INTEGRATED SUPERCONDUCTING HETERODYNE RECEIVERS AT SUBMILLIMETER WAVELENGTHS FOR DETAILED MOLECULAR INVESTIGATION OF EXTRA-SOLAR PLANETARY ATMOSPHERES

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INTRODUCTION

Since the first detection of extra-solar planets, a growing interest for novel techniques allowing direct detection, imaging an spectral analysis of these « Earths » has emerged.

It has been speculated that the simultaneous presence of H_2O, O_3, CH_4, and N_2O in a planetary atmosphere, would indicate the likely presence of life on this planet [1-4]. Therefore, detection of these molecules in their near-IR absorption bands is essential, and the main goal of TPF/Darwin, with a spectral resolution R=3-300.

These and *other* molecules can also be detected at **mm** and **submm wavelengths**, using **heterodyne** techniques characterized by a **very high spectral resolution** (R>>1000).
Detecting these molecules in this frequency range will allow to eradicate ambiguities (for instance, a Candidate ozone feature at 10 µm contaminated or induced by a strong exozodi dust silicate band).
It will also provide, due to the very high spectral resolution, extremely valuable information for the study of these planets : temperature / density vertical profiles, and the detection of trace molecular species through weak narrow lines, unaccessible via IR techniques.

Several molecules of interest for the study of extra-solar disks, planetary atmospheres, and astrobiology can be studied with the ground-based interferometer ALMA. Some other molecules, however, e.g. *water*, can only be detected from space. High-*J* molecular transitions and several hydride fundamental transitions fall only within the THz range, requiring space-based observations.

To match the angular resolution of TPF/Darwin, a space-based interferometer in the submm/THz range will require very large baselines, typically 10-100 km.

However, the difficulty in stabilizing such long baselines is about the same as for a 1 km baselineTPF/Darwin, since spacecraft positioning tolerance scales as the wavelength. Technological challenges for large aperture dishes (possibly deployable in space) are also easier at these wavelengths than in the visible/IR range.

Concepts of space-based free-flying submm interferometers are currently under study (e.g. ESPRIT), mostly for astrophysical objectives other than extra-solar planetary science. Nevertheless, it seems worthwile to investigate the possible use of such or similar interferometers for high resolution, deep-integration spectral surveys of extra-solar planet, once they have been detected by TPF/Darwin.

For the frontend of these future receivers, **we propose a newly developed submm-wave heterodyne technology** well adapted to these space projects : ***integrated superconducting receivers*** [11,12]. Due to their ultimate compactness, they reduce by two orders of magnitude the constraints on volume, masse, power and cryogenics.

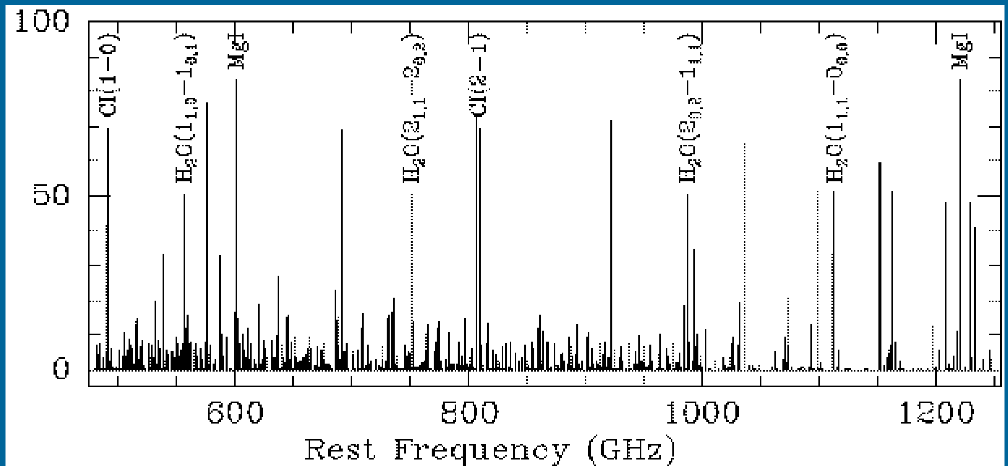
MOLECULES OF INTEREST FOR EXOBIOLOGY

- H_2O, CH_4, N_2O, O_2, O_3, OH, HCN, HCl, ClO, HS, HF, SO, SO_2...
- molecules expected in a primitive Earth atmospheric composition [4] : CO, CO_2, N_2, H_2O.
- molecules present in volcanic gases : SO_2, H_2S, SO, OCS, HCl, HF, NH_3.

