Terahertz Technology for ESPRIT – A Far-Infrared Space Interferometer

W. Wild, Th. de Graauw, A. Baryshev, J. Baselmans, J.R. Gao, F. Helmich, B.D. Jackson, V.P. Koshelets, P. Roelfsema, N.D. Whyborn, and P. Yagoubov

Abstract— In the Terahertz regime the angular (and sometimes spectral) resolution of observing facilities is still very restricted despite the fact that this frequency range has become of prime importance for modern astrophysics. ALMA (Atacama Large Millimeter Array) with its superb sensitivity and angular resolution will only cover frequencies up to about 1 THz, while the HIFI instrument for ESA'a Herschel Space Observatory will provide limited angular resolution (10 to 30 arcsec) up to 2 THz. Observations of regions with star and planet formation require extremely high angular resolution as well as frequency resolution in the full THz regime. In order to open these regions for high-resolution astrophysics we propose a heterodyne space interferometer mission, ESPRIT (Exploratory Submm Space Radio-Interferometric Telescope), for the Terahertz regime inaccessible from ground and outside the operating range of the James Webb Space Telescope (JWST). ESPRIT will employ heterodyne receivers from 0.5 to 6 THz.

The ESPRIT mission concept is described with an emphasis on Terahertz heterodyne receivers and cooling. The required technology development of mixers, local oscillators and integrated systems will be outlined.

***Index Terms*—Radio astronomy, Interferometry, Space technology, Submillimeter wave receivers.**

I. Introduction

THE study of star and planet formation is one of the prime topics in modern astrophysics. Important questions include the physical conditions for star-formation to occur, the evolution of circum-stellar disks, the decoupling of dusty proto-planetary regions from the gas, and the chemistry that leads to the pre-biotic conditions of early Earth-like planets. In addition, we also would like to know what role star-formation, and in particular starbursts, play in external galaxies and how this interacts with the general interstellar medium.

The phenomena connected to star and planet formation are best studied in the far-infrared/Terahertz regime (0.5 THz to several THz). This wavelength range holds the most important spectral signatures of the material (atoms, ions, molecules) as it is processed. The low extinction at these long wavelengths allows unique observations of details of the star formation process, in particular during its early phases, when these regions are completely obscured by the surrounding dust.

The Earth atmosphere severely limits the possibility to observe at THz frequencies from ground-based observatories. ALMA will cover the atmospheric windows at very high angular resolution up to about 1 THz which is the limit for observations even from high-altitude sites (with the exception of a few small atmospheric windows around 1.3 and 1.5 THz accessible only from the very best sites on Earth).

Astronomical observations above 1 THz need to be done from space. However, all past, current and planned missions have limited angular resolution. The relatively small ratios of aperture diameter to wavelength, like for example in ISO, Spitzer Space Telescope and Herschel, provide only angular resolutions of the order of 5 arcsec in the 100µm region. This does not match the 0.1 arcsec resolution which is required for these studies. In order to achieve the required angular resolution, to investigate for example the distribution of key molecules in a circum-stellar disk, application of interferometer techniques in space is the only way forward. At the same time, high spectral resolution is required to measure the chemical composition, the dynamics and other physical conditions. In particular, studies of water and other hydrides, together with the isotopic/deuterated versions, are of prime interest for the star formation process.

A mission concept that combines all these capabilities is uniquely suited to address these questions: a free-flying, 6 element, far-infrared imaging interferometer using heterodyne detection: ESPRIT – the Exploratory Submm sPace Radio-Interferometric Telescope. After presentation of the mission concept, scienc goals and configuration aspects, we will outline the THz technology needed for such an instrument and the required development.

II. ESPRIT Mission Concept

Table I gives the main characteristics of ESPRIT. The 6-element interferometer will be in a free-flying configuration with precise metrology to determine the exact position of each satellite. The array will fly in a constantly moving configuration filling the u-v plane (see below). In a preliminary trade-off between signal strength, primary beam size and practical considerations, it appears that a 3.5 to 4

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The authors are with SRON Netherlands Institute for Space Research, Groningen and Utrecht, the Netherlands. (Corresponding author: W. Wild, phone +31-50-363 4074, fax +31-50-363 4033, W.Wild@sron.rug.nl).

W. Wild, Th. de Graauw, A. Baryshev, F. Helmich, and P. Roelfsema are also with the Kapteyn Astronomical Institute, University of Groningen, the Netherlands.

Th. de Graauw is also with Leiden Observatory, the Netherlands.

V.P Koshelets is with the Institute of Radio Engineering and Electronics, Russian Academy of Science, Mokhovaya 11, 125009, Moscow, Russia, and part-time with SRON Netherlands Institute for Space Research, Groningen, the Netherlands.

meter diameter of the primary mirrors would satisfy the overall mission goals.

TABLE I
MAIN CHARACTERISTICS OF ESPRIT

Telescope sizes	~ 3.5 meter ; off-axis
Number of elements	N =6 (15 baselines)
Frequencies	Spots in the range 0.5 – 6 THz (600 µm – 50 µm)
Projected baselines	~ 7- 200-1000 meter
Front Ends (0.5 – 1.5 THz)	SIS mixers, multiplier LO
Front Ends (1.5 – 6 THz)	HEB mixers, QCL as LO
System temperature	1000 K
IF bandwidth	> 4 GHz (goal 8 GHz)
F.O.V. / primary beam size	~ 6” at 100 µm
Spatial Resolution	0.02” at 100 µm
Pointing Requirements	accuracy: 0.2” measurement: 0.1”
Image Dynamic range	> 100
Spectral Dynamic range	> 1000
Correlator	4 sections of 1 GHz, each 128 channels
Configuration	Free-flying

From ground-based interferometer experience it is evident that in order to get an acceptable imaging capability one needs a minimum of 6 antenna elements. Each antenna will be equipped with a number of heterodyne receivers covering selected ranges between 0.5 and 6 THz (600µm to 50µm). The exact choice of frequencies will depend on the scientific priorities, and the number of receivers will depend on technical limitations (mass, size, cooling power etc.).

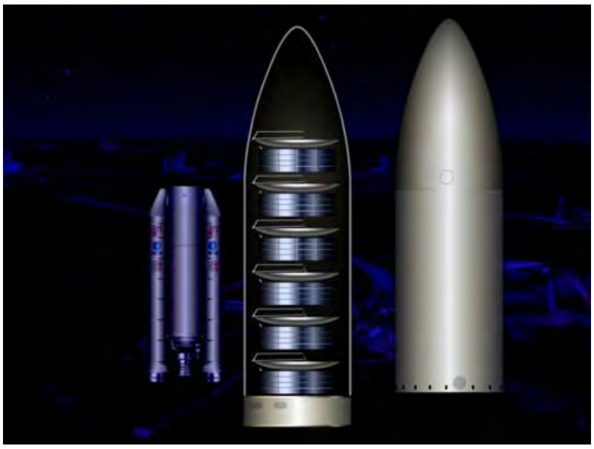


Fig. 1. The six elements of ESPRIT in an Ariane 5 faring. The telescope design has unfoldable subreflectors allowing dense packing and thus aiming for a single launch of the whole interferometer (artist conception).

A distributed correlator seems to be the most practical solution for this mission. Pointing requirements are proportional to the diffraction diameter and are roughly a factor of 10 more stringent than is being provided today in ESA’s space missions. An important point is the aim to have all six satellites put into space with a single launch. A telescope design with subreflectors that unfold after leaving the launch vehicle in space would make this feasible (Fig. 1). ESPRIT is preferably situated in the Sun-Earth Lagrange point L2 about 1.5 million km from Earth because of thermal stability.

III. SCIENCE GOALS

The study of the formation and evolution of stars and solar systems is one of the main themes of modern astrophysics. In particular the indirect detection of more than 100 Jupiter-like extra-solar planets has enforced these studies and the development of missions. Although Spitzer and JWST will address these subjects in detail, there is a clear missing link in these studies. This concerns mainly the epoch before the objects are becoming strong IR emitters. And Herschel, although the largest space telescope planned for the FIR, will have a too modest angular resolution (ranging from 6 to 40 arcsec) for unraveling the star/planet formation process.

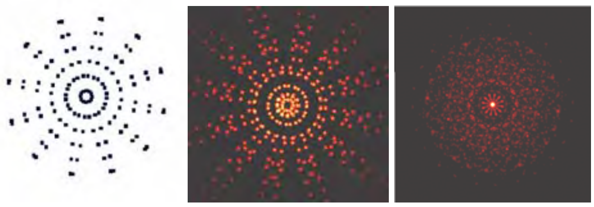
The most critical and unique spectral lines for studying this process are from H_2O, H_3O^+, OI, C^+, N^+, CH, OH, CH^+, and their isotopes including their deuterations. ESPRIT will trace the movements and spatial distribution of the ionic and molecular material and its specific components, from cold dark pre-stellar clouds through the final stages of star formation process. In particular measuring the distribution of water in the pre-stellar clouds and proto-planetary nebulae and disks is crucial, not only for its unique diagnostics but also for assessing the cloud’s thermal conditions during its evolution.

Similar observations of circum-stellar material of evolved stars are most relevant for understanding the evolution of extra-solar planetary systems. In this sense the detection by SWAS of circum-stellar water vapor towards the evolved carbon-rich star IRC10216 is very interesting. The most plausible explanation for the presence of the amount of detected water vapor is evaporation of ice on Kuiper Belt type objects by the central star. ESPRIT will have sufficient sensitivity to detect in detail many of these objects.

The facility will be the high-frequency/short-wavelength complement of the ground-based ALMA, without any atmospheric attenuation and disturbance in phase and transmission. It will be a follow-up mission of ISO-LWS, SWAS, ODIN, SIRTF, ASTRO-F, Herschel-PACS and -HIFI and of MIRI on JWST. Nevertheless, with the rapid development and increase of observing capabilities of ground-based and space/airborne facilities it will be important to update the scientific case as new discoveries are made.

IV. INTERFEROMETER CONFIGURATIONS

The six satellites of ESPRIT will be positioned in space in a three dimensional configuration. By combining the down converted and digitised signals of the elements in a correlator a set of complex visibilities are obtained corresponding to different locations in the sky fourier transform plane. Thus by fourier transforming these visibilities an image of the sky is obtained. Different configurations are being studied. A simple radial expansion and contraction of the array does not yield a high-quality beam, whereas a combined movement of radial expansion together with overall rotation of the array results in a more uniform u-v coverage and thus a "better" synthesized beam (Fig. 2). Clearly more detailed studies will have to determine the best strategy for moving the individual satellites.



a) b) c)

Fig. 2. One example of a possible ESPRIT array configuration which rotates while it expands and contracts. a) Motion of ESPRIT elements, b) Resulting u-v coverage, c) Synthesized beam.

It is anticipated that ESPRIT will make use of small ion thrusters like FEEPs (Field-Emission Electric Propulsion) . Due to weight and power constraints it will not be possible to move the satellites very quickly. Therefore the thrust and duration of each thrust period determines the velocity each telescope will get and thus limits the number of instantaneous configurations, within one observing run for a particular source. Likely it will typically take several days before the array has expanded from its smallest configuration to its full size of around 1 kilometre.

V. Front End Technology for ESPRIT

A. *Heterodyne Receivers*

The focal plane instrumentation of ESPRIT will consist of cryogenic heterodyne receivers. Two types of mixer technology will be used: from 0.5 to about 1.3 or 1.5 THz SIS mixers offer best sensitivity, and above 1.5 THz up to 6 THz HEB mixers are the best choice. Both types of mixer have been space qualified (up to 1.9 THz) for Herschel-HIFI and will be flown in 2007 (see next section).

Fig. 3 shows a block diagram for two channels (one SIS with integrated LO, and one HEB). ESPRIT will cover as many spots in the frequency range from 0.5 to 6 THz as possible within the technical limitations (such as volume, mass, cooling capacity etc.). In addition, a low frequency channel (80…200 GHz) will be included for phase calibration. Since the astronomically observable velocity width scales inversely with the observing frequency for a given IF bandwidth, a large IF bandwidth of the receiver is important at THz frequencies. For example, a 4 GHz IF bandwidth corresponds to only 200 km/sec at 6 THz, and an 8 GHz IF bandwidth still provides only 400 km/sec velocity coverage.

The performance of a heterodyne front-end is largely determined by three components in the system: the local oscillator, the mixer, and the IF amplifier chain:

- LO: The LO must provide sufficient power to drive the mixer (typically 10's of µW), must be spectrally pure, and must be stable. The tuning range of the LO is also critical to the tuning range of the receiver.

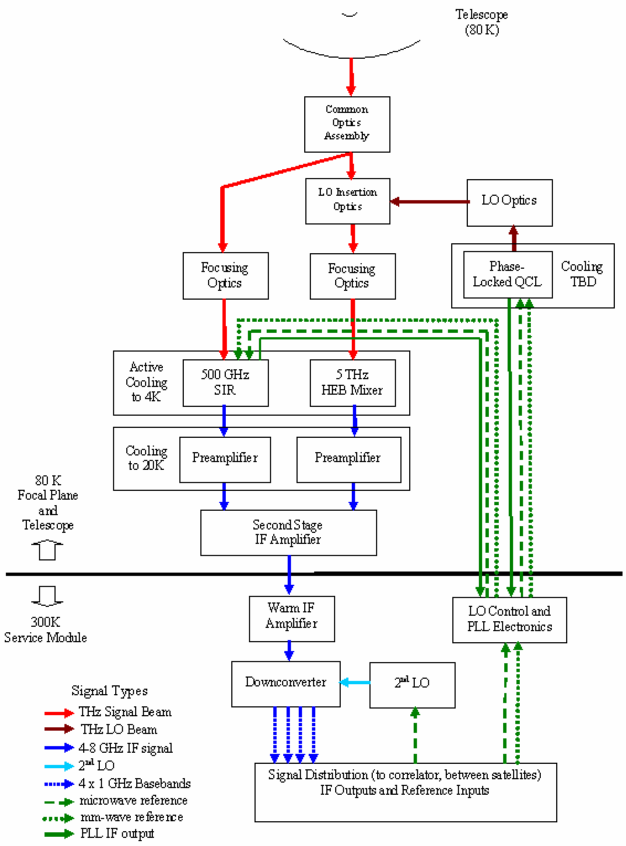


Fig. 3. Functional block diagram for an ESPRIT front-end (here for two channels) and the satellite IF systems.

- Mixer: The noise and gain of the mixer dominate the sensitivity of a high-frequency heterodyne receiver (especially for a space-based instrument that is not affected by an atmosphere or cryostat windows). The mixer may also limit one or both of the RF tuning range and IF bandwidth of the receiver.
- Cryogenic IF amplifier: The noise contribution of the IF amplifier chain (especially the "pre-amp" which immediately follows the mixer) is an important part of the overall system noise budget, while its bandwidth may limit the IF bandwidth of the receiver.

The state-of-the-art of these components and the required development / improvements for ESPRIT will be discussed in the following sections.

TABLE II
Space Qualified Heterodyne Technology for HIFI-Herschel

	Band 1 to 5	Band 6
Mixer type	SIS	HEB
Frequency	0.48-1.25 THz	1.4 – 1.9 THz
IF	4 – 8 GHz	2.4 – 4.8 GHz
Local oscillator	Multiplier chain	Multiplier chain
Sensitivity	3 - 5 hν/k	20 hν/k
Status	Space qualified	Space qualified

B. *Mixers and local oscillators up to 2 THz*

SIS and HEB mixers as well as multiplier chain local oscillators have been developed and space qualified for Herschel-HIFI covering the range up to 2 THz, with a 4 and

2.4 GHz IF bandwidth, respectively. Table II and Fig. 4 give an overview. During the last few years the multiplier chain LO development for HIFI has progressed significantly. For details on the current status of high-frequency multiplier chain LOs see [4]-[6].

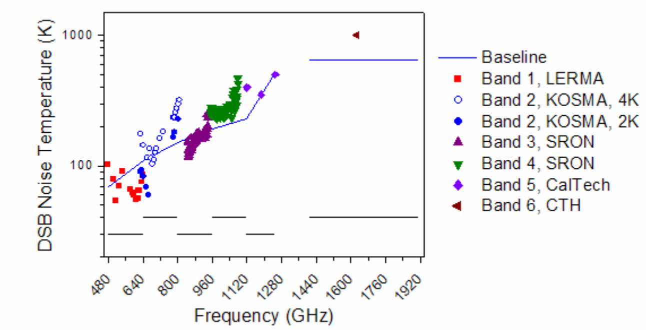


Fig. 4. DSB noise temperatures of the HIFI mixers (Bands 1-5: SIS; Band 6: HEB), Sep 2004.

For ESPRIT some development in the areas of noise temperature and IF bandwidth would be required. The sensitivity of the ESPRIT interferometer depends to a large extent on the front end noise with the mixer being the most important element. Mixer noise temperatures have improved significantly over the past years, in particular for SIS mixers, and it is desirable that continued development further decreases the mixer noise. Concerning HEB mixers, improvement of the mixer noise is required for ESPRIT. Present state-of-the-art noise temperatures are around 8-10 times the quantum limit (Fig. 5).

For ESPRIT an IF bandwidth of up to 8 GHz or even more is desirable. Extending the IF bandwidth of the SIS mixers is possible, 8 GHz has been achieved up to 720 GHz [1], [2]. However, reaching 8 GHz IF bandwidth for the HEBs needs more development work. For both types of mixers a development to integrate mixers and pre-amp could simplify the instrument. Another development, the use of superconducting integrated receivers (SIR) with the (flux flow) local oscillator located on the same chip as the mixer, as is developed by Koshelets et al. [3], could lead to more compact receivers.

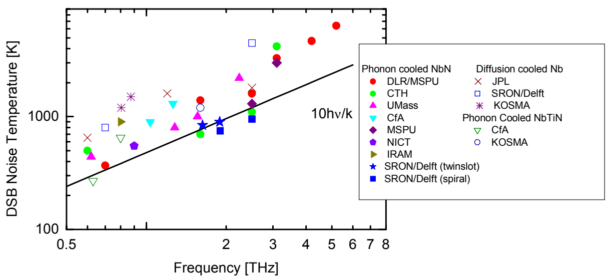


Fig. 5. State-of-the-art DSB noise temperatures of HEB mixers from 0.6 to 5.3 THz. Best results correspond to about 10 hν/k (compilation by Gao et al. and Huebers).

At present a SIR channel at 650 GHz is developed for the balloon-based atmospheric mission TELIS (Terahertz and submm limb sounder, see Yagoubov et al. [7] and reference therein). Fig. 6 shows the chip containing all major elements of a heterodyne receiver. Based on the results of this development, the SIR could become an interesting option for some of the ESPRIT frequency channels with the corresponding advantages in terms of mass, size, and lower system complexity.

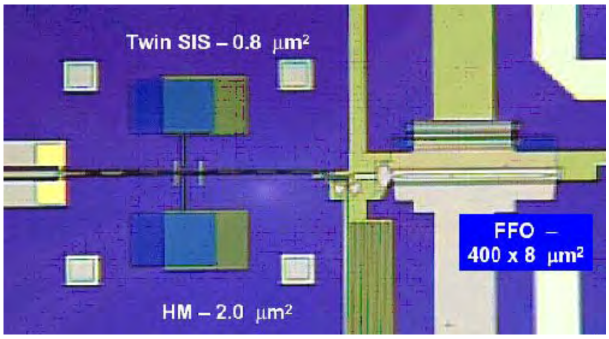


Fig. 6. Microscope photograph of a central part of the SIR chip (field of view is about 1.5mm by 1.0mm). All main elements of the Integrated Receiver (double-dipole twin SIS mixer, Flux Flow Oscillator and Harmonic Mixer) are present.

C. Mixers and local oscillators above 2 THz

Above 2 THz a number of HEB systems have been demonstrated in the lab by various groups, but none has been used for astronomical observations due to a lack of suitable (space) platforms. All of these systems have been operated at specific frequencies with a small tuning range (due to the use of a laser LO) and fairly low IF bandwidth (typically 2-3 GHz, or less). The highest demonstrated frequency is 5.3 THz. Fig. 5 shows reported noise temperatures with best values around 8-10 hν/k. For ESPRIT, both a larger IF bandwidth and lower noise temperatures will be needed. An extension of the IF bandwidth (ideally 8 GHz) and improved sensitivity (to ~ 3 hν/k) will require development work. Note that the drop in demonstrated sensitivities at 3 THz is due to the bulk of developments to-date being aimed at receivers for 2.5 THz or less – it does not reflect a limitation of the HEBs themselves.

The Local Oscillator development for Herschel-HIFI has pushed the operation of multiplier chains driven by high-power millimeter-wave sources to 2 THz. With some effort this could probably be extended to 3 THz. Coming from the mid-IR side of the spectrum, the recent successful development of Quantum Cascade Lasers (QCL) has opened up the possibility for heterodyne receivers operating at 6 THz (=50μm). QCLs have been demonstrated in CW operation in the THz range from 2.1 to 4.7 THz with output powers of several hundred μW to tens of mW (an HEB mixer only requires ~0.5 to 1 μW of LO power). The tuning range is on the order of 10 GHz and thus quite limited. The line-width of a QCL is small - 30 kHz has been measured. These characteristics make QCLs interesting THz local oscillators, and first experiments using a QCL as LO in a heterodyne system have been performed recently. For a THz heterodyne receiver system issues like phase-locking, tuning range and stability need to be considered and investigated. Furthermore, since the QCL chips are very small (millimeter size) and fairly compact integrated systems could be developed possibly containing many QCL chips for one mixer, to overcome the tuning range limitation.

D. IF amplifiers

Existing cryogenic IF amplifiers provide bandwidths of up to 8 GHz (with discrete elements) or beyond (with MMIC-based designs) with very good noise temperatures (below 5 K). For HIFI, IF amplifiers in the 4-8 and 2.4-4.8 GHz ranges have been space qualified. For ESPRIT, existing designs may be either used directly or modified to accommodate a different IF range, depending on the exact IF range and bandwidth requirements. Integration of the first IF amplifier with the mixer might reduce system complexity.

E. Telescope, optics and front-end cooling

The cooling requirements for ESPRIT can be divided in several components like telescope cooling, detector cooling and everything in between. It is beyond the scope to provide a complete overview of the ESPRIT cooling and a careful system study is mandatory. However, the requirements of a number of key system components can be considered.

1) Telescope cooling requirements

While older FIR telescopes relied on liquid Helium for the cooling of the telescope to suppress the telescope's own background, newer ones rely on passive cooling, as is the case for the Herschel telescope. The advantage is clear: since the telescope dish doesn't have to fit in the helium cryostat it can be larger, such that the size of the telescope dish is now mainly determined by the mass of the dish itself and the space available in the launch vehicle. Cooling of the Herschel telescope (3.5m) is done passively by radiating heat away into cold deep space. Although it is not yet certain what the final temperature of the telescope will be, studies show that it will be close to 70-80K. Note that due to the heterodyne nature of HIFI, it is the least susceptible of the Herschel instruments to the telescope background radiation. This advantage is also available to ESPRIT, so an 80K dish is sufficient. Since it is assumed that the ESPRIT telescope will be similar in size to that of Herschel, very similar passive cooling is needed.

2) Front-end optics cooling requirements

The front end optics for ESPRIT are expected to be at similar temperatures as the telescope dish. Due to the heterodyne nature of ESPRIT, thermal background and stray-light problems are not expected, but standing waves may occur if parallel surfaces exist within the light paths. Detailed quasi-optical modeling would show whether and how standing waves could be avoided, even at temperatures of 70-80K. Note that for Herschel-HIFI the Focal Plane temperature of 15K is sufficient to keep the background low, and although some parallel surfaces do exist within HIFI, the standing wave amplitudes are within reasonable bounds.

3) Front-end electronics cooling requirements

The SIS and HEB mixers will need to be cooled to 4K or below (with dissipation powers of less than a mW each), while the IF pre-amplifiers will need to be cooled to at least 20K (dissipation ~ 8mW per pre-amp). The second-stage IF amplifiers may be heat-sunk to the passively cooled front-end optics, at about 70-80 K (dissipation ~ 10 mW per amplifier).

TABLE III
COOLING REQUIREMENTS FOR ESPRIT THZ RECEIVERS

Temperature level	**One receiver with 2 mixers and LO**	
Between 30 K and 120 K	LO (QCL)	2.5 W
70 K	2 Amplifiers	20 mW
25 K	2 Pre-amplifiers	16 mW
4.2 K	2 Mixers	0.5 mW
	Parasitics	1 mW

The local oscillators (multiplier chain and/or QCL) may require active cooling, with operating temperatures between 30 and 120K. The QCLs will have power dissipations on the order of 1 W.

An overview of the cooling requirements for THz receivers is given in Table III for observations at one frequency dual polarization (i.e. using two mixers per satellite). These estimates apply only to the active channels (the instrument will likely operate with 1 or 2 active channels and several inactive channels at any one time) and do not include the mechanical support structure of the cryostat. A more detailed thermal design is needed to evaluate the overall heat-loads in the cryostat, front-end, and cable harnesses.

In order to achieve a long life time of ESPRIT, the active cooling of the front-end electronics to 4 K will require the use of mechanical, sorption/Joule-Thompson or similar coolers. The thermal stability of this 4K temperature level may also form an important aspect of the cooler design.

While a study needs to be conducted to show the exact figures for passively cooling the telescope and the optical bench, the real technology step lies in space-qualifying coolers such as now developed e.g. at the University of Twente (Netherlands) and elsewhere. Since the cooling of the front-ends is critical, this should receive early attention, but it should also be noted that many missions require similar technology, and studies dedicated to the cooling of these missions will provide the necessary knowledge for ESPRIT.

The bias and control electronics for the front-end electronics can be located with the other warm electronics. If it is defined as part of the front-end, the 2nd LO (which down converts individual sub-bands of the 4-8 or 4-12 GHz IF band to a common lower-frequency base band that is then sampled in the correlator) can also be located with the other warm electronics.

VI. CONCLUSION: WHAT IS NEEDED FOR ESPRIT

Concerning THz receiver and cooling technology for ESPRIT, the following technology steps are needed:

- *SIS Mixers:* Further improvement of noise temperatures is desirable. An IF bandwidth of 8 GHz, now demonstrated for mixers up to 720 GHz, should also be possible beyond that frequency. The frequency limit for quantum-limited SIS receivers should be pushed up to 1.5 THz or even higher.

- *HEB mixers:* Noise temperatures should be optimized to comply with the science requirements (T<1000 – 1500K at 100 µm / 3 THz), preferably up to 6 THz. IF bandwidths should be increased to at least 4 GHz, with a goal of 8 GHz.
- *Multiplier chain LO:* The development should be pushed to 3 THz. A decrease in system complexity is desirable.
- *QCL LOs:* Demonstration as a heterodyne LO is needed, including investigations of phase-locking, tuning range, and stability. The possibility to improve tuning range by parallel combinations of QCLs should be investigated. Power and cooling requirements for optimized QCLs should be investigated.
- *IF amplifiers:* Existing designs can be used or modified for use.
- *Front-end cooling:* Space-qualified coolers with low mass and power consumption as well as high thermal stability are required. Needed temperature levels are 4 K, 25 K, 70 K, and a TBD level between 30 and 120 K for QCL cooling (depending on QCL properties).

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