

## ESPRIT – A Far-Infrared Space Interferometer

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### ABSTRACT

In the far-infrared (FIR) / THz regime the angular (and often 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's 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). This interferometer will use coherent detectors in the range 0.5 to 6 THz on six free-flying telescopes and a distributed correlator.

**Keywords:** Submillimeter wave receivers, Interferometry, Space mission, Space Instrumentation, Radio astronomy, FarInfrared, Submillimeter.

### 1. 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, current research concerns the question 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 100 $\mu$ m 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, are of prime interest for the star formation process.

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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. Here we will present the ESPRIT mission concept including science goals, configuration aspects, the needed receiver, local oscillator and correlator technology as well as cooling and system considerations.

## 2. MISSION CONCEPT

### 2.1 ESPRIT baseline design

Table 1 gives the main characteristics of ESPRIT. The 6-element interferometer with 15 baselines 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 meter diameter of the primary mirrors would satisfy the overall mission goals.

Table 1. The main characteristics of ESPRIT

<i>Item</i>	<i>Value (at 100 <math>\mu\text{m}</math> / 3 THz when no wavelength / frequency is specified)</i>	<i>Goal</i>	<i>Satisfies Science requirement</i>
# of telescopes	6 (15 baselines)	>6	Sensitivity
Telescope design	3.5m off-axis	4m off-axis	
Configuration	Free-flying 3-D		
Projected baselines	7 – 200 – 1000m		Spatial resolution
Frequencies	Several ranges between 0.5 and 6 THz		Spectral coverage
Spectral resolution	1 km/s	0.1 km/s	Spectral resolution
Field-of-view	6 arcseconds		
Angular resolution	<0.02 arcseconds		Spatial resolution
Pointing accuracy	0.3 arcseconds		
Image dynamic range	>100		Image quality
Spectral dynamic range	>1000		Image quality
T(sys)	<1000K		Sensitivity
Mixer technology	SIS/SIR up to ~1.5 THz HEB > 1.5 THz		Wavelength coverage
IF bandwidth	4 GHz	8 GHz	Velocity coverage
Local Oscillators	FFO for SIR channels Multiplier chain up to ~2-3 THz QCL > 2-3 THz		Wavelength coverage
Correlator	Distributed with base -bands		
Metrology	<1 micrometer (total in all directions)		
Cooling	Mixers < 4K, ambient telescope (70K)		Sensitivity

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 – possibly small arrays - covering selected ranges between 0.5 and 6 THz (600 $\mu\text{m}$  to 50 $\mu\text{m}$ ). The exact choice of frequencies will depend on the scientific priorities, and the number of receivers as well as pixels for the arrays will depend on technical limitations (mass, size, cooling power, correlator etc.).

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. ESPRIT is preferably situated in the Sun-Earth Lagrange point L2 about 1.5 million km from Earth because of thermal stability.

## 2.2 Interferometer considerations

The six satellites of ESPRIT will be positioned in space in a three dimensional configuration to avoid collision danger (Fig. 1). By combining the down converted and digitized 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