Volcanism is an important driver of prebiotic chemistry on early Earth-like planets.

(Explosive volcanism generates intense spark discharges which lead, in the presence of reduced gases, to more complex organic molecules including amino acids [5].)

- amino acids precursors, formed by irradiation by high energy cosmic rays [6]:
- HCN, simplest precursor of amino acids [7]
  (found in Titan [8], Neptune, and Jupiter after Shoemaker-Levy 9 collision [9])
- HCOH
- Cyanopolynes : HC_3N, HC_5N [8]
- N-organics such as CH_3N_3, CH_2N_2, HOCN
- hydrocarbons : C_2H_6, C_2H_4, C_2H_2, C_3H_8, CH_3C_2H, C_4H_2.
- High polyynes, e.g. C_6H_2 and C_8H_2
- many other...tbd…we'll be in 2010+ !



Example of molecules accessible to the Herschel HIFI intrument from 480 GHz to 1250 GHz, in the Orion molecular cloud (simulation) (courtesy P. Schilke, hifiscience)

INTEREST OF SUBMM HETERODYNE DETECTION

• Submillimeter-wave heterodyne detection,

achieves high spectral resolution (R = 10^5–10^8)
(flexible, R set by spectrometer bandwidth, e.g. digital correlator),

allows the detection of weak, narrow lines (emission & absorption)
(minor compounds, e.g. CH_4, greenhouse gases,...),

provides information on key molecular chemistry in high tropospheric altitudes
(high energy deposition by cosmic protons, photochemistry) [6],

resolves spectral shape : allows to derive the vertical temperature profile
(e.g. solar system planets) [6],

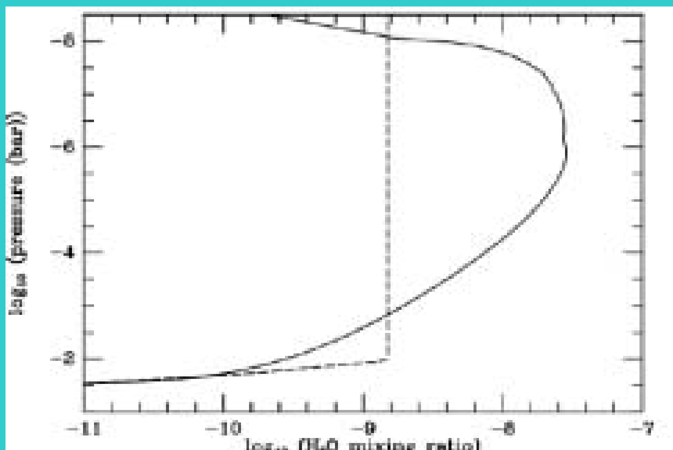
numerous transitions, and isotopes, can be observed,

alleviates ambiguities by confirming observations in the NIR, MIR,

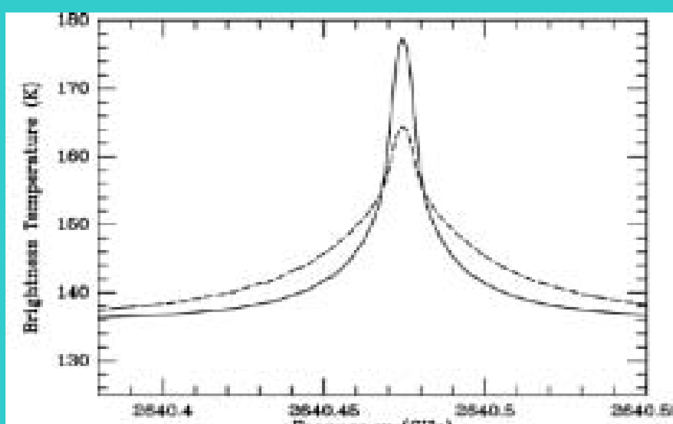
star-planet continnum brigthness contrast smaller / orders of magnitude.

