Hunt for Molecules
F. Combes, F. Casoli, E. Falgarone, L. Pagani (eds)

HETERODYNE DETECTION IN MM & SUB-MM WAVES DEVELOPED AT PARIS OBSERVATORY

Beaudin, G., Encrenaz, P. and the Microwave Team[1]

Abstract. Millimeter and submillimeter-wave observations provide important informations for the studies of atmospheric chemistry and of astrochemistry (molecular clouds, stars formation, galactic study, comets and cosmology). But, these observations depend strongly on instrumentation techniques and on the site quality. New techniques or higher detector performances result in unprecedented observations and sometimes, the observational needs drive developments of new detector technologies, for example, superconducting junctions (SIS mixers) because of its high sensitivity in heterodyne detection in the millimeter and submillimeter wave range (100 GHz - 700 GHz), HEB (Hot Electron Bolometer) mixers which are being developed by several groups for application in THz observations. For the submillimetre wavelengths heterodyne receivers, the local oscillator (LO) is still a critical element. So far, solid state sources are often not powerful enough for most of the applications at millimetre or sub-millimetre wavelengths: large efforts using new planar components and integrated circuits on membrane substrat or new technics (photomixing, QCL) are now in progress in few groups. The new large projects as SOFIA, Herschel, ALMA and the post-Herschel missions for astronomy , the other projects for aeronomy , meteorology (Megha-tropiques-Saphir) and for the planetary science (ROSETTA, Mars exploration,...), will benefit from the new developments to hunt more molecules.

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, F-75014, Paris

1 Introduction

In France, millimeter radioastronomy started in the early seventies at the Paris - Meudon Observatory pushed by the interest of E.J. Blum and Pierre Encrenaz for the "Large Millimeter waves Interferometer" project. This study was started with the technology available at the time (cooled Schottky mixers, frequency- and phase-locked klystrons) permitting spectroscopic studies of giant molecular clouds in our Galaxy and of planetary atmospheres in the rotational transitions of simple molecules. Small radiotelescopes were developed in the early eighties by the French millimetre groups at Meudon, ENS, Bordeaux and Grenoble observatories: POM 1 in the 3mm and POM2 in the 1.3 mm ranges, covering two of the main atmospheric windows. IRAM was created and later on, antennas were installed in dry places (mountain tops at Pico-Veleta, Spain and Plateau de Bure, France). The new generation of international radiotelescopes will be installed in high altitude sites (ALMA) or will fly in space (Herschel HIFI), needing high resolutions, wide band and very low noise receivers using new technological developments.

2 The early pionnering days

As often in science, the radioastronomers pioneering the field had access to a relatively insensitive equipment, but discovered rapidly the new domains accessible to these wavelengths: carbon monoxyde CO (1-0), HCN in giant molecular clouds, CO in planetary atmospheres, CO, H_2O in comets outgassing when approaching the sun: this is the cold part of the Universe. The isotopic abundances could be measured in great detail using the H,C,N,O,S, Si atoms in the molecules excited by collision with H_2 molecules, and the relation between gas phase reactions and surface grain reactions became apparent. The discovery of stellar winds ejected with great velocities in molecular form came as a surprise, along with the disk-like shape of the surroundings of young stars.

- The advent of interferometers

Single dish antennas can only be build up to a certain size: mechanical, thermal and cost constraints are such that 30 m in the millimeter range, 10 to 15m in the submillimeter domain cannot be easily surpassed.

The properties of the atmosphere were poorly known, and phase fluctuation of large amplitude expected. The two sources of phase fluctuation (inhomogeneous water vapour content over the line of sight of the antenna and temperature fluctuations) were so badly understood that two prototype interferometers (Bordeaux, 2×2.5-m antennas with a 64 m baseline, Hat Creeks, 3×6 m antennas with an 85 m baseline) were build in relatively poor quality sites. Fringes could be obtained over those baselines, and a correlation with the amount of precipitable water vapour content found. It was therefore necessary to go to far better sites in altitude: Plateau de Bure, Owens Valley, Mauna Kea in Hawai permit baselines of hundreds of meters, bringing the spatial resolution to a fraction of an arc second (").

3 Heterodyne receiver technologies

3.1 Schottky diode mixers

In order to reduce the assembly cost and to improve the reliability and reproductibility of heterodyne receivers for space missions throughout the millimeter and submillimeter wavelength bands, two major changes have been incorporated into current radiometer designs. First, the whisker-contact honeycomb diode (used in POM1, POM2, KAO, ... and MLS, SWAS, ODIN,...) have been replaced by planar diodes, mainly for subharmonically pumped mixers (SHP), (Fig. 1, Thomas et al. 2005), for applications up to (or above) 600 GHz (MHS, MIRO/ROSETTA, EOS-MLS, ...); second, the diodes are integrated with the mixer circuitry (MMIC-like). An added benefit to this latter approach is the all planar photolithographic structure scalable to frequencies well beyond 1 THz. A major goal is to advance the state-of-the-art in millimeter-wave with the planar-diode technology associated with micro-machined mixer structures (RAL, U.Va) to the point at which it can be used readily at frequencies as high as 2.5 THz (EOS-MLS, ...). The Schottky diodes can be cooled to 70 or 20-30 K, increasing the performances, but work even at room temperature which is an advantage for several space applications (planetary and Earth observations).

3.2 Superconducting tunnel junctions and HEB mixers

In order to obtain ever higher sensitivities, shorter observation times and the use of smaller collecting surfaces, the submillimeter-wave astrophysics community has devoted much of their resources towards the development of heterodyne radiometer front-ends based on superconducting mixers. The

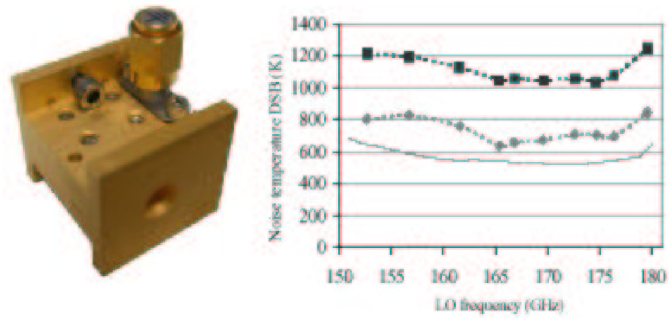

Fig. 1. Paris Observatory wide band planar Schottky diodes SHP mixer in the 300 - 360 GHz range: receiver and mixer noise temperature(measured/simulated) versus the LO frequency.

small area superconductor-insulator-superconductor (SIS) Nb tunnel junction offers the potential of near quantum limited sensitivity throughout the millimeter-wave bands up to 700 GHz and possibly at frequencies as high as 1.3 THz with NbTiN. The THz domain is now achievable by using Hot Electron Bolometers heterodyne (HEB) mixers. The SIS and HEB mixers must be physically cooled to temperatures well below the superconduction transition temperature, (4 K or less). However, the requirement for a liquid helium ambient environment poses a significant limitation for remote, long lifetime space operation.

SIS mixers: Heterodyne front-end receiver at 420-440 GHz using SIS Nb junction with a classical tuning circuit have also been developed at Paris Observatory for PRONAOS and for the PIROG 8 balloon borne experiment (SSC-ESTEC-CNES), (Febvre et al. 1997).

Herschel -HIFI channel 1 in the 480-640 GHz band (Fig. 2, Salez et al. 2000), is developed at Paris Observatory, with the IRAM collaboration. Today, an important part of the research in this field aims at developing receivers combining ultra wide bandwidths (around 30% relative or more) with ultra low-noise capabilities (a few times the quantum limit), with no mechanical tuning for space applications (noise and band performances are the state of the art).

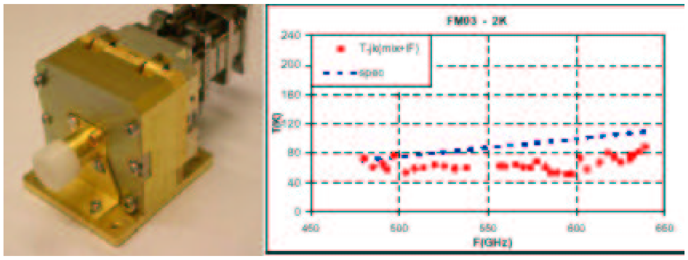

Fig. 2. Left 480 -640 GHz tunerless flight model SIS mixer for Herschel channel 1 (3cm / 3cm) **Right** state of the art noise performances (red points) to compare to the project specifications (doted grey line)

ALMA channel 8: from this study using multi-junctions design, an SIS wide-band tunerless breadboard mixer has been developed for the ALMA project in the 385 - 500 GHz range, having state of the art performances (Boussaha et al. 2005).

Integrated SIS front-end: The purpose of superconducting integrated receiver is to integrate FFO (Flux-Flow Oscillator) in SIS mixer chip and make use of FFO as LO (Local Oscillator) for the mixer (Fig. 3).

HEB mixers: Superconducting Hot Electron Bolometers become very sensitive mixing elements for THz observations (Tong et al. 2000) and they also show good performances even below the gap frequency of Nb. Superconducting HEB may become competitive with SIS junction at millimeter and submillimeter wavelengths since it provides several advantages compared to SIS mixers: smaller LO power, no need of external magnetic field to suppress Josephson current noise, relative ease to match into the antenna impedance due to its nearly resistive impedance, and no upper frequency limit. But there are some problems to be resolved for radioastronomical applications like relatively narrow IF bandwidth (few GHz).

A NbN HEB wave guide mixer at 1.5 THz has been developed at Paris Observatory (Fig. 4); a HEB camera on SiO_2 membrane in open structure mixer in the 2.5 and 4.5 THz ranges, is under development at Paris Observatory with the cooperation of the University of Chalmers, Moscow and the LAAS in Toulouse (Fig. 4, Baubert et al. 2005a,b).

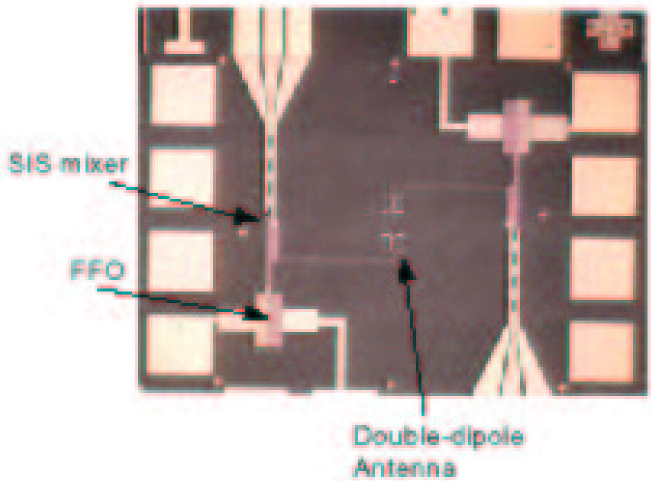

Fig. 3. An SIS mixer chip (4mm / 4mm) including FFO, double-dipole antenna and diverse super-conducting RF passive circuits have also been designed and the realization is now in progress at Paris Observatory (Chung & Salez 1999, Salez et al. 2000, Chung & Salez 2000). FFO is one kind of superconducting oscillator. There are many research works about Josephson junction oscillator to search for alternatives to the usual LOs, like solid state, because of the difficulty to make LOs at millimeter and submillimeter wavelengths.

3.3 Local oscillator generation technologies

For millimetre and sub-millimetre wavelength heterodyne receivers, the local oscillator (LO) is still a critical element. So far, solid state fundamental sources are not often powerful enough for most of the applications at sub-millimetre wavelengths -THz range. The LO power needed for Schottky diodes or SIS junctions, is currently obtained by Gunn oscillators cascaded with frequency multipliers using whiskered varactor diodes (Zimmermann 1997). HBV components have been developed at IEMN -Lille and tested with success at the Paris Observatory up to 300 GHz (Mélique et al. 1999). New planar schottky varactor devices have been developed in the THz range

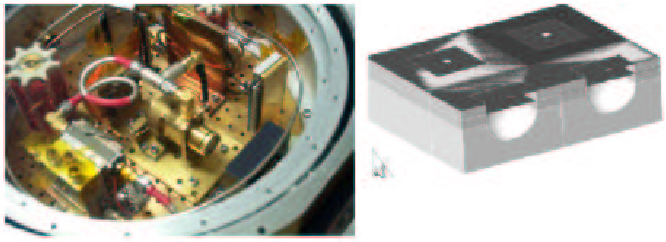

Fig. 4. Left 1.5 THz HEB test bench at 4K **Right** 2.5 THz, 4 pixels HEB camera designed on membrane substrat

(Erickson 1998) and designed on membrane substrate at frequencies up to 2 THz for the Herschel Space project channels 6ab (Fig. 5, Maestrini et al. 2004, 2005). This work was made with a strong collaboration in between JPL and the Paris Observatory & UPMC.

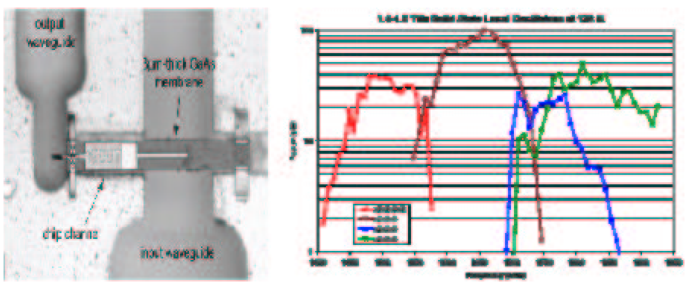

Fig. 5. Left 1.9 THz tripler on membrane circuit designed by Paris Observatory-UPMC with JPL planar technology. **Right** measured tripler output power in the THz range for Herschel channel 6 LO chains.

