LA MÉTROLOGIE AU CŒUR DES TECHNOLOGIES CONTEMPORAINES

Mesurer les ondes millimétriques pour la radioastronomie
Millimeter-wave radioastronomy measurement challenges

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Résumé/Abstract

La radioastronomie dans les longueurs d'onde millimétriques est un domaine qui a vu le jour il y a plus de 50 ans. Les techniques ont évolué avec le temps pour atteindre des sensibilités sans précédent. Pour obtenir une résolution spectrale extrêmement élevée, la spectroscopie est réalisée à l'aide de techniques hétérodynes. Les composants cryogéniques critiques utilisent des mélangeurs supraconducteurs et des amplificateurs très faible bruits. Un aperçu de l'état de l'art dans ce domaine sera fourni, ainsi que les perspectives pour la future génération d'instruments. Une discussion sur les techniques de mesure et d'étalonnage sera également fournie, montrant les nombreux défis auxquels il faut faire face lors de la mesure de signaux extrêmement faibles dans le régime millimétrique.

Radioastronomy in the millimeter wavelengths is a field that started more than 50 years ago. Techniques have evolved with time to reach unprecedented sensitivities. To achieve extremely high spectral resolution, spectroscopy is achieved using heterodyne techniques. The critical cryogenic components are using superconducting mixers and amplifiers. An overview of the state of the art in this field will be provided together with the perspective for future generation of instruments. A discussion on the measurement techniques and calibration will also be provided, showing the many challenges that are faced when measuring extremely weak signals in the millimeter regime.

1 Introduction

Millimeter radioastronomy usually refers to observations performed between 1 mm to 4 mm wavelengths, or equivalently between 70 GHz and 300 GHz. This area of astronomy is crucial to understand better the life-cycle of stars, where this wavelength allows better probing the cold universe.

Within this field, there exists different instrumentation families. The first allows to measure large RF bandwidths with low to moderate spectral resolution. Such instruments are called continuum instruments, using technologies such as Ge:Ga photoconductors, NTD Ge bolometers, superconducting transistion edge sensors (TES) or more recently superconducting microwave kinetic inductors (MKID). This technology has reached a level of maturity where thousands of pixels can populate large arrays, performing efficient mapping.

The second type of instruments using coherent detectors allow achieving extremely high resolution, in particular this permits to extract kinematics information of the atomic or molecular emission/absorption lines. In this work, we will restrict ourselves to this field, using heterodyning techniques to allow very high-resolution spectral measurements. More information on both type of instrumentation can be found in [1].

2 Heterodyne receivers for millimeter astronomy

To be able to measure frequencies between 70-300 GHz, historically observatories have used Schottky mixers, cryogenically cooled to improve the sensitivities. Figure 1 shows a schematic of a representative receiver for millimeter waves, using a mixer as first active component in the system. A local oscillator reference signal is needed to allow mixing the RF input down to intermediate frequencies (IF), in the microwave range where commercial components allow further processing.

In the 1980s, development of superconductor-insulator-superconductor junctions (SIS) allowed to improve drastically the performance [2]. Indeed, compared to the best Schottky mixers available at the time, sensitivities were improved by an order or magnitude. Figure 2 shows typical layout of a SIS junction and how it is incorporated onto a quartz chip, with RF tuning circuit and antenna to couple the RF signal from the waveguide to the SIS junction. It is interesting also to note the progress done at IRAM. Some of the first SIS mixers used movable backshorts in the 1990s to allow single band operation (Figure 3 - left). Now, SIS mixers use much more complex architecture, performing sideband separation without movable backshorts, using several junctions, with input RF hybrid and output IF hybrids, all integrated into a single mixer block (Figure 3 - right).

Very recently, in 2020 [3], high electron mobility transistors (HEMTs) have equaled the SIS mixers in term of noise performance up to 115 GHz and work is ongoing to push further in frequency their performance [Manchester?].

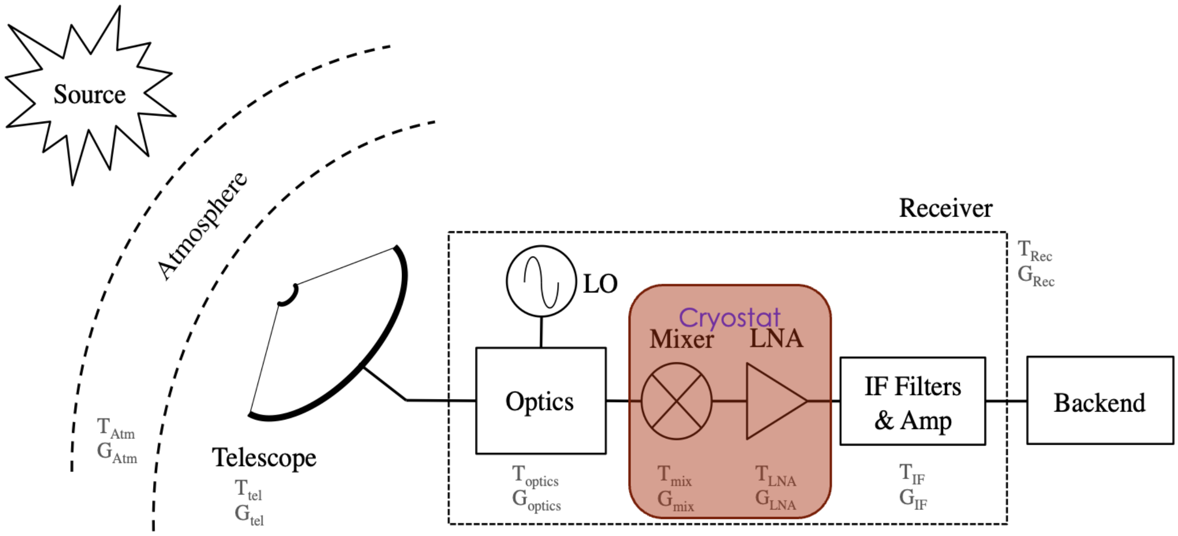

Figure 1: Schematic of a heterodyne receiver. Usually, a cryostat is used to cool down the critical components, the mixer and the low noise amplifier.

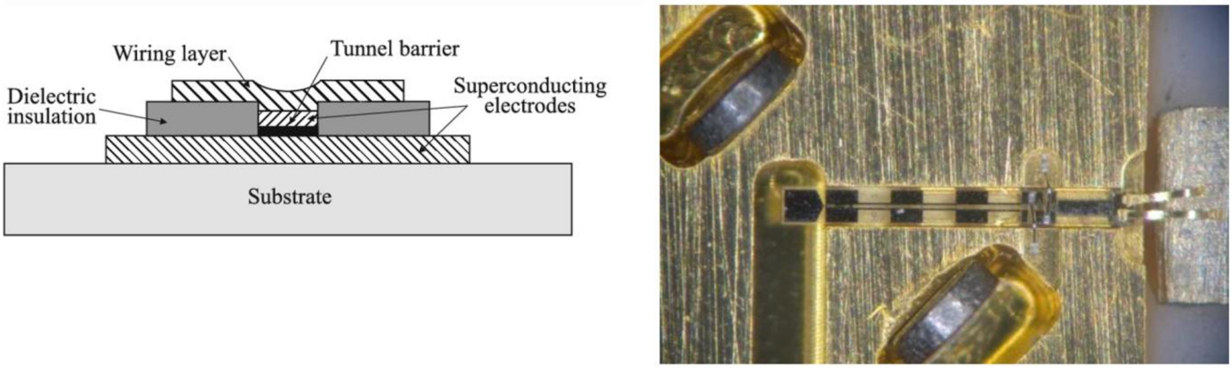

Figure 2: Left: SIS mixer cross section view. Right: SIS mixer on a quartz substrate integrated into a mechanical block.

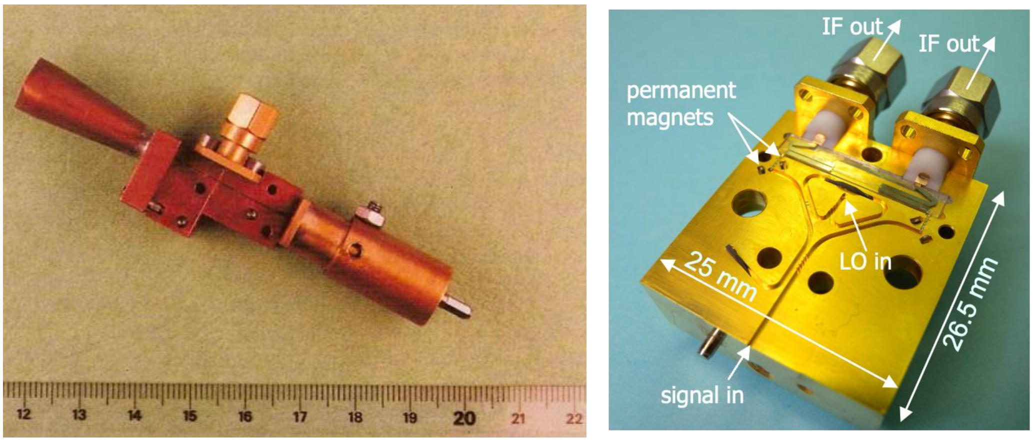

Figure 3: Left: View of a single sideband SIS mixer at used at IRAM in the 1990s. Right: current generation of sideband separating SIS mixer, integrating all components in one mechanical block with no movable parts

3 Measurement techniques for millimeter astronomy

To characterize the millimeter wave receivers, several steps are usually performed.

Component level

All components are usually characterized individually before their integration into the full system. For the optical elements, mirrors, RF windows/filters, dichroics and corrugated horns, they are characterized using beam measurement setups of varying complexity. Typically, beam direction and characteristics are measured in those setups using a motorized X-Y stage. The emitter is usually an RF signal in the millimeter range of interest, using Gunn oscillators or harmonic mixers driven by low frequency synthesizers. The measurement setups allow to recover both the phase and amplitude of the signal.

For some individual components, S-parameters measurements can be performed using commercial and customized vector network analyzers. IRAM has built in the early 2000s several frequency extenders for a PNA-X VNA, exactly adapted for our frequency bands of interest (see for example Figure 4). For example, the band 70-116 GHz that we use on our observatories is not coinciding perfectly with the commercial W-band, where extenders cover only 75-110 GHz.

Losses estimation for some components can be achieved with more accuracy than using the VNAs, by using a test SIS receiver. We perform noise temperature measurement of the test receiver with and without the device under test (DUT) placed at the receiver input. Difference of the receiver noise temperature between measurements will allow estimating a more precise loss value for the DUT. Typically, better than 0.5% accuracy can be achieved as opposed to about 3-5% with VNA S-parameter S21 measurements.

Figure 4: Measurement in reflection of an IRAM dichroic, using custom made frequency extenders connected to a PNA-X vector network analyzer.

Full system characterization:

With the full instrument assembled, before its installation on a telescope, the final characterization is performed in the laboratory (see Figure 5) and then a technical commissioning on site is typically performed (Figure 6).

- Laboratory characterization:
  - Noise temperature determination of the full system – can be limited to the receiver with input optics but can also include the full representative backend and corresponding IF pre-processing, if available. The receiver operation when looking at the cold sky at various weather conditions should always be linear. Therefore, the calibration procedure consists of:
    - Cold load measurement – historically done at 77K using an absorber dipped into liquid Nitrogen
    - Hot load measurement – historically done at 290K using an absorber at room temperature
  - Having two independent measurements at distinct temperatures allow then to calibrate the sky observations using these two sets of data. The assumption is that the receiver behaves linearly between those two measurements, which is usually the case. Nowadays, the cold/hot temperatures can be quite different than what was mentioned earlier. Several observatories, for simplicity, use a hot and hotter load (for example 290K and ~380K – heated load). In those cases, linearity issues are more likely and must be considered.
  - Optics verification: with the beam measurement setups, final adjustment of the beam alignment and verification of the beam quality of the full system are performed.
  - Tuning table preparation: During this measurement session, usually many tuning points are prepared to fully optimize the receiver performance. The SIS mixer bias setting, DC voltage and pumping levels are determined. At IRAM, we usually provide tuning tables every 0.5 GHz step. Major difficulty is to avoid spurs or spurious signal within our intermediate frequency band (IF). Therefore, this tuning step ensures that we will have clean bandpass.
  - Receiver stability and standing waves: The final verification and tuning optimization also ensures that the receivers is stable enough for deep integrations and that the receiver bandpass is exempted from large standing waves, which would also hinder observation of weak lines.

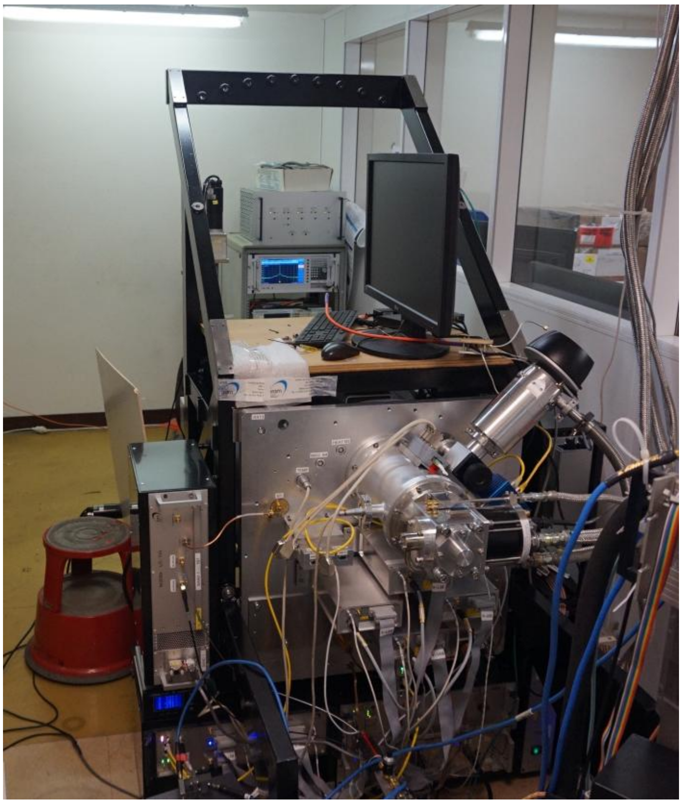

Figure 5: In the Grenoble laboratories, the full receiver is installed in the same support frame which will then be connected to the telescope receiver cabin interface ring. Full characterizations are performed in this configuration. Detail of the receiver design can be found in [4]

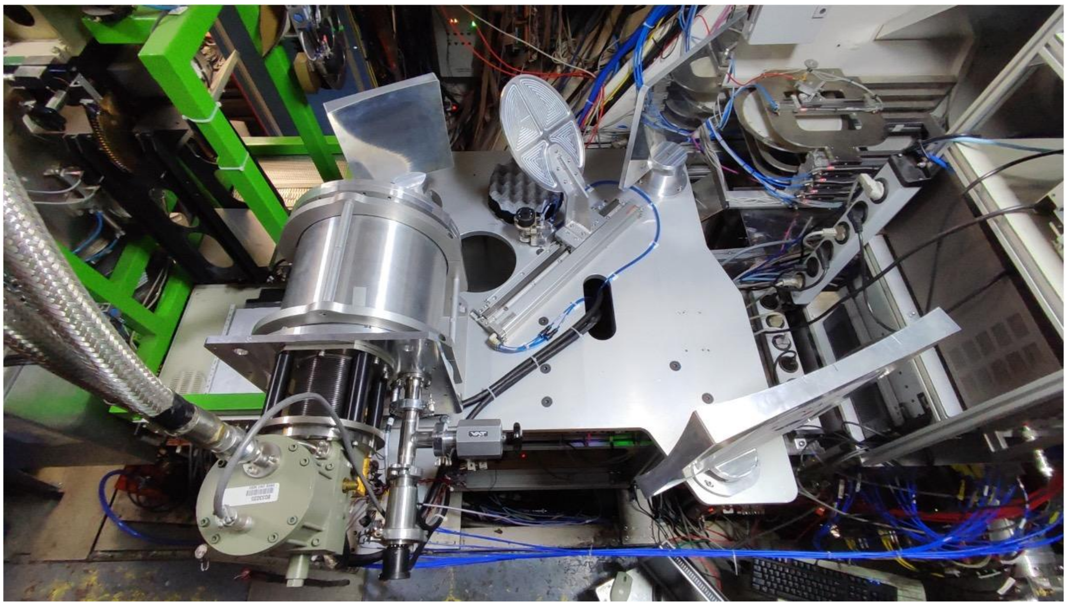

Figure 6: Example of installation of a receiver on a telescope. In this case, a 1x3 W-band HEMT receiver is installed at the 30m IRAM telescope in southern Spain for a test campaign.

- On-site technical commissioning:
    - One the receiver system is installed on site, before releasing it to the scientific community, final verifications and characterizations are needed. This will verify the laboratory measurements, but more importantly will verify that in its final configuration and environment, no surprises are present, such as RFI or standing waves from the telescope optics.
    - Optical alignment is crucial. Verification on site will allow to verify that the RF beam is well centered on the telescope optical axis. If not, this will translate into efficiency losses, pointing offsets which can also produce beam aberrations.
    - The cold/hot calibration ate usually performed every 20 minutes, allowing to measure the receiver noise temperature and those measurement allow the sky observations to be calibrated. For the proper signal calibration, a SKY measurement will be needed (not looking at the scientific source, but close-by). This will allow determining the atmospheric contributions, atmospheric features, opacity, allowing to derive the precipitable water vapour (PWV).
    - Before the observations, the telescope should also be well focused and pointed, to allow achieving the best signal to noise and accurate observations.

4 Perspectives

We have provided a short overview of the state-of-the-art instrumentation used for very high-resolution spectroscopy in millimeter waves and some of the measurement techniques. For the instrumentation evolution in the near future:

- HEMT cryogenic amplifiers highest frequencies of operation have finally reached the ~100 GHz range where they can achieve comparable performance as SIS mixers. Work is undergoing to push this frequency limit to 200 or 300 GHz range.
- Other components are being studied for the past 20 years, such as superconducting traveling wave amplifiers (KID or Josephson mixer based), with the promise of event lower sensitivities.
- As current components are almost quantum noise limited, efforts can also be placed into more complex architectures, for example balanced sideband separation mixers.
- Integration of multi-pixel arrays is progressing, though still at a low pace. Compared with continuum instrumentation which already use thousands of pixels, heterodyne receivers only successfully demonstrated tenths of pixels.

For the measurement techniques, historically millimetre wave astronomical instrumentation needed to develop its own method and tools to characterize the components. With the commercial advent of millimetre waves (and THz in general), commercial products are spreading very quickly and will therefore allow easier and cheaper measurement for our field. Only drawback is that the commercial W-band (75-110GHz), D-band (110-170 GHz) and H-band (220-330 GHz) do not overlap so well with our receiver frequency bands (70-116 GHz, 125-180 GHz, 200-280GHz).

References

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