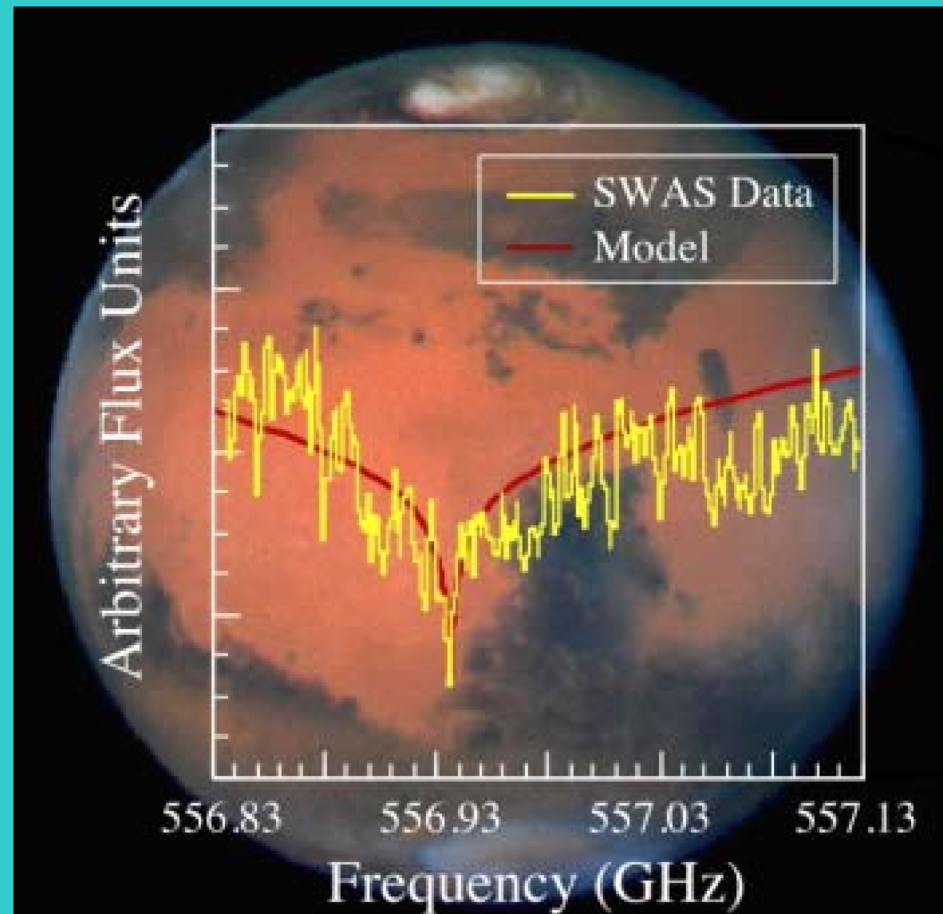
INTEREST OF SUBMM HETERODYNE DETECTION

• **The vertical profile of the mixing ratio of molecules in planetary atmospheres can be derived from the high spectral resolution of lineshapes.**



(Feuchtgruber et al. 1999, ESA SP-427)





Left : Simulation of the H2O lineshape for two vertical mixing profiles ;
Right : High spectral resolution detection of H2O in Mars by SWAS (www.sron.rug/hifiscience).