4 Applications of these techniques to astronomy and remote sensing

The sensitivity of uncooled schottky mixers can be expressed in hundreds of $h\nu/k$, in the tens of $h\nu/k$ if cooled to 20 K while super conducting mixers at 2-4 K are almost quantum limited. The technology involved for such a complex system make it difficult to install aboard a satellite. It took almost 10 years to convince the aeronomy and planetary communities that these heterodyne techniques had unique applications (limb sounding for T(z), P(z) in the earth atmosphere, outgassing of molecules in comets, zonal and latitudinal winds in planetary atmospheres), and that the space qualification of such system could be done without endangering the other instruments on board the spacecraft .

4.1 Airborne and balloon-borne observatories

Atmospheric attenuation is important in the submillimeter range. As a first step, before installing it on a satellite, suborbital platform have been used on stratospheric airplanes (KAO) and balloons (PIROG, Fig. 6).

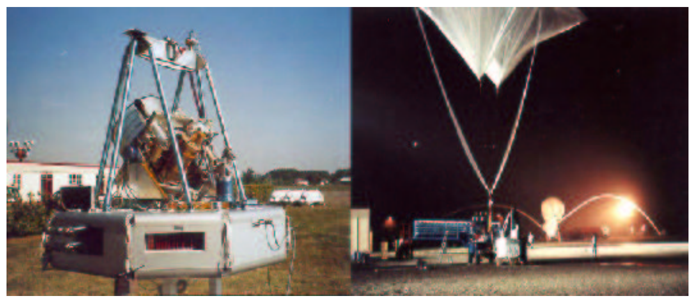

Fig. 6. Left PIROG 8: gondola with the 420 GHz Nb SIS receiver developed at Paris Observatory. **Right** Stratospheric balloon borne observatory (SSC - CNES -ESTEC - Paris Observatory): experiment launched from Aire sur l'Adour, september 1997 . It was the 1st superconducting (SIS) receiver succesfully flying with a balloon.

4.2 Spacecraft observatories

The first satellites carrying submillimeter wave heterodyne instruments (SWAS, ODIN) have been opening the path to the Herschel Observatory satellite (4th cornestone of ESA, to be launched in 2007, Fig. 7).

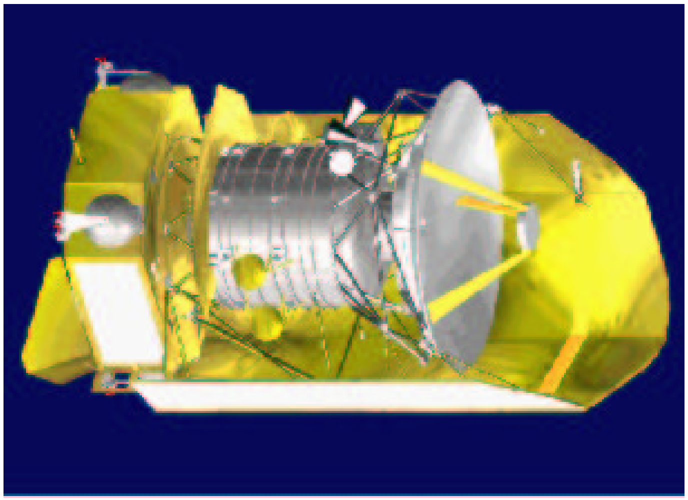

Fig. 7. Herschel submm observatory: 3.6 m cassegrain telescope, two direct detection instruments in the far infra-red, heterodyne high spectral rsolution instrument (HIFI) in the 500-1900 GHz range; Cooled in a liquid He4 and He3 cryostat. HIFI heterodyne receivers bands: 1 SIS 480-640 GHz, 2 SIS 650-800 GHz, 3 SIS 800-960 GHz, 4 SIS 960-1120 GHz, 5 SIS 1120-1250 GHz, 6a-6b HEB 1.4-1.9 THz.

4.3 Probes for comet and planet observations

MIRO is an heterodyne instrument in the 190 and 550 GHz ranges on board of ROSETTA (Fig. 8), on which the Paris Observatory was involved strongly with JPL and the MPAE. Rosetta is a cometary probe launched in March 04 on the Ariane 5 rocket; MIRO will observe for the first time how the molecules CO, H_2O and CH_3OH are ejected and accelerated into the coma of the comet.

After several asteroid flybys and three planetary gravity assists (Mars & Earth), the spacecraft will approach the comet Gerasimenko in 2014 after a 10 years cruise phase. The spacecraft will accompany the comet on its way towards the Sun. The instrumentation will remotely measure gas volatile composition, coma temperature, gas velocity, and subsurface temperatures of the cometary nucleus to a depth of 2 cm or more. The long-range scientific goals are to understand the origin and evolution of comets and asteroids and the conditions that led to the formation of the Solar System.

Fig. 8. Left MIRO instrument at mm -submm wavelengths under tests at JPL **Right** MIRO telescope at the top of the Rosetta cometary probe

5 Conclusion

Paris Observatory is involved in the main heterodyne projects in the millimetre and submillimeter domains. For most observations in the Earth, planet and comet atmospheres, sensitivity is not nearly as critical an issue as it is for interstellar astrophysics. A large number of key molecular transitions can be observed with the sensitivity available from current room-temperature of passively cooled semiconductor planar schottky diode radiometers. Earth remote sensing applications have been on pushing to higher frequencies, increasing the instantaneous bandwidth, improving device reliability and reducing radiometer complexity and cost.

For astrophysics, very sensitive and very high spectral resolution heterodyne spectroscopy (R $> 10^6$) are required. SIS mixers up to 1.3 THz, HEB mixers above 1 THz have made significant progress in performances and reliability over the last years. There is no doubt that heterodyne techniques are among the most promising in the next decade to hunt new molecules for astrophysics, Earth and planetary atmospheric chemistry research.

Acknowledgments: Thanks for the French and European administrations supporting these activities; thanks very much for all of our colleagues in France, in Europe, in US and in Russia for their efficient and friendly collaborations.

References

Baubert J., Khosropanah P., Desmaris V. et al, 2005a, 16th Int.Symp.on Space THz Technology, Göteborg, Sweden, May 2-4 2005, in press

Baubert J., Salez M., Merkel H. et al, 2005b, IEEE Trans.Appl.Superconductivity, Vol.15, 2, pp.507-510

Boussaha F., Salez M., Delorme Y. et al, 2005 16th Int.Symp.on Space THz Technology, Gteborg, Sweden, May 2-4 2005

Chung M-H. and Salez M., 1999, 4th European Conference on Applied Superconductivity, EUCAS-1999, Sept. 14-17, 1999, Barcelone, Spain , pp.651-654

Chung M-H. and Salez M., 2000, 11th Int. Symp. on Space Terahertz Technology, Ann Aarbor, MI, May 1-3, 2000

Erickson, N., 1998, in 2nd ESA Workshop on Millimeter Waves Technologies and Applications: Antennas, Circuits and Systems, MilliLab, Espoo, Finlande, 27-29 mai 1998, pp. 423-428

Febvre P., George S., Deschamps A., Lecomte B., Peron I., Olofsson G., 1997 URSI North American Radio Sci.Meet., July 13-18th 1997, Montreal, Canada

Maestrini A., Ward J.S., Gill J.J., et al, 2004, IEEE Microwave & Wireless Comp.Lett.; Vol.14, 6, pp.253-255

Maestrini A., Ward J.S., Gill J.J., et al, 2005, IEEE Trans.Microwave Theory Tech., Vol.53, 9, Pp 2835-2843

Mélique X., Maestrini A., Mounaix P. et al, 1999 IEEE MTT symposium, Anaheim, California, USA, June 12-19 1999, pp.123-126

Salez M., Delorme Y., Dauplay F., Marchand B., and Lecomte B., 2000, WOLTE 4 : 4th Europ. Workshop on Low Temp. Electron., ESTEC, Noordwijk, The Netherlands, 21-23 juin 2000, pp 239-244

Salez M., Delorme Y., Chung M-H., and Dauplay F., 2000, 11th Int. Symp. on Space Terahertz Technology, Ann Aarbor, MI, May 1-3, 2000

Thomas B., Maestrini A., Beaudin G., 2005, IEEE Microwave & Wireless Comp.Lett., Vol.15, 12, 865-867

Tong C.-Y.E., Kawamura J., Hunter T., et al., 2000, 11th Int. Symp. on Space Terahertz Technology, Ann Aarbor, MI, May 1-3, 2000

Zimmermann R., 1997, 20th ESTEC Workshop on Millimeter Wave Antenna Technology and Antenna Measurement, ESA WPP-128, pp. 297-299, 1997

Gérard Beaudin