Hunt for Molecules
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COMPONENTS, RECEIVERS, AND INSTRUMENTATION FOR GROUND-BASED MM/SUBMM ASTRONOMY

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Abstract. After listing the scientific drivers for the developments in mm/submm instrumentation, we discuss the current technologies (HEMT amplifiers, SIS and HEB mixers) and their domain of application. We then compare the performance limits arising from quantum fluctuations, the atmosphere's photon background, and the current state of the technology. Next, we present ongoing developments and results achieved. Finally, we briefly discuss the outlook for future developments.

1 Introduction

While astronomy in the optical range could (at least up to the time of Tycho Brahe) make progress with the unaided eye as a detector, molecular astronomy relies on observations in the mm/submm domain, and is to a large extent driven by the progress of instrumentation in that wavelength range. That progress has been very significant in the last decades. Arguably the most important specification (but definitely not the only one) for an astronomical detector in the mm/submm is low noise. Early observations of molecules in the decimeter range (OH) or in the centimeter range (water,

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[1] IRAM

ammonia) relied on such technologies as parametric amplifiers and masers. Already then, the first stages of the signal chain were cooled to achieve the lowest possible noise. The number of molecules observed in space started an "exponential" growth in the early seventies, based on observations in the millimetre domain using mixers with Schottky diodes. The emergence of the SIS junction as a low-noise mixing element in the eighties enabled the construction of receiving systems with even lower noise. In the following decade, two other technologies were put to use in astronomical frontends: HEMT amplifiers, and hot electron bolometers, the former former in the low-millimetre range, and the latter in the submm range. Together with SIS, these technologies form the basis of current receiving systems. Schottky mixers continue to play a role in some submm space-borne instrumentation, where it is not possible or desirable to implemenmt a cryogenic system. In this short presentation we focus on ground-based astronomy.

2 Driving projects and requirements

The IRAM telescopes in Pico Veleta and Plateau de Bure are arguably the premier facilities for ground-based mm-wave astronomy. While these mature instruments keep being improved, notably as concerns signal electronics: frontends and spectrometers, the ALMA instrument, currently under construction, will provide an order-of-magnitude improvement in oberving capabilities over all previous instruments. IRAM is an active participant in that effort.

Fig. 1. The IRAM telescopes. Left: the 30m telescope at Pico Veleta; right: the Plateau de Bure interferometer (photo A.Rambaud).

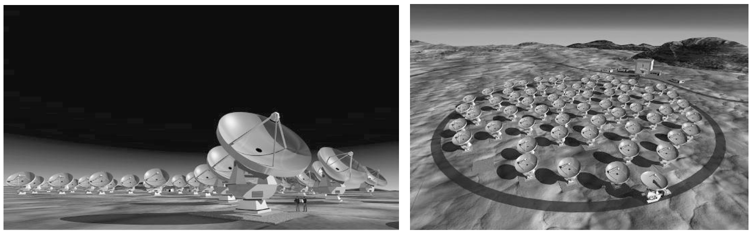

Fig. 2. The ALMA instrument. Artist's view. Image courtesy of NRAO/AUI and ESO.

Whether built for ALMA, IRAM, or other facilities, receiver frontends are driven by the same set of requirements.

- Sensitivity, the limit being the noise of the background radiation field.
  - Receiver: electronics, optics
  - Atmosphere
  - Source (solar observations!)
  - Vacuum fluctuations
- Frequency coverage
  - Tuning range. Goal: cover all atmospheric windows
  - Instantaneous coverage. Goal: one atmospheric window, i.e. several 10's of GHz(!)
- Mapping speed. Significant for extended objects. A combination of sensitivity and number of pixels.
- But also:
  - Stability: amplitude, phase
  - Linearity
  - Polarization purity
  - Maintenance interval
  - Mean time between failures
  - Cost

3 Active component technologies

Many (but not all) of the performances of a receiver are determined by the first active component in the signal chain. Currently three types of components play a significant role in the construction of millimetre wave receivers.

- HEMT amplifiers. These low-noise cryogenic amplifiers have benefitted from an intense development effort for spatial astronomy projects, notably cosmic background mapping. In the laboratory, operation has been demonstrated up to about 200GHz, while actual systems have been implemented up to 115GHz. They operate at typically 15K, with little improvement in noise at lower temperatures. Their most interesting property is their very wide instantaneous bandwidth, up to 30%.
- SIS mixers. They are based on the tunneling through an insulating barrier of electrons resulting from the breaking of Cooper pairs, caused by the cooperation of the DC bias and the RF photons. Their current-voltage characteristic is strongly non-linear on a scale of order mV, which allows to pump the mixer with typically a fraction of a μW, about three orders of magnitude less than a cooled Schottky mixer. The instantaneous bandwidth achievable with an SIS mixer is between 8 and 16 GHz for dual-sideband systems. Among available technologies, SIS mixers achieve the lowest receiver noise in the range 80–1000 GHz, the upper limit being dependent on the gap energy of the superconducting material used in the junction itself and in the surrounding RF circuits.
- HEB mixers. Their operation relies on a very small (sub-micron) volume of superconductor, heated up to the transition temperature by the combination of DC bias and RF (LO+signal) power. Their LO requirements are even lower than those of SIS mixers, in effect a TES bolometer with a fast response. In contrast with SIS mixers, HEB mixers have in principle no sharp upper frequency limit. They are therefore the prime choice for frequencies above one THz.

The achieved performance of these three technologies is shown on figure 3. Figure 4 shows their domain of applicability, overlaid on the atmospheric transmission curve for typical good conditions on the ALMA site.

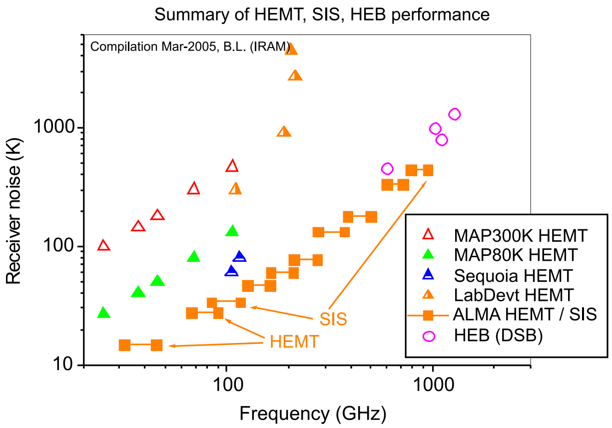

Fig. 3. Achieved noise performance with the three frontend technologies: HEMT, SIS, HEB. Actually, in the case of SIS receiver, the performance shown is the ALMA *specification*; note that at the time of writing, these specifications appear to be realized.

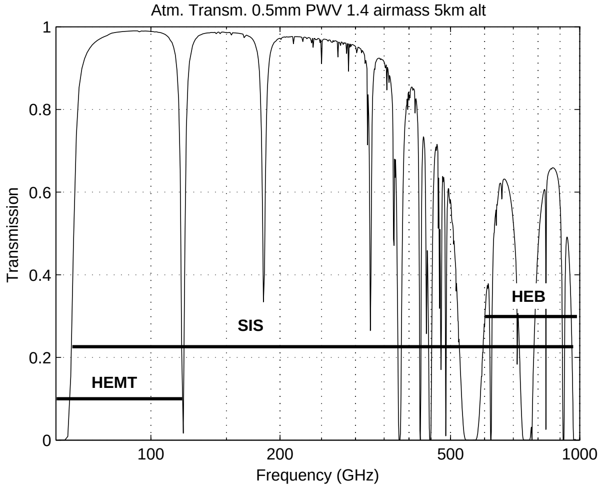

Fig. 4. Atmospheric transmission curve for good conditions on the ALMA site, with the approximate domain of application of HEMT, SIS, and HEB technologies.

4 Ultimate limits to receiver noise

4.1 Quantum limit

The value $h\nu/k$ is often mentioned as the "quantum limit" for receiver noise. This is not quite true; this issue has been investigated and clarified by Kerr *et al.* (1997); their conclusions are summarized in Table 1. The value $h\nu/k$ nevertheless is a convenient unit against which to measure the noise performance achieved by a receiver.

Receiver type	SSB	DSB	
Calibration type	SSB	SSB	DSB
Tsys	$h\nu/k$	$h\nu/k$	$h\nu/2k$
Tmxr	$h\nu/2k$	0	0

Table 1. Values of the quantum limit according to the receiver type SSB/DSB, the calibration type, and to whether the vacuum fluctuations in the signal band(s) are included (system) or not (mxr) in the definition of noise.

4.2 Practical limits

In practice, the lowest achievable noise is limited by the atmosphere's radiation and by the optical components that are inevitably in the signal path like, e.g., a vacuum window and an infrared-blocking filter. Losses and added noise that were considered negligible 15 years ago are now significant. The various limits are shown on Figure 5. One can see that in an excellent site, and within the atmospheric transmission windows, the noise remains determined by the receiver performance.

5 Device development at IRAM

5.1 SIS junctions

The IRAM SIS group fabricates Niobium SIS junctions for IRAM receivers and for ALMA band 7. The junctions for Herschel/HIFI band 1 were also fabricated at IRAM. The main parameters of the IRAM SIS process are listed in Table 2.

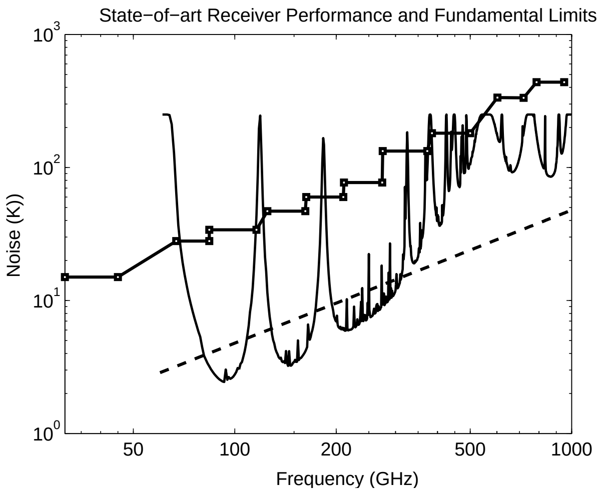

Fig. 5. Noise limits for gound-based mm/submm astronomy. Continuous curve: atmospheric radiation for 0.5mm PWV and 1.4 airmass; staircase plot: ALMA SSB specifications (the DSB specification is a factor of 2 lower); dotted line: $h\nu/k$.

Area (μm^2)	Area Tol. (%)	Critical current density (kA/cm^2)	Quality $R_{sg}(2mV)/R_n$	Process yield (%)
1-4	10	6-15	15-30	>60

Table 2. Main parameters of the NB SIS process at IRAM

5.2 Other devices

IRAM's "SIS" group also develops other devices. A systematic investigation has been undertaken of the superconducting and transport properties of thin NbN films. HEB mixers are fabricated using these films and optimized for, among other, maximum IF bandwidth. This is illustrated on Figure 8.

The SIS group also develops microelectronic mechanical devices: voltage-tunable capacitors, with a process compatible with the co-fabrication of superconducting junctions. Such a device is shown on Figure 9.

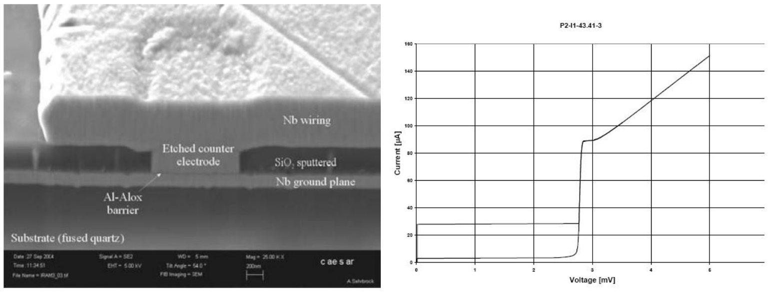

Fig. 6. Left: a scanning electron microscope view of a cutaway SIS junction; the cut was realized with the FIB (focused ion beam) technique. Right: Current-voltage curve of an SIS junction with a current density of $10kA/cm^2$.

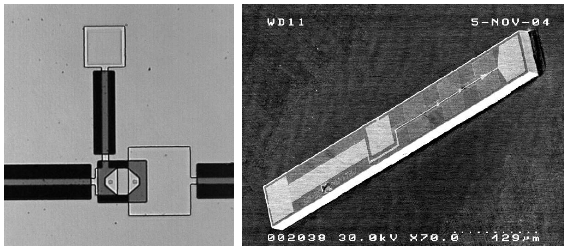

Fig. 7. Left: detail of a 100GHz-band SIS mixer chip, showing the RF circuit that is designed to tune out the junction capacitance and provide a good impedance match over the design bandwidth. Right: a mixer chip for the ALMA band 7 mixer. The chip is fabricated on a quartz substrate having dimensions 2mm x 250μm x 80μm.

6 SIS mixers

The IRAM receiver group develops and implements various types of SIS mixers: DSB mixers, SSB mixers that are tuned with a moving backshort, and sideband-separating mixers (2SB) that deliver the LSB and USB sidebands on physically distinct IF ports.

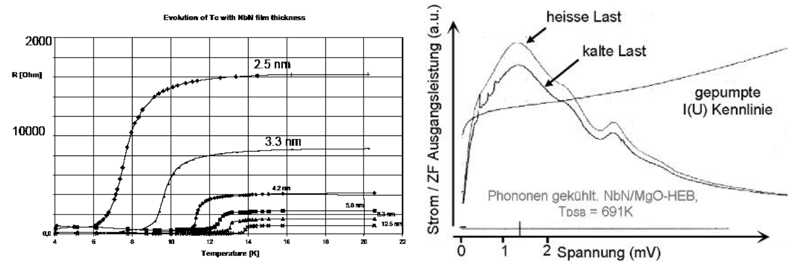

Fig. 8. Developments of NbN thin films and HEB mixers. Left: dependence of the critical temperature upon the film thickness. Right: Performance of an HEB mixer: pumped I-V curve, and IF power versus bias.

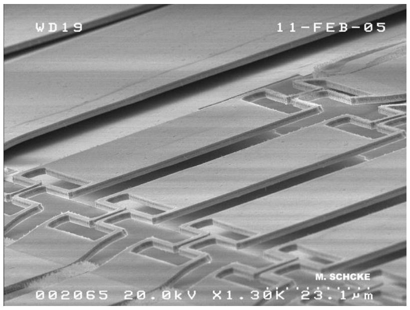

Fig. 9. An example of MEM devices realized at IRAM's SIS group. These parallel-plate capacitors are suspended by meander lines and can be voltage-tuned.

6.1 DSB mixers

While they are not used directly in IRAM receivers, DSB mixers serve as building blocks for 2SB mixers. Figure 10 display results obtained at IRAM and at SRON, showing that DSB receiver noise at the level of 2-3 $h\nu/k$ can be obtained. For this and subsequent SIS mixer results, the noise includes the test dewar optics and the contribution of the IF chain.

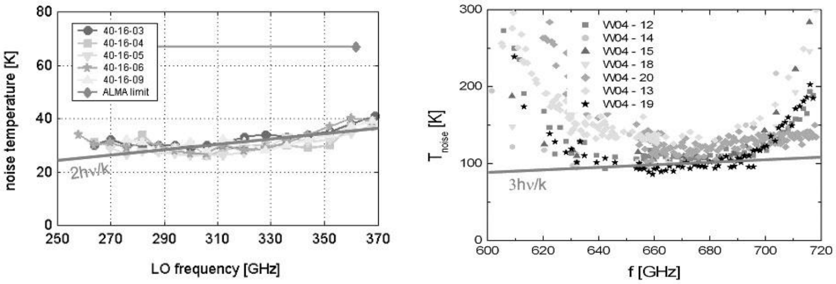

Fig. 10. Two examples of DSB mixers with a noise temperature of a few "photons" ($h\nu/k$). Left: DSB building block for ALMA Band 7 2SB mixer (IRAM). Right: DSB mixer for ALMA Band 9 (SRON, graph courtesy of A.Baryshev).

6.2 SSB mixers

A mixer where the mixing element is coupled by a probe to the input waveguide can be designed to operate SSB by adjusting a moving backshort in the waveguide such that a virtual short circuit is created at the probe position, for the image frequency. As a rule of thumb, the receiver noise as measured by the Y-factor method will be approximately twice that of a similar mixer operating in DSB mode. However, the figure of merit for spectroscopic obervations, i.e. the SSB receiver noise will have equal values for these two mixers, so, in a laboratory environment, it seems that nothing is gained. However, in actual astronomical use, the SSB mixer rejects the atmosphere's noise in the image sideband, resulting in a better system noise. All mixers currently operating on IRAM telescopes realize (to some degree) the SSB operation with a moving backshort. An example of the performance achieved is shown on the left panel of Figure 11.

6.3 2SB mixers

By suitably associating a quadrature RF hybrid, a pair of DSB mixers, and a quadrature IF hybrid, one can realize a sideband-separating mixer (2SB), in which the mixing products from the two RF sidebands (LSB and USB), despite being in the same IF frequency band, appear on physically distinct ports. The principle of operation is briefly explained in Figure 12.

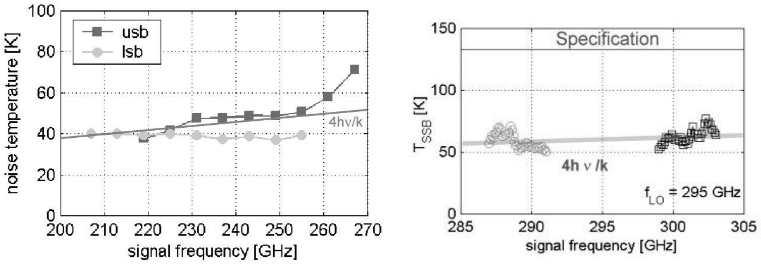

Fig. 11. Left: performance of a 230-GHz band SSB mixer developed for the new Plateau de Bure interferometer receivers. Right: performance of a 2SB mixer built for ALMA BAnd 7. In both cases, an SSB noise at the level of $4h\nu/k$ is achieved.

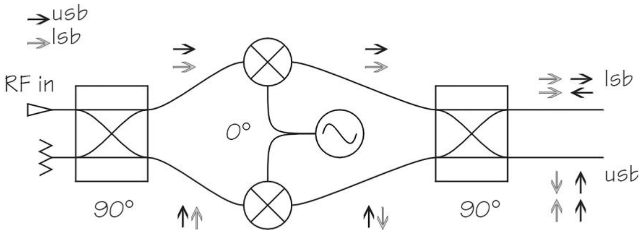

Fig. 12. Principle of operation of a sideband-separating (2SB) mixer. Depending on the path followed and on the sideband (L/U), the 90 deg phase shifts arising from the RF and IF quadrature couplers either add or cancel, resulting in physical separation of the sidebands. The key to this "trick" is that a phase shift applied on the RF signal appears with the opposite sign on the IF when the signal is converted from the (L)ower sideband.

7 Receiver systems

IRAM builds receiving systems for its own telescopes at Plateau de Bure and Pico Veleta, and also modular front-end cartridges for Band 7 of the ALMA project. This involves many design issues besides superconducting devices and mixers, that cannot be addressed here in a limited space.

The new Plateau de Bure receivers under construction feature four frequency bands (83-115 GHz, 130-170 GHz, 203-265 GHz, and 277-371 GHz), each dual-polarization, each having an IF band 4-8 GHz. The ALMA Band 7 cartridge covers 275-373 GHz, dual-polarization and sideband separating, for a total of four IF channels 4-8 GHz. These systems are depicted in Figure 13.

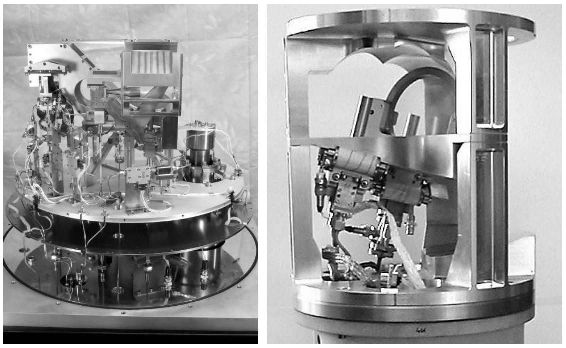

Fig. 13. Left: A view of the open cryostat for one of the new Plateau de Bure receivers. Right: the 4K optics and mixers assembly of the ALMA Band 7 cartridge.

8 Instrumentation

Proper instrumentation is absolutely necessary to verify the performance, not only of complete systems, but also of components and subsystems at various stages of integration. IRAM has developed in-house two major pieces of laboratory equipment: a millimetre-wave vector network analyzer, and a vector (amplitude and phase) beam scanner, each one covering all four bands of interest (3mm, 2mm, 1.3,mm, and 0.9mm) for ongoing receiver construction.

9 Perspectives

As the noise performance of mm/submm receivers approaches fundamental limits, and might be even closer to practical limits, the scientific throughput of the instruments can still be enhanced in other dimensions. Multibeam receivers will increase the mapping speed in proportion to the number of pixels, at least for extended objects. Pushing the IF bandwidth of SIS receivers to maybe 10% of the RF frequency will benefit multi-line observations (including spectroscopic surveys), and also continuum observations with interferometers. The same can be stated concerning the implementation of HEMT frontends with a noise performance equal to what is achieved with SIS mixers.

In order to achieve not only a quantitative progress, but a qualitative jump, in the number of pixels of multibeam receivers, it will be necessary do develop more highly integrated structures suitable for mass fabrication.

One may speculate further whether a totally new detector principle is behind the corner.

Finally, one can express the hope that the development of commercial applications, whose economical weight massively surpasses that of astronomy, will leave the millimetre spectrum pollution-free.

It is a pleasure to thank Pierre Encrenaz and Emile Blum for introducing me to the domain of receiver development thirty years ago.

References

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Bernard Lazareff