# MILLIMETER-WAVE FRONT-END INSTRUMENTATION FOR THE ESTEC COMPACT ANTENNA TEST RANGE.


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## ABSTRACT

In preparation of antenna testing for future space exploration missions, ESA ESTEC decided to upgrade its Compact Antenna Test Range into the mm-wave region. As a goal, the same functionality as at lower frequencies should be realized. That means: full (octave) frequency band coverage, sweep or step frequency capability, high dynamic range in the order of 70-80 dB, computer controllable and compatibility with the existing HP8530 receiver equipment. The 110 - 170 GHz band was chosen as a first step to test the concept. With a transmitter, based on a PLL-locked Backward Wave Oscillator, and a receiver based on sub-harmonic mixing in combination with multiplexing of the LO, a system was created with unsurpassed performance in terms of band coverage and dynamic range.


## INTRODUCTION

Mankind, or at a least part of the scientific community, always wanted to know what happened at the beginning of time, how galaxies were formed in the early universe, how stars were and are formed, in order to get a clue how the earth became what it is now. Traces can be found as emissions from stars or small perturbations of the cosmos.
Other scientists study the processes taking place in the atmosphere of the earth as it is today. Study of the spectral absorption lines of chemicals like $H_2O$, $CO_2$, $O_2$, $O_3$ etc can tell us a lot about processes like the greenhouse effect or ozone depletion.

Many of these effects take place in the millimetre and sub-millimetre wave region of the spectrum. Several Earth observation instruments and astronomical missions, like Planck, Herschel, Master and Achechem [1], equipped with instruments operating on these frequencies, are being planned and developed by ESA. The design and manufacturing of these instruments is a challenge of its own. However, at the end the performance has to be verified by measurements so test techniques and instrumentation have to keep up with these developments.

Most of the instruments operate in a few narrow bands, for example the spectral absorption lines of certain chemicals. On the other hand, remote sensing instruments are designed for the “windows” were there is minimal absorption. All of these instruments can be based on narrow band components, like e.g. Gunn oscillators, however a test engineer, faced with the combined requirements of all the instruments will prefer a wideband coverage and easy tunability.

ESA-ESTEC decided to upgrade its Compact Antenna Test Range instrumentation into the mm-wave region. As a goal, the same functionality as at lower frequencies should be realized. That means: full (octave) band coverage, sweep or step frequency capability, coherent measurement of amplitude and phase, high dynamic range in the order of 70 to 80 dB, computer controllable and preferable compatible with existing receiver equipment (HP8530). The 110-170 GHz band (sometimes denoted as D-band) was chosen as a first step to test the concept. Further upgrades, up to 350 GHz, are foreseen if the quality of the Quiet Zone, mainly determined by the (unknown) surface profile of the Compact Antenna Test Range reflectors, remains acceptable.

## SYSTEM DESIGN CONSIDERATIONS

When passing the 100 GHz border, the RF engineer will notice that he has entered a new zone were a term like “standard catalogue item” fades away. Nevertheless, a good starting point for the design is still the power budget.

Starting at the receiver end, it is clear that there is no equipment that can do coherent measurements at mm-wave frequencies. The signal has to be down-converted to a (standard) measurable frequency. These receivers, e.g. an HP8511, have a minimum detectable power of about –110 dBm. Taking into account the cables losses between mixer and receiver (> 5 dB), the conversion loss of the harmonic mixer (15-20 dB for sub-harmonic mixing, 30-50 dB for high harmonic numbers) and the free space loss in a Compact Antenna Test Range (including the gains of range feed and AUT: 10-15 dB), the conclusion is that the minimum available output power of the transmitter should be 0 dBm. So besides the requirements, mentioned in the introduction, the dynamic range requirement translates to:
-Transmit power: minimum 0 dBm
-Low receiver conversion loss

The system can be divided in three major components: the transmitter, the receiver front-end and the range feed antenna.

### The transmitter.

There are a number of sources available for generating output power at mm-wave frequencies. A good overview is given by Zimmermann [2]. Synthesizers are not in his list for obvious reasons. Commercial available synthesizers stop at about 50 GHz. HP/Agilent offers frequency extensions up to 110 GHz by means of multipliers (HP83557-8). Above that, Oleson Microwave Labs (OML) offers HP-compatible multiplier sources [3], however the multiplication number to be used reduces the efficiency and the output power does not match the required 0 dBm.

Other popular sources are the GUNN-oscillators. They are frequently used in instruments with narrow banded operation. Their main limitation is their tunability. Mechanical tuning is not the preferred solution for a measurement range and electrical tuning is limited to about 5%. Every AUT would require the purchase of a dedicated GUNN-oscillator front-end.

Solid-state sources are emerging, however, their output power is still very limited.

The Backward Wave Oscillator (BWO, also known as carcinotron) combines both the requirements of output power and tunability. The main drawbacks are that it is a tube with a limited lifetime (typical 2000 hrs) requiring high voltage supply. Another drawback is the phase noise and stability of this source. Since the oscillator frequency is voltage controlled, any ripple (e.g. 50 Hz) will cause a frequency modulation. Recently, there have been some developments:
ELVA-1 [4], supported by FARRAN Technology Ltd. [5], has developed a BWO-based Millimetre Wave Generator with integrated power supply and control unit.
Säily reported about a BWO, phase locked to an external source to improve the phase noise [6]
Combination of these two developments yields a promising concept as pictured in figure 1.
To get sufficient bandwidth for the PLL, the reference frequency is set to 300 MHz.

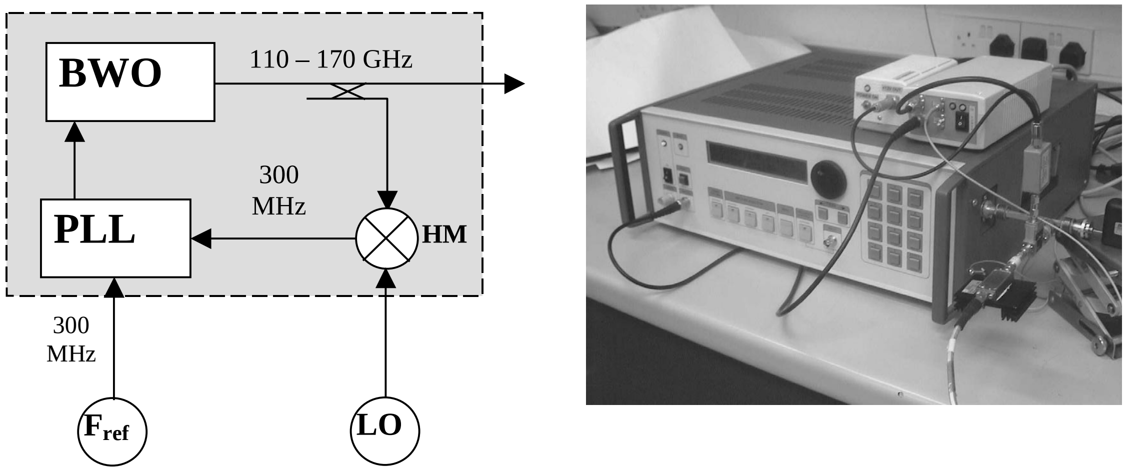


Figure 1: Transmit part: a phase-locked BWO.

The reference frequency for the PLL and the LO are externally supplied.

**The receiver front-end.**

On the receiver side, the most obvious choice for down-mixing the millimetre wave frequency is a harmonic mixer. The only freedom of choice is the harmonic number, and connected to that, the LO-frequency. Keeping in mind that this concept should be expandable to 350 GHz with an LO below 40 GHz, the harmonic number should be at least 9. With these high harmonic numbers, the conversion loss is in the order of 30 dB. Compared to the 15 dB as assumed in the power budget of the introduction, this would reduce the dynamic range by 15 dB.

The only solution to keep the conversion losses to 15 dB is the use sub-harmonic mixing with a harmonic number of 3 in combination with a multiplication of the LO frequency by a factor 3. This combination was available by ELVA-1 as their model DC-THM/9-06-N. Figure 2 shows the receiver front-end, with an extra LNA in the IF line.

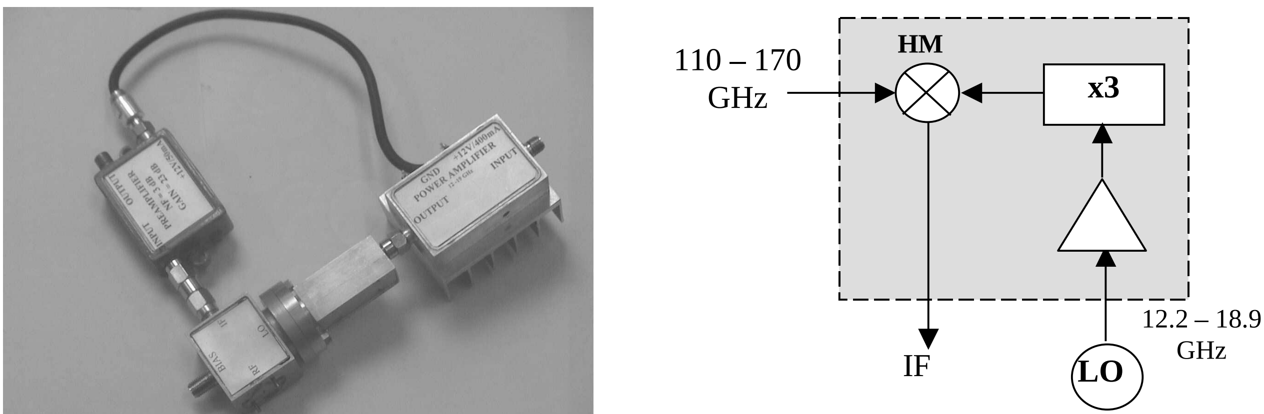


Figure 2: Receiver front-end

**System design**

For the system design, choices have to be made for the harmonic number N on the transmit side and the IF to be fed into the receiver. On the transmit side, the relation between the frequencies is:

$$F_{BWO} = N*LO_1 + F_{ref} = N*LO_1 + 300 \text{ MHz} \quad (1)$$

On the receive side, the frequency relation is:

$$F_{BWO} = 9*LO_2 + IF \quad (2)$$

Substitution yields:

$$9*LO_2 = N*LO_1 + 300 \text{ MHz} - IF \quad (3)$$

Three alternatives have been considered:

1. IF = 20 MHz N = 9 ➔ $LO_2 = LO_1 + 31.11$ GHz
2. IF = $LO_2$ N = 10 ➔ $LO_2 = LO_1 + 30$ MHz
3. IF = 300 MHz N = 9 ➔ $LO_2 = LO_1$

The first choice is driven by the idea that the 20 MHz IF can be fed directly into the HP8530, a common practise when using remote mixers. This choice has a few disadvantages. To provide the receiver with a stable reference signal for locking, a second (expensive) receiver module is required together with a directional coupler at the transmitter output. Besides that, 3 external sources are required: $LO_1$, $LO_2$ and $F_{ref}$.

The second solution is based on a configuration of an HP8511 frequency converter in combination with the HP8530, since this is part of the standard equipment of the CATR. The $LO_2$ source can be used for locking the receiver. An attractive aspect of this choice is that the triple frequency of $LO_2$ is again a standard RF band, even for extensions up to 360 GHz (170 – 250 GHz, 250 – 360 GHz), which increases the availability of components. However, for the mixer operation it is not an optimal choice since the third harmonic of the IF is equal to the mixer-LO (=3*$LO_2$). This can give al kind of unwanted mixer products. And also in this case, 3 external sources are required.

In the last option, the IF is equal to the PLL reference frequency (300 MHz). Since $LO_2$ is equal to $LO_1$, only two external sources are needed and these can be controlled conveniently by the multiple source capability of the HP8530. A reference signal for locking the receiver and monitoring the TX-output can be obtained by a directional coupler in the line between harmonic mixer and PLL. This is the most attractive solution and has been implemented. The complete system is shown if figure 3.

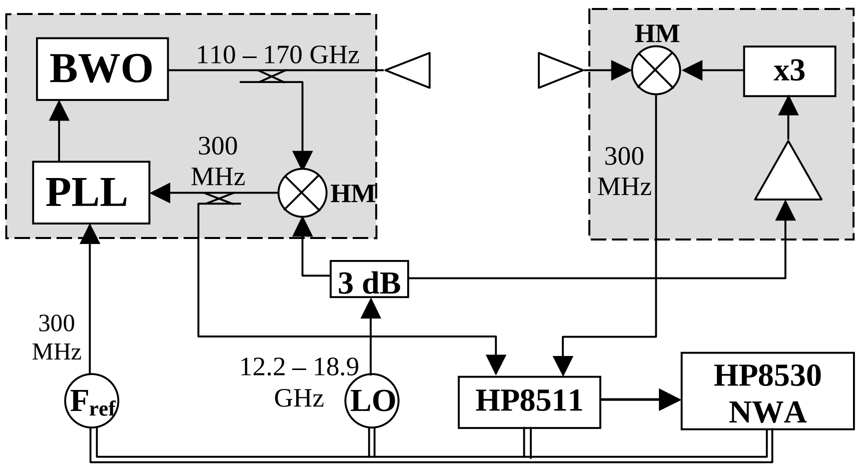


Figure 3: Complete system diagram.

**Corrugated horns**

The range feeds have been designed by the manufacturer of the ESTEC Compact Antenna Test Range, March Microwave. The manufacturing by means of electroforming has been done by Thomas Keating Ltd [7]. Several design iterations and a scaled test model at X-band have been made to match the design goals to the manufacturing limitations. The design goals could not be met over the full frequency range of 110 – 170 GHz. A much better performance has been achieved by covering this range with two antennas. In the last iterations, the horns have been optimised for equal E- and H-patterns, Cross-polar radiation in an area up to 12° from boresight (illumination of CATR reflectors) and Return Loss. Figure 4 shows a picture of the manufactured horns.

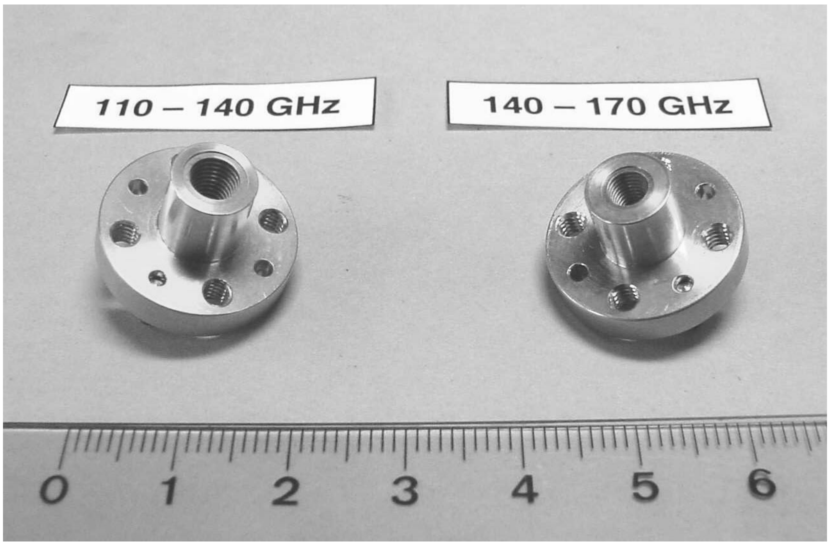


Figure 4: Corrugated Range antennas

Some characteristic design numbers of the horns are:

| | |
|---|---|
| Half cone angle: | 10° |
| Corrugations: | 13 |
| Aperture diameter: | 4.6 mm (110 – 140 GHz) |
| Directivity: | 13 – 15 dBi |
| HPBW: | 36° |
| X-polar: | < -40 dB for θ < 12° |
| Return loss: | < -25 dB |
| Waveguide: | WR06 |

Test data of the horns are not available yet.

**Test results**

At the moment of writing, the Factory Acceptance Tests have just been finalized. These tests were limited to the Transmit and Receive module of the system, the grey blocks in figure 3. The system integration with the HP8530 and HP8511 will be done on site at a later stage.

Figure 5 shows that maximum transmit output power is well above 10 dBm over the whole frequency range.

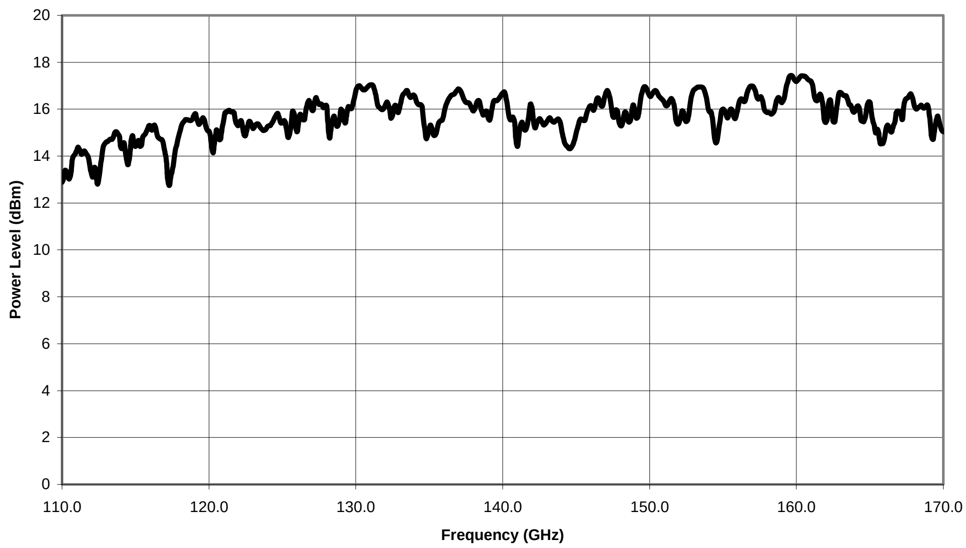


Figure 5: Maximum transmit output power of BWO-Tx module

The frequency spectrum at the 300 MHz IF reference channel of the TX module at the upper band edge of 170 GHz (see figure 6) shows that the spurious spectral components are below –60 dBc. The spectra at 110 and 140 GHz are similar.

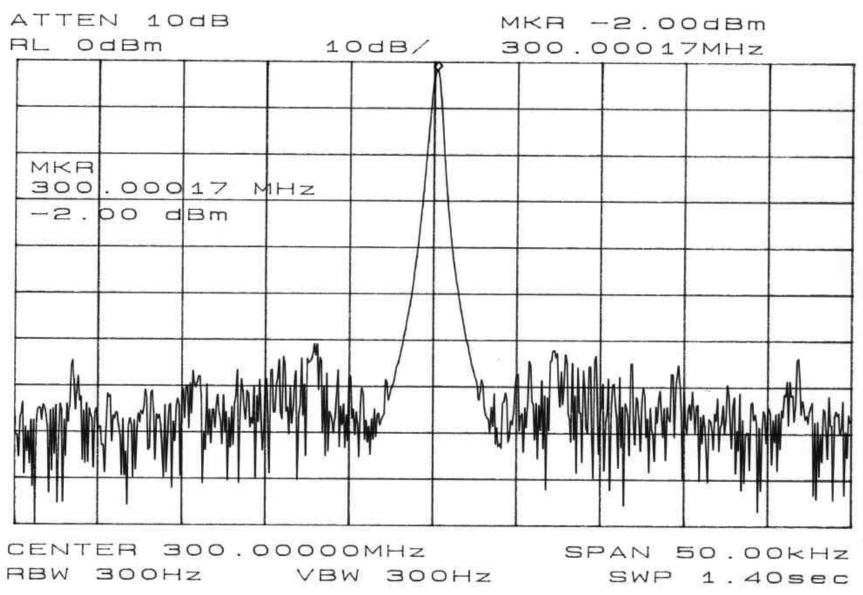


Figure 6: IF frequency spectrum of Tx-reference output for RF = 170 GHz.

Figure 7 shows the conversion loss of the Rx-module. The 15 – 20 dB assumption in the power budget of the introduction proves to be realistic, apart from the spikes. Since the results are fresh, there is no explanation yet for this spiky characteristic.

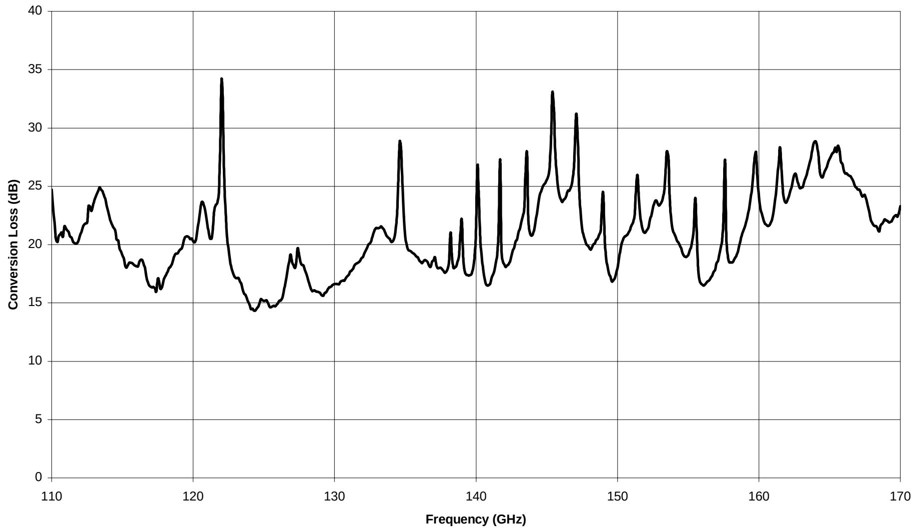


Figure 7: Conversion Loss of Receive Module.

Finally, in figure 8, the sensitivity of the receive module is shown.

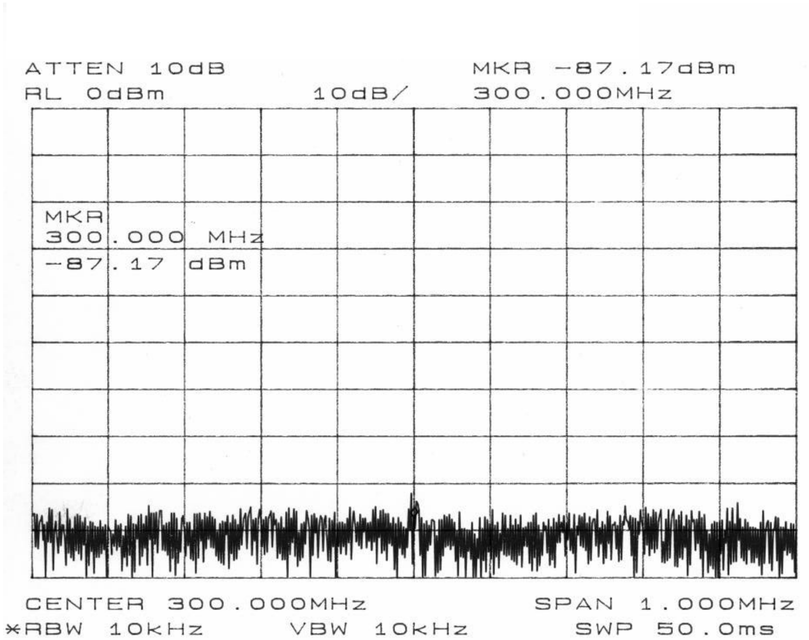


Figure 8: Sensitivity of Receive module at 140 GHz.

These Factory Acceptance Test results show that the requirements for Transmit Power and Dynamic Range are achieved. Other intended features, like the compatibility with the HP8530 Network Analyser and the sweep capacity have to be proven during a Site Acceptance Test at a later stage. After that, the performance of the whole Compact Antenna Test Range, i.e. the Quiet Zone amplitude and phase ripple, has to be tested. But the realized equipment is a powerful and promising starting point for a Compact Antenna Test Range, capable of measuring at mm-wave frequencies with the same functionalities and error correction techniques as at lower frequencies.

## CONCLUSIONS

The realized equipment for measuring antennas in the ESTEC Compact Antenna Test Range at mm-wave frequencies has unsurpassed performance in terms of band coverage, tunability and Dynamic Range. The concept is very attractive due to its compatibility with the widely used HP8530 Network Analyser. Another attractive point is the coherent measurement capability that enables the use of correction techniques like time gating (based on frequency to time conversion) and AAPC.

## REFERENCES


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[3] http://olesonmicrowave.com/index.html

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