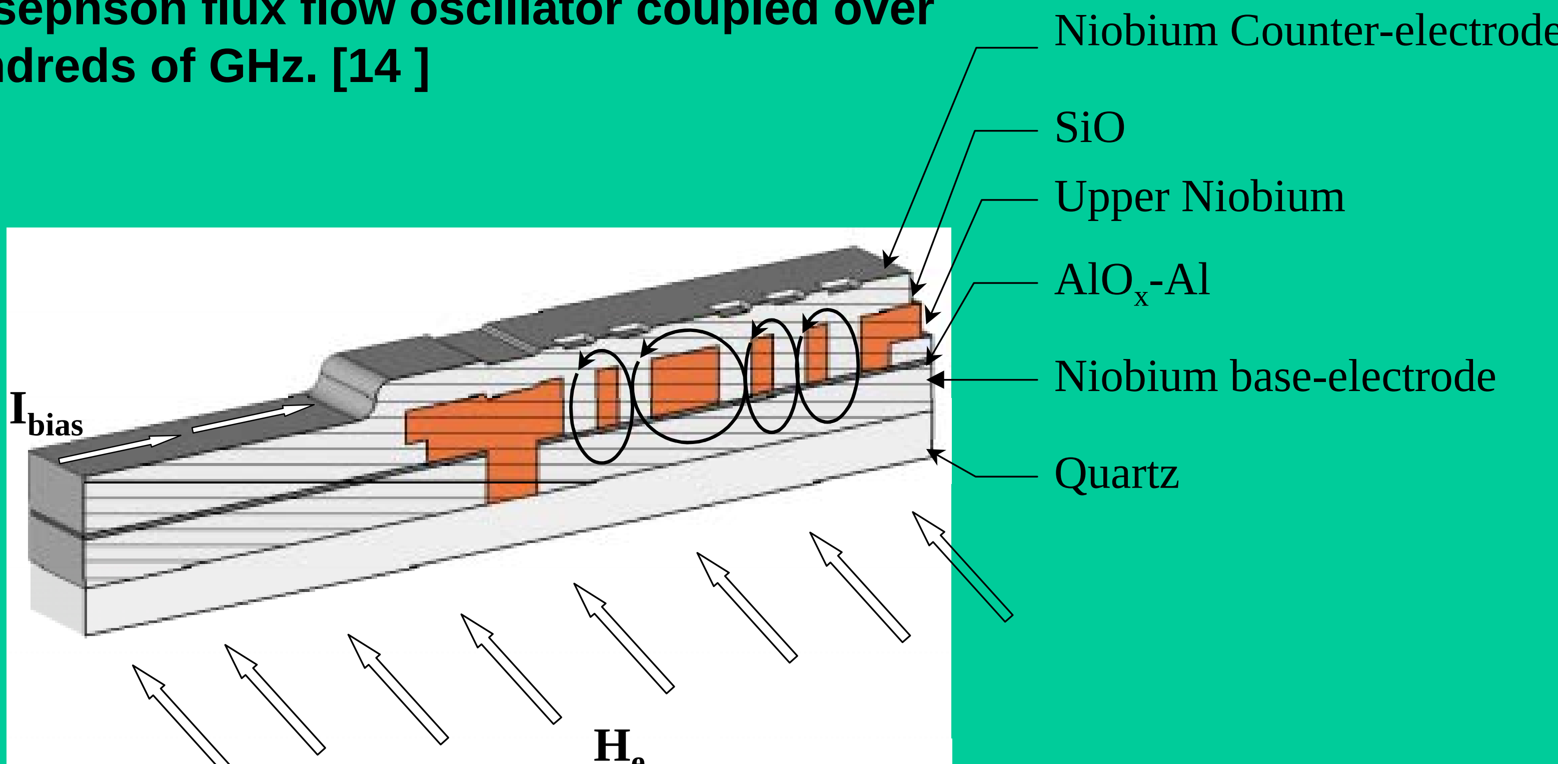
Parallel superconducting junction arrays with *non-uniform* spacings

N junctions embedded in a superconductive niobium stripline, can be used in two ways :

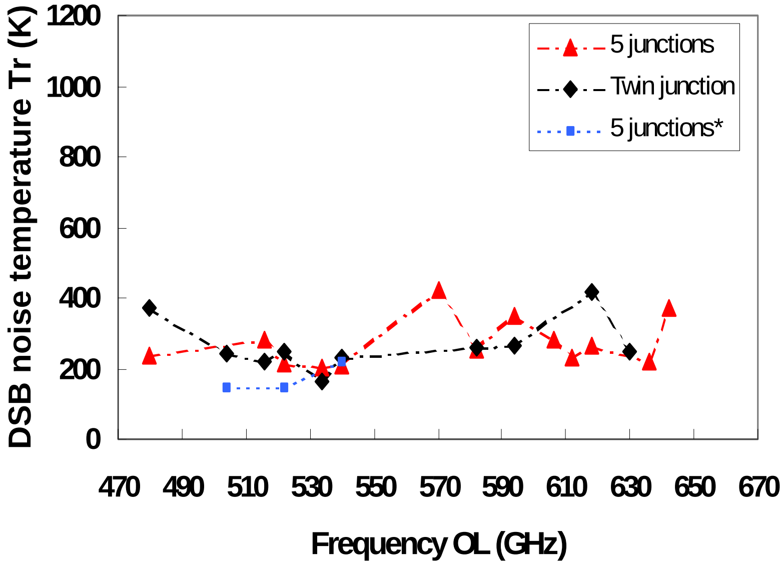
- ultra wide band SIS mixers (hundreds of GHz) [13]
- Josephson flux flow oscillator coupled over hundreds of GHz. [14]

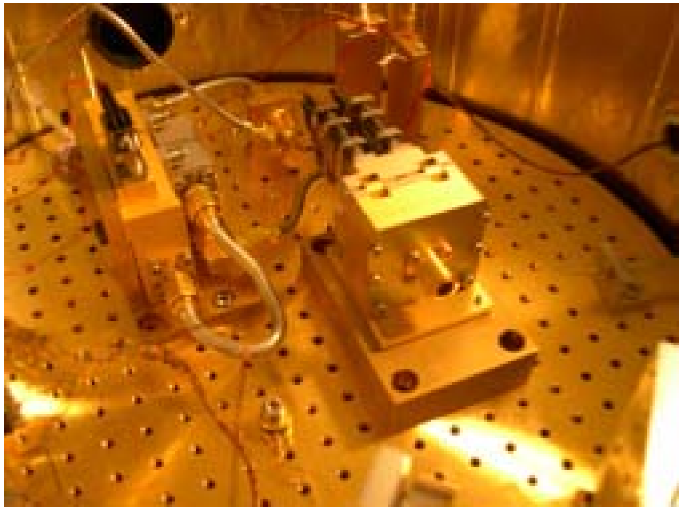
LERMA fabrication process :

Nb/AlOx/Nb junctions
Nb/SiO/Nb stripline
Junction area : 1 μm²
Number of junctions : 5
Current density : jc = 4 - 30 kA/cm²

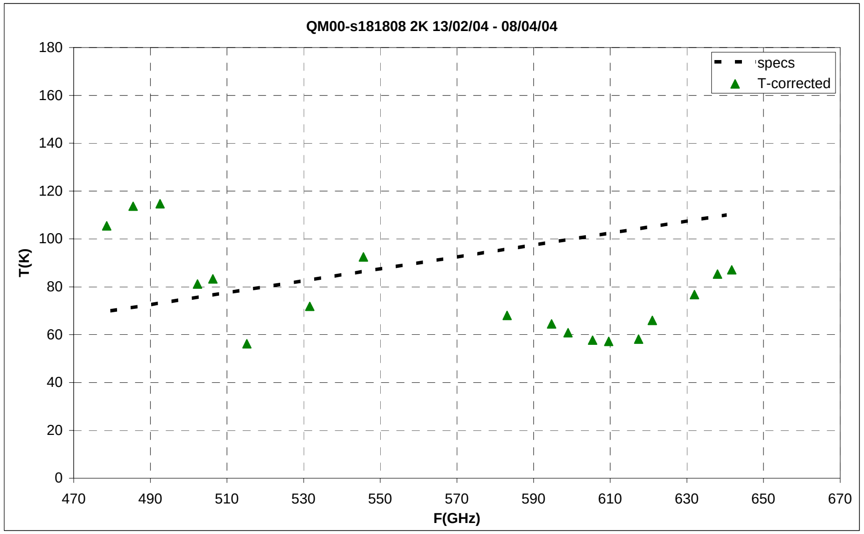


SIS junction arrays in the frequency range of Herschel HIFI Band 1
(F. Boussaha, Ph.D. thesis, 2003)



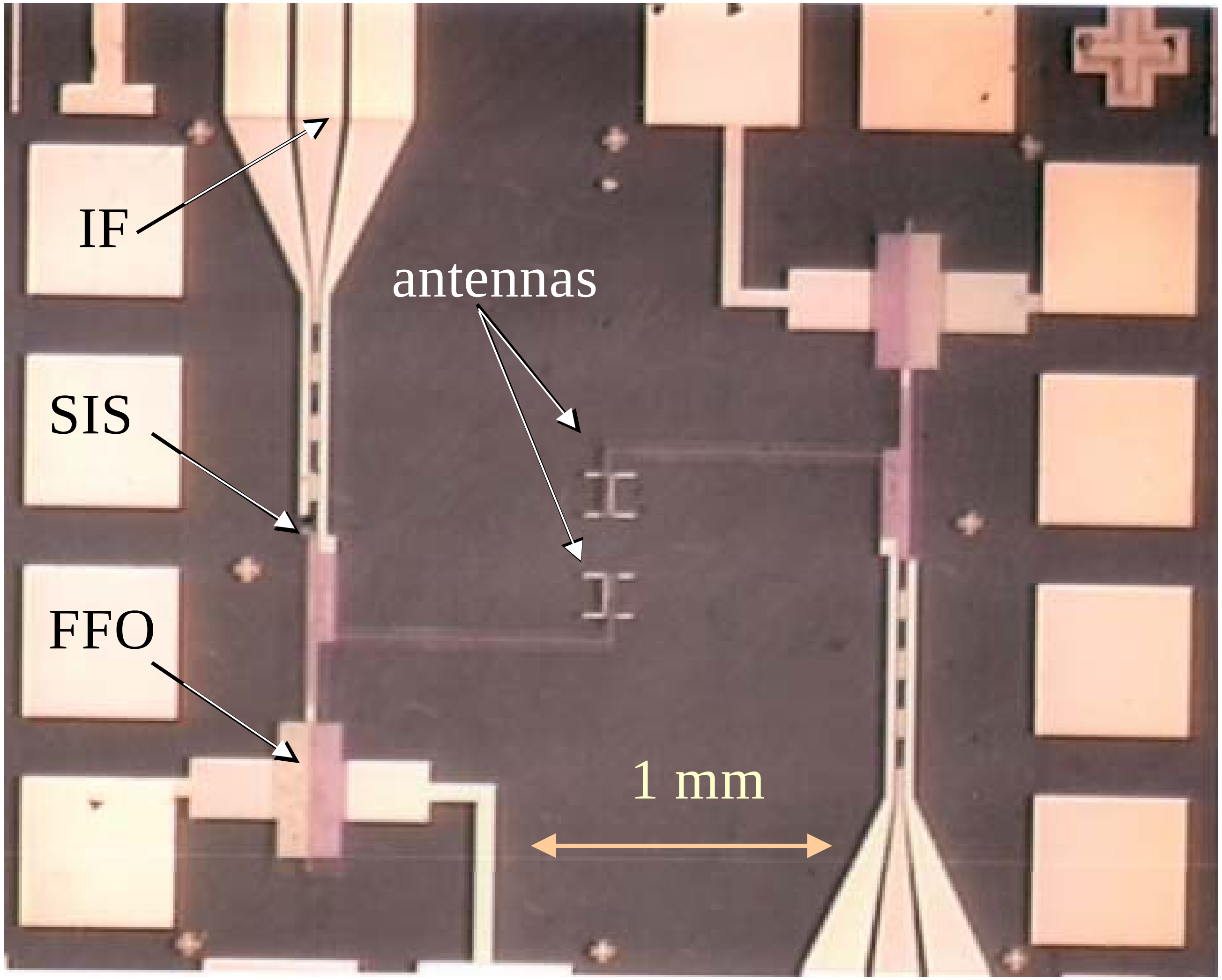


Flight model heterodyne mixer for Herschel HIFI band 1 : 480-640 GHz.



Upper left: Uncorrected noise temperature of a mixer with junction arrays.

Lower left: Noise temperature corrected for the optics loss, of a mixer with two junctions (dashed line is specs for 480-640 GHz.



Integrated receiver chip for 400-440 GHz (Ph.D. Thesis M.H.Chung, 2000) :
SIS = superconducting submm/THz mixer
FFO = superconducting submm/THz oscillator
IF = intermediate frequency (output) signal

Advantages of *integrated* receivers :

- Ultra small (few mm² chip) & ultra light [11, 12, 16]
- Small power consumption (mW level) & dissipation
- Very small thermal load / cryogenic power
- State of the art (quantum limited) sensitivity (Tm~50 K @ 500 GHz) [15]
- Wide RF bandwidths (several 100 GHz) [13]
- Phase lock possible (< 1 Hz) [11]
- Demonstrated technology [11, 14]
- Space qualification [15]

Integrated receivers are ideal for a multi-spacecraft interferometer, to minimize mass, power, and cryogenic requirements. Microsatellites could be used for the *N* telescopes/receivers. *N* optical beams modulated at the intermediate frequency (less than 10 GHz) can be used to convey the down-converted coherent signals to a minisatellite, housing the demultiplexer / combiner / digital correlator. Optical link technology for the multiplexing (and positioning) is available (SILEX).

CONCLUSION, PERSPECTIVES, FUTURE WORK

Space-based submm-wave interferometry **complementary to TPF/Darwin :**

- **to detect molecules in extra-solar atmospheres through their submm/TH rotational spectra, with high resolution.**
- **to detect weak, narrow lines from high altitudes in tropospheres**
- **to derive abundances, pressures and temperature profiles.**

Integrated heterodyne SIS-type receivers **are ideally suited to the realization of small, low power and reliable spacecraft for a free-flying submm interferometer.**

Multijunction technology **for integrated receivers covering hundreds of GHz in a single on-chip receiver.**

Demonstrate interferometric mode between two integrated receivers in the lab.

Investigate submm/THz space interferometric missions applied to extra-solar disk / planet studies.

Acknowledgements :

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