Suppression of mechanical vibrations within the test environment.
- Accounting for water vapor and oxygen molecule radio frequency (RF) attenuation.
- Choosing test separation distance for overcoming large sub-THz free-space path losses.
- Sub-THz test site validation.
- Equipment under test (EUT) pedestals and test table restrictions for Sub-THz measurements.
- Need for precision (EUT) micro-positioners and 3D spherical roll antenna positioners or gimbals for mounting receive frequency extension modules and/or receiving antennas.
- Test equipment Sub-THz measurement capabilities.
- Requirement to expand the test laboratory's Scope of Accreditation for testing emissions up to 750 GHz.

3.1 Suppressing Mechanical Vibrations in the Test Environment

Suppressing mechanical vibrations within the test environment is crucial for making repeatable and accurate sub-THz radiated emission measurements. At sub-THz wavelengths, a stable EUT position and precise alignment to the receive test horn antenna are a necessity for precisely capturing the maximum field strength. For example, even a 100-micron EUT displacement of a receiving antenna caused by mechanical vibrations in the test setup can make a significant difference. In some cases, even cooling fans in the EUT/ancillary/test equipment, or other vibrations present in the laboratory, may induce displacements of the test setup and affect the results.

The preferred tools for achieving mechanical stability of the test setup are anti-vibration test tables, typically integrated with pneumatic dampeners on the underside of a thick slate slab top to minimize

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[5] FCC OET Laboratory KDB Publication 842590 D01, "Basic Certification Requirements and Measurement Procedures for Part 30 Upper Microwave Flexible Use Service (UMFUS) Devices." For millimeter-wave band devices, refer to § 2.1057 (47 C.F.R. § 2.1057) for frequencies to be investigated with respect to mmW radiated spurious emissions. The mmW procedures within this publication are based on the mmW test procedures developed by the USEMSC ASC C63® Subcommittee 4 mmWave Joint Task Group (JTG) and are provided on an interim basis while the procedure is being finalized in the upcoming release of ANSI C63.26.

[6] *See* ANSI C63.10-2020 Clause 9, "Procedures for testing millimeter-wave systems."

[7] Decimillimetric waves over the 300-3000 GHz range, per ITU-R V.431-6

displacements. If anti-vibration test tables are not available, a conventional table or EUT pedestal could be retrofitted by adding dampeners and/or increasing the weight to reduce vibration-induced displacements. It is a good engineering practice to include in the test report information about the mitigation method used to ensure the mechanical stability of the measurement setup.

3.2 Factoring in Water Vapor and Molecular Oxygen Attenuation

In August of 2022, the International Telecommunication Union Radio Communication Sector (ITU-R) published a recommended guidance for calculating gaseous attenuation caused by oxygen molecules and water vapor at various densities in an RF propagation path[8]. Path attenuation is defined as the loss of RF signal strength (or of equivalent RF power density) as electromagnetic waves travel through the medium. Sub-THz waves propagating through the atmosphere are exponentially attenuated with the propagation distance due to molecular oxygen and water vapor; this attenuation must be factored in when evaluating the link budget[9] and emission test results. In the sub-THz frequency range, the attenuation from water vapor is more than six orders of magnitude larger than from molecular oxygen; thus, in this case oxygen attenuation losses can be neglected.

Figure 1 illustrates the water vapor attenuation (dB/m) for dry atmospheric conditions (e.g., stratosphere) against the standard 50% relative humidity (RH) terrestrial condition, as a function of frequency. Two primary frequency bands identified around 557 GHz and 750 GHz, at 50% RH, significantly impact the overall link budget by about 17 dB/m and 10 dB/m of attenuation, respectively. This example shows the importance of factoring in the atmospheric attenuation for sub-THz frequencies.

To properly account for atmospheric gaseous attenuation in the lab, it is essential to characterize precisely the test environment's relative humidity. Annex 1 of ITU-R P.676-13 (08/2020) provides guidance on calculating specific path losses for atmospheric gaseous attenuation at given temperatures and water vapor density saturation conditions.

3.3 Reduced test separation distance to overcome large free space path losses

Sub-THz radiated emission measurements will likely require choosing a test separation distance that is small enough to provide a good signal-to-noise ratio, to overcome large free space losses and account for the test equipment's dynamic range. In most cases, when making sub-THz emission measurements, the separation distance between both the transmit and receive (test) antennas should be greater than or equal to the far-field[10] distance.

For instance, in the sub-THz test scenario at 750 GHz and with a 1-meter path distance, the free space path losses is 90 dB, calculated using the equation

$$L_P\ (dB) = 20\log_{10}(f_{MHz}) + 20\log_{10}(d_m) - 27.5$$

where L_P is the free-space path loss, f_{MHz} is the frequency in MHz, and d_m is the distance in meters.

[8] ITU-R P.676-13 (08/2020), "Attenuation by atmospheric gases and related effects."

[9] An RF link budget is a general term that accounts for all of the gains and losses from the transmitter to the receiver, including all component losses (e.g., from RF cables and attenuators), gains (e.g., due to antennas and pre-amplifiers), and the free-space losses due to path length in the RF propagating medium.

[10] Far Field transition distance is here considered as $2D^2/\lambda$, where D is the characteristic linear size of the antenna and λ is the wavelength. *See* ANSI C63.10-2020 section 9.1.4.

While 90 dB of free-space loss certainly impacts the test equipment's overall dynamic range, one can overcome these path losses by either moving closer to the EUT or utilizing test equipment with improved sensitivities, low-noise figures, and higher gain horn antennas. Furthermore, an EUT operating in the sub-THz frequency range may utilize both electrically small integrated antennas, which allow for closer test separation distances, or other electrically large antenna arrays, thus requiring larger test separation distances. In general, the receiver test antenna must be far enough from the EUT to ensure that the measurements are in the far field. As an example, a 300 GHz source ($\lambda=10^{-3}$ meters) with a D=0.1 meter antenna array would require a distance of at least 20 meters[10] for measurements in the far-field. On the other hand, the same 300 GHz source with a 2.4 mm diagonal horn antenna aperture would result in a far-field transition distance of about ~1.2 cm.

To verify the far-field conditions, emission measurements at multiple distances may be performed to demonstrate the electric field roll-off vs. distance (1/distance, or -20 dB per decade, where a decade is a tenfold distance increase). It is good practice to document the separation distances in any measurement test report.

To compute the total attenuation due to the RF propagation in the atmosphere, the water vapor and oxygen attenuation are added to the free-space path loss (FSPL) attenuation, as in the following equation:

$$\text{Atten}_{\mathbf{TOTAL}}\,(\text{dB}) = \text{Atten}_{\mathbf{FSPL}}(\text{dB/m}) + \text{Atten}_{\mathbf{WaterVapor}}\,(\text{dB/m}) + \text{Atten}_{\mathbf{Oxygen}}\,(\text{dB/m})$$

3.4 Sub-THz Test Site Considerations

Currently, there are no established test site validation criteria for making sub-THz emission measurements. As always, it is advisable to reduce any reflections in the test environment caused by nearby objects. Fully and semi-anechoic chambers using properly rated RF absorbers, or outdoor test sites, are suitable locations for making sub-THz measurements. For outdoor test sites in particular, humidity conditions need to be checked and accounted for as atmospheric gaseous attenuation losses in the measurement path. In many cases, for floor-standing sub-THz devices, an open laboratory floor, free of nearby reflecting objects, provides a suitable test site.

3.5 EUT Pedestals and Test Tables

Tabletop-positioned sub-THz EUTs shall be placed on an RF-transparent test pedestal, so that, including the height of the anti-vibration test table's base (Section 3.1 above), the EUT is at about 1.5 m height from the floor. The EUT pedestal shall be constructed using a low permittivity and low loss material, for instance styrene or building insulation foam.

For sub-THz emission measurements, wooden test tables or pedestals are not recommended, as wood is susceptible to humidity changes and attenuates higher sub-THz frequencies.

3.6 Micro-positioners and 3D Spherical Roll Antenna Positioners

As previously discussed in Section 3.1, at sub-THz wavelengths, a stable EUT position and precise alignment to the receive horn antenna is critical for capturing the maximum field strength of over-the-air (OTA) emissions. For this purpose, it is recommended to use manual or automated three-axis micro-positioners to precisely control and displace clamped objects (i.e., EUT and down converter horn antenna assemblies). As an example, Figure 2 illustrates a receiver down-converter horn assembly mounted on a manual XYZ micro-positioner.

In addition, one may use three-axis spherical roll antenna positioners, designed to connect behind the

EUT, essentially eliminating any obstructions of the propagating EUT's emissions from being coupled to the receiver downconverter horn antenna assembly. Three-axis spherical roll antenna positioners may feature accuracy levels down to 0.1° and include boresight laser options to assist in aligning the EUT to the measurement horn antenna assembly.

When using micro-positioners and/or three-axis spherical roll antenna positioners, it is good engineering practice to document the alignment and positioning method in a test report.

3.7 Test Instrumentation

Typical required instrumentation to perform mmW and sub-THz emission measurements includes:

- Spectrum or Signal Analyzers with external mixing option.
- External up/down converter(s) with known conversion losses.
- Properly frequency-rated horn antennas with sufficiently high gain to overcome atmospheric attenuation and free space path losses.
- Low-loss cables, connectors, etc. (e.g., 2.4 mm or 1.0 mm connectors, keeping cable length at a minimum).

Although it is possible to perform mmW and sub-THz emission measurements using legacy spectrum analyzers with traditional harmonic mixers, this may complicate the measurement process further because of the reduced sensitivities and the lack of signal identification functions in the instrumentation from traditional harmonic mixer imaging. On the other hand, state-of-the-art signal analyzers and spectrum analyzers overcome these challenges with higher dynamic ranges and integrated "external mixer" measurement options that simplify the measurement setup and data collection.

When the measured fundamental frequency exceeds the spectrum analyzer's maximum frequency range, an RF down-converter or external harmonic mixer in the test measurement path will become necessary. The higher the conversion loss of the up/downconverter, the lower the measurement equipment's dynamic range, which, in turn, constrains the minimum required instrumentation's dynamic range.

For external downconverters, the conversion loss table must be factored into the Signal or Spectrum Analyzer corrected test results; additionally, the up/downconverter's bandwidth must always be greater than the emission bandwidth. In the absence of a spectrum analyzer's pre-selector filter (typically used to remove unwanted out-of-tune frequencies), it is important to ensure that test data does not contain artifacts caused by downconverters and mixers, e.g., introducing undesired image frequencies into the measurement results.

Most advanced Spectrum analyzers or signal analyzers have an internal signal ID recognition function to eliminate undesired image frequencies in the measurement. Additional information regarding external mixer precautions for mmW measurements can be found in the FCC Office of Engineering and Technology technical report TR 14-1001.

When a spectrum analyzer is used to perform peak power measurements of pulsed emissions (a radar being a typical example), a phenomenon known as "pulse desensitization" may lead to inaccurate measurement results. In this case, a pulse desensitization factor must be included to adjust the displayed signal amplitude. More information regarding pulse desensitization can be found in Clause 4.1.5.2.7 and Annex C of ANSI C63.10-2020.

Similarly, when using a spectrum analyzer to perform peak power measurements of frequency-modulated continuous wave (FMCW) radar emissions, decreased sensitivity and resolution may require an FMCW correction factor to be applied to the displayed value. Additional information regarding FMCW desensitization can be found in Clause 4.1.5.2.8 and Annex L of ANSI C63.10-2020.[11]

Within their appropriate designated frequency bands,[12] the following WR[13] horn antennas are commonly used in conjunction with mmW and sub-THz up/down-converters:

- Horn antennas for use with mmW up/down-converters
    - U Band, WR-16 standard, 40-60 GHz
    - V Band, WR-15 standard, 50-75 GHz
    - E Band, WR-12 standard, 60-90 GHz
    - W Band, WR-10 standard, 75-110 GHz
    - F Band, WR-08 standard, 90-140 GHz
    - D Band, WR-06 standard, 110-170 GHz
    - G Band, WR-05 standard, 140-220 GHz
        - WR-04 standard, 170-260 GHz
- Horn antennas for use with sub-THz up/down-converters
    - G Band, WR-03 standard, 220-325 GHz
        - WR-02.8 standard, 260-400 GHz
    - Y Band, WR-02 standard, 325-500 GHz
        - WR-01.5 standard, 500-750 GHz
        - WR-01 standard, 750-1100 GHz

Typically, these horn antennas have high gain, increased directionality and narrow beamwidths; therefore, making any slight adjustments in their relative position during testing could lead to inaccurate data, as it may not capture the maximum amplitude of the EUT's emission.

3.8 EUT Considerations

In general, RF emission compliance testing must include the worst-case scenarios (i.e., the most challenging from a compliance perspective) for each EUT's mode of operation; typically, that includes the highest duty cycle settings and operations with the largest RF power available. For transmitters that utilize multiple modulation schemes, it may be necessary to independently test each modulation scheme to correctly demonstrate compliance.

For above-95 GHz radar devices employing FMCW or other frequency-agile techniques, the required RF parameters shall be measured with the active frequency sweep, hop, or step function (accordingly, in these cases, the measurement provisions in section 15.31(c) of the rules, 47 CFR § 15.31(c), does not apply).

[11] ANSI C63.10-2020 Cor 1-2023 (Corrigendum to ANSI C63.10-2020).

[12] IEEE 521-2002, "Standard Letter Designations for Radar-Frequency Bands." IEEE maintains a webpage for this standard at https://standards.ieee.org/ieee/521/768/.

[13] "WR" designation indicates the width of the waveguide opening in hundredths of an inch.

3.9 Test Laboratory Scope of Accreditation

To be FCC-recognized for Sub-THz emissions measurements, test laboratories must demonstrate to an Accreditation Body (AB) the capability of performing measurements in the frequency range between 95 GHz and up to 750 GHz, for each FCC test lab scope under consideration. The AB shall specify to the designatingauthority the maximum frequency range capability of the test laboratory, including demonstration of technical competence, proper laboratory management and Quality Assurance (QA) procedures, in accordance with the requirements contained in KDB Publication 974614 D01, "Accredited Test Laboratory Program Roles and Responsibilities," at paragraph 4 of Section 4, and in ISO/IEC 17025.[14] ISO/IEC 17025 is an international standard that specifies technical competence, quality, and measurement traceability requirements for test laboratories to provide confidence and credibility with their test results.

All test laboratories must be recognized by a qualified Accreditation Body, in accordance with ISO/IEC 17025 and, in their scope of accreditation, identify the highest RF test frequency for which the test laboratory is recognized.

4. APPLICABLE FCC RULE PARTS AND TEST PROCEDURES

The following subsections identify specific procedures related to the rule parts applicable to sub-THz devices:

- Part 15.258 - Intentional radiators above 95 GHz
- Part 18 - ISM devices above 95 GHz
- Part 5 - Experimental Radio License devices above 95 GHz

4.1 Intentional Radiators above 95 GHz

For unlicensed devices operating above 95 GHz, emission measurements shall be performed from the lowest radio frequency signal generated in the device (noting that frequencies below 9 kHz are not required to be tested) to the third harmonic of the highest fundamental frequency or to 750 GHz, whichever is lower. Procedures applicable to these measurements are discussed in Sections 2 and 3.

Section 15.258 of the rules (47 CFR § 15.258) provides emission limits for devices operating in the bands of 116-123 GHz, 174.8-182 GHz, 185-190 GHz and 244-246 GHz.

Equipment Authorization applications shall be done following the Section 2.907 Certification Procedure under Part 2 subpart J. Applications for certification shall use equipment class DXX and select rule part 15.258[15] in Form 731.

[14] ISO/IEC 17025:2017(E), *General requirements for the competence of testing and calibration laboratories,* Third Edition, November 2017. The Commission has incorporated this publication by reference for §§ 2.948(e); 2.949(b); 2.950(a); 2.962(c) and (d) of the rules. *See* 47 CFR § 2.910(c)(3).

[15] TCBs are required to select 15.258 as the rule part for these devices.

4.2 ISM Devices above 95 GHz

For ISM devices operating above 95 GHz using Supplier's Declaration of Conformity (SDoC) equipment authorization procedures, the measurement of radiated emissions is required up to 10th harmonic of the fundamental or to 750 GHz, whichever is lower, using the guidance in Sections 2 and 3. Emissions compliance is based on Part 18.305 of the rules (47 CFR § 18.305).

Equipment Authorization applications shall follow either the Section 2.906 Supplier's Declaration of Conformity (SDoC) or the Section 2.907 Certification Procedure under Part 2 Subpart J of the rules. For applications under the Certification procedure the Form 731 shall refer to equipment class 8CC and rule part 18. Guidance for SDoC can be found in KDB Publication 896810.

Additional information for equipment authorization of THz Spectroscopy devices can be found KDB Publication 974614 D01, "Accredited Test Laboratory Program Roles and Responsibilities."

4.3 Experimental Radio License Devices above 95 GHz

For Spectrum Horizons Experimental Radio license[16] under 47 CFR Part 5 Subpart I, sections 2 and 3 above offer guidance, aligned with technical requirements under 47 CFR Part 5 Subparts I and C. Further information is available in 47 CFR Part 5 Subpart I of the rules.

Change Notice:

mm/dd/yyyy: 800303 D01 Sub-THz emission measurement guidance v01 initial publication.

[16] A Spectrum Horizons Experimental Radio license may be granted for the purpose of marketing devices operating above 95 GHz, where there are no existing service rules. This permission can be provided before the radio frequency device has been authorized by the Commission under 47 CFR § 5.54(f) on a case-by-case basis through OET's Experimental Licensing System (ELS). Visit https://apps.fcc.gov/oetcf/els/index.cfm.

ANNEX — Figures

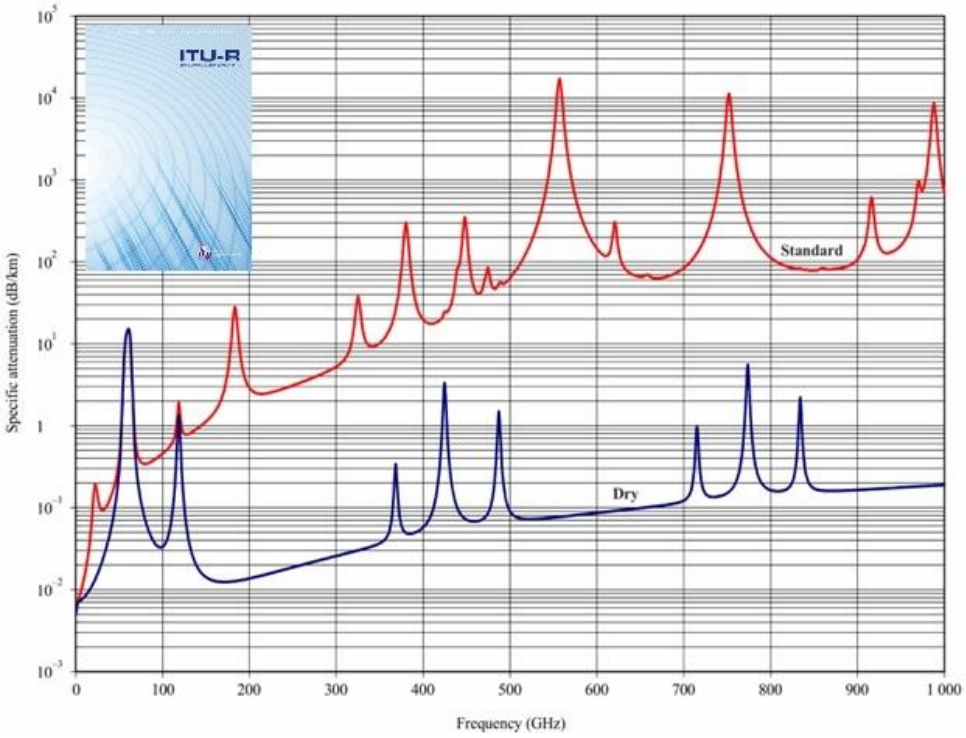

Figure 1 — Water vapor attenuation for RF propagation in the atmosphere (ITU-R P.676-13 (08/2020), Figure 1)

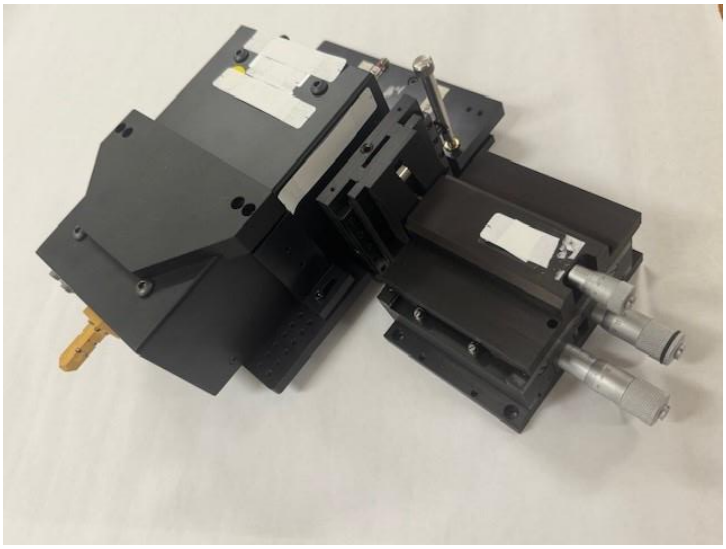

Figure 2 — Example of down-converter horn antenna assembly mounted on a micro-positioner