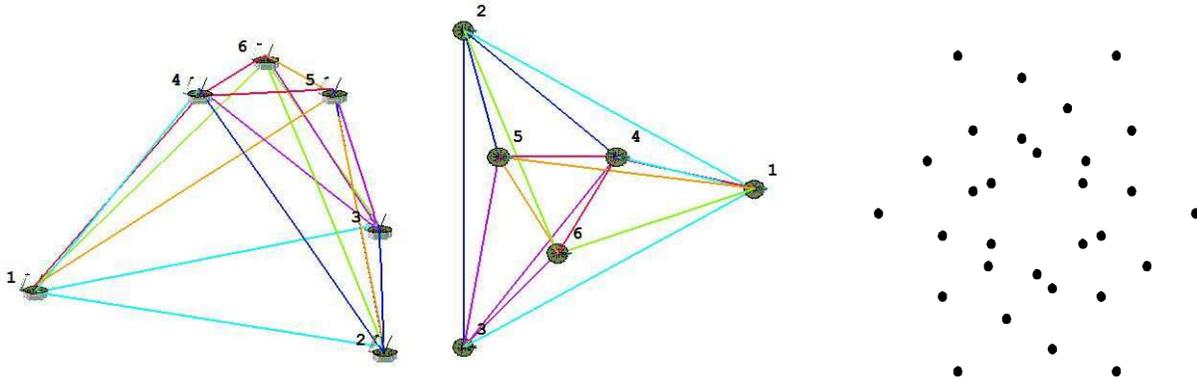


Figure 1. Three-dimensional instantaneous ESPRIT array configuration (left) and corresponding instantaneous coverage of the UV-plane (right).

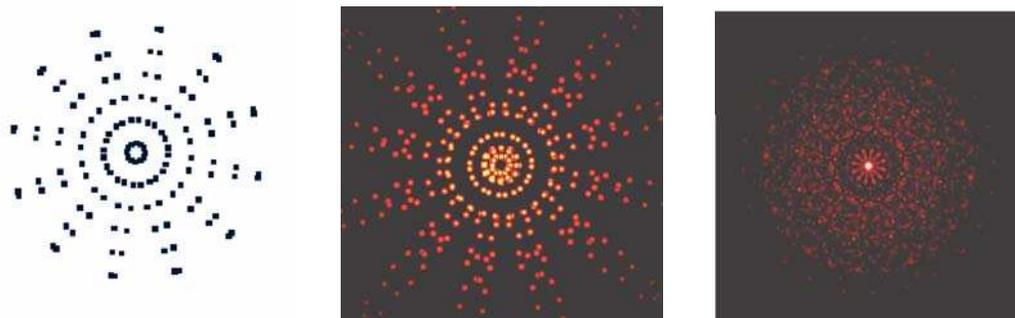


Figure 2. One example of a possible ESPRIT array configuration which rotates while it expands and contracts. Left: Motion of ESPRIT elements. Middle: Resulting u-v coverage. Right: Synthesized beam.

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 positioning and moving the individual satellites.

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 kilometer.

## 3. SCIENTIFIC AIMS

ESPRIT will be able to address one of the major themes of modern astrophysics: the formation and evolution of stars and planetary systems. 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  $\text{H}_2\text{O}$ ,  $\text{H}_3\text{O}^+$ ,  $\text{OI}$ ,  $\text{C}^+$ ,  $\text{N}^+$ ,  $\text{CH}$ ,  $\text{OH}$ ,  $\text{CH}^+$ , 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 [1]. 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.

#### 4. HETERODYNE DETECTION AND ITS IMPLICATIONS

ESPRIT will use the heterodyne detection technique in order to achieve a very high spectral resolution. In general, interferometers can either use coherent (heterodyne) or incoherent (direct) detection. Each type of detection scheme has its own advantages and disadvantages. Here we will point out a number of advantages for a heterodyne interferometer which will make a space mission of such an interferometer easier than a direct detection interferometer.

Coherent (heterodyne) detection advantages include: high spectral resolution is easily achieved, the output (IF) signal can be copied/split and amplified without adding noise, and spectral analysis can be done with digital correlators without noise penalty or need of optical delay lines. In the particular case of a FIR interferometer, the heterodyne technique offers the following advantages:

- **Ambient temperature (~90 K) telescopes and optics can be used.** This aspect leads to lower system complexity and increased mission life time (if the detector cooling can be guaranteed over long time periods). It probably also allows lower launch mass. All these points should lead to lower mission cost. For an interferometer with direct detection, cooled optics is mandatory in order to reduce the background. A heterodyne instrument can operate with uncooled optics.
- **Very high spectral resolution.** Many science goals in far-IR astronomy demand very high spectral resolution (see also Section 3) which in the case of heterodyne detection is not determined by the receiver but the backend. Typically resolutions of  $10^6 - 10^7$  are achieved.
- **Large coherence length.** Due to the smaller signal bandwidth, a heterodyne interferometer has a large coherence length (up to several tens of meters). This means two things: Simple (electronic) delay line compensation can be used (for example in the correlator), a very precise, real-time optical/RF path-length compensation is not required, and the metrology requirements are less demanding. Instead of precise, sub-micron *control* of the relative positions of the telescopes, only *knowledge* of the positions is required. In principle, the slow drifting of the telescopes (dynamic configuration) could even be used to fill the u-v plane during observations.
- **Number of telescopes.** For a heterodyne interferometer, the correlation is done after detection and amplification of the signal. This means that the signal can be "multiplied" in as many copies as needed. As a consequence, the number of antennas for a heterodyne space array is not limited by the signal itself but rather by other considerations such as launch mass. This is different for a direct detection interferometer. Since the signal has to be correlated before detection, only a limited number of antennas can be used because the available signal power needs to be divided for correlation.

This, together with other typical heterodyne characteristics, makes a heterodyne interferometer relatively simple as compared to a direct detection interferometer. Table 2 summarizes some of the differences between the two types of interferometers.

Table 2. Comparison of interferometers using direct or heterodyne detection.

<i>Item</i>	<i>Direct detection</i>	<i>Heterodyne detection</i>
Correlation	Pre-detection (requires precision optical delay line)	Post-detection (requires electronic delay)
Signal bandwidth	Large (few 10s to 100s of GHz)	Small (4-16 GHz)
Background reduction	Cooled telescopes and optics needed (~4 K)	Telescopes and optics at ambient temperature (~90 K)
Spectral resolution	Low (max. few $\times 10^3$ )	High ( $>10^6$ )
Velocity resolution	Low (~100 km/sec)	High (<1 km/sec)
Metrology	Accurate position control needed	Accurate position knowledge sufficient
Coherence length	Small ( $\ll 1$ micron)	Large ( $\gg 1$ mm to 150m)
Number of telescopes	Limited due to signal division for correlation	Unlimited due to post-detection correlation
Detectors	Need improved detectors with NEP $\sim 10^{-20}$ W/ $\sqrt{\text{Hz}}$	Present and novel detectors approaching quantum limit

## 5. FOCAL PLANE INSTRUMENTATION

### 5.1 Heterodyne Receivers

The focal plane instrumentation to be used for ESPRIT will consist of cryogenic heterodyne receivers of the type in use at many ground-based submm observatories and to be used for SOFIA and Herschel-HIFI [2]. Two types of mixer technology are envisaged: 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 2008 (see next section).

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) is considered 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 mixer, the local oscillator (LO), and the IF amplifier chain.

- 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.
- LO: The LO must provide sufficient power to drive the mixer (typically 10's of  $\mu\text{W}$ ), must be spectrally pure, and must be stable. The tuning range of the LO is also critical to the tuning range of the receiver.
- Cryogenic IF amplifier: The noise contribution of the IF amplifier chain (especially the first stage "pre-amp") can be an important part of the total system noise, while its bandwidth may limit the overall receiver IF bandwidth.

In the following sections we will discuss the present status of these components and the required development / improvements for ESPRIT.

Table 3. Space qualified heterodyne technology for HIFI-Herschel

	Bands 1 to 5	Bands 6L and 6H
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 hv/k	$\sim 10$ -15 hv/k
Status	Space qualified	Space qualified

## 5.2 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 3 and Figure 3 give an overview. During the last few years the multiplier chain LO development for HIFI has progressed significantly. For details on the status of high-frequency multiplier chain LOs see e.g. [3]-[5]. For ESPRIT some development in the areas of noise temperature and IF bandwidth would be required. The sensitivity of the 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.

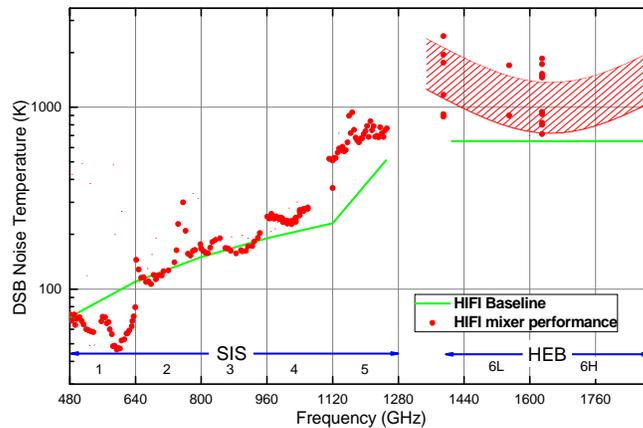


Figure 3. DSB noise temperatures of the HIFI mixers integrated into the Focal Plane Unit (Bands 1-5: SIS; Bands 6L and 6H: HEB), Apr 2006.

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 [6], [7]. 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. [8], could lead to more compact receivers. At present a SIR channel at 650 GHz is being integrated into the balloon-based atmospheric mission TELIS (Terahertz and submm limb sounder, see Yagoubov et al. [9] and reference therein) for which a first flight is scheduled for November 2007. Figure 4 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.

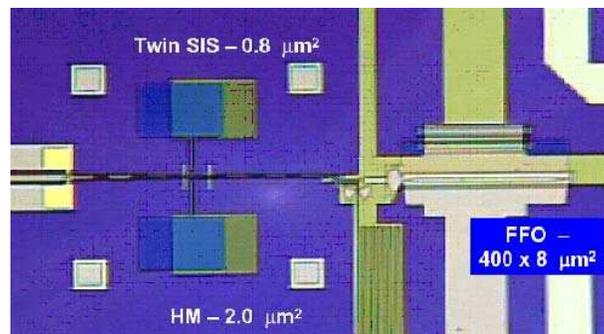


Figure 4. Microscope photograph of the central part of the SIR chip (field of view is about 1.5 mm by 1.0 mm). All main elements of the Integrated Receiver (double-dipole twin SIS mixer, Flux Flow Oscillator and Harmonic Mixer) are present.

### 5.3 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. Figure 5 shows reported noise temperatures with best values around 8-10  $h\nu/k$ . 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  $\sim 3$   $h\nu/k$ ) 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.

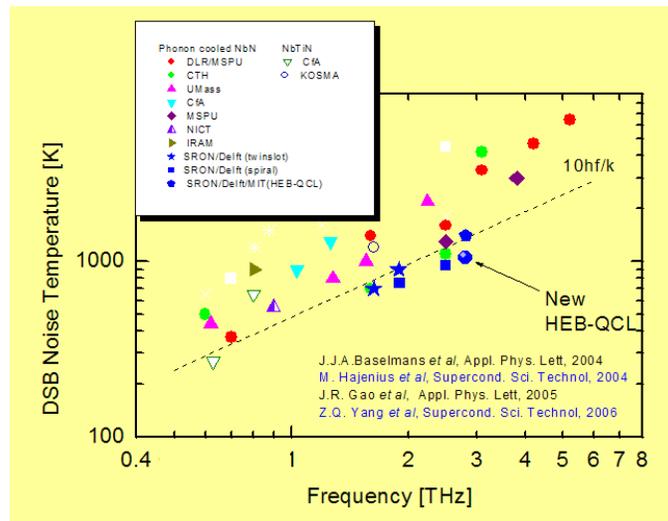


Figure 5. State-of-the-art DSB noise temperatures of HEB mixers from 0.6 to 5.3 THz. Best results correspond to about 8  $h\nu/k$  (compilation by Gao et al. and Huebers). Recently, a HEB-QCL system has reached 1050 K at 2.84 THz [11].

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 ( $\approx 50\mu\text{m}$ ). QCLs have been demonstrated in CW operation in the THz range from 2.1 to 4.7 THz with output powers of several hundred  $\mu\text{W}$  to tens of  $\text{mW}$  (an HEB mixer only requires  $\sim 0.5$  to  $1$   $\mu\text{W}$  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. Recently, a heterodyne receiver at 2.8 THz using an HEB mixer and QCL local oscillator has been demonstrated for the first time [10], and a receiver noise temperature of 1050K has been measured at 2.84 THz [11]. 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.

### 5.4 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.

## 6. CORRELATOR DESIGN

### 6.1 Distributed correlator

For ESPRIT a distributed correlator implementation is proposed. In this concept each satellite has a correlator on board resulting in several advantages. Redundancy prevents the occurrence of a single point of failure. Furthermore, distributing the correlator over all satellites has the advantage that all satellite can be identical (resulting in cost savings). There are a number of ways to distribute the correlator. For ESPRIT the baseline design splits the total band of 4 GHz up in 6 pieces with analog filters. To sample the bands of 667 MHz an A/D converter sample rate of about 1.4 GHz is required per baseband.

Since the satellites are moved to different positions in a 3D space, delay compensation is necessary. The delay compensation can be implemented by means of electrical delay lines. This requires the knowledge of satellite locations at micrometer precision. Furthermore, the rate of the delay compensation depends on the stability and velocity of the satellites.

The key items determining the dimensions of the ESPRIT correlator include: (1) Number of antennas, (2) Number of polarizations, (3) Total bandwidth, (4) Total number of spectral channels, and (5) Number of bits.

### 6.2 Data rates in the correlator

The correlator is distributed over all six satellites in the current baseline concept, meaning that each satellite is responsible to correlate 1/6 of the total bandwidth. Hence, each satellite transports 5/6 of the bandwidth to the other satellites and receives one baseband from all the other satellites. The total data rate, which is transmitted by each satellite, is 26.7Gbps (two polarizations assumed) and the total data rate received by each satellite is 26.7Gbps as well. The reason for doing the correlation in space is to save on the downlink budget. After correlation the data is reduced significantly, the factor depending on the integration time. We estimate that for the ESPRIT baseline configuration the total output data rate will be in the order of 1 Mb/s.

### 6.3 Current Technology

To give an idea of the size of the ESPRIT correlator, the ALMA correlator design (i.e. without the current enhancement) [12] and Omnisys correlator [13] are used for comparison (only the digital part is considered). The ALMA correlator is a ground based crosscorrelator while the correlator of Omnisys is an autocorrelator for space applications. An overview of all three correlators is given in Table 4. It can be seen that – concerning the number of correlations – the proposed ESPRIT correlator is about a factor 114 smaller than the ALMA correlator, if the same architecture is used. The ESPRIT correlator will be 32 times larger than the Omnisys correlator.

Table 4. Key numbers of the ESPRIT, ALMA and Omnisys correlators

	<b>ESPRIT</b>	<b>ALMA</b>	<b>Omnisys</b>	<b>ESPRIT/ALMA</b>	<b>ESPRIT/Omnisys</b>
Antennas	6	64	1		
Polarizations	2	2	1		
# of correlations	72	8192	1	0.01	72.0
Bandwidth (GHz)	4	8	4	0.50	1.0
# of lags	1024	512	4096	2.00	0.3
Number of bits	2	2	1.5	1.00	1.8
<b>Total scale factor</b>				<b>0.01</b>	<b>32.0</b>

Projecting the power of the ALMA and Omnisys correlator to the ESPRIT correlator results in a first order total power estimation of about 600 W, to be distributed over 6 ESPRIT elements. Furthermore, the Omnisys correlator weighs 600 grams [13]. Based on this, we estimate in the first order about 30 kg for the ESPRIT correlator (taking into account a more complex architecture). This mass is also distributed over 6 ESPRIT elements. Clearly, these estimates will have to be refined in a more detailed study, but they nevertheless indicate that the ESPRIT correlator would stay within a reasonable power and mass budget.

In principle the digital correlator design can be developed with current technology for ground based systems. However, the required operation power and mass should be minimized for this space application. The two steps to be taken are: development of a distributed correlator (communication and synchronization needs to be correctly dealt with), and mass and power optimization as well as space qualification of this distributed cross correlator.

## 7. 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.

### 7.1 Telescope cooling requirements

While older FIR space 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.

### 7.2 Front-end optics cooling requirements

The front end optics for ESPRIT is expected to be at a similar temperature 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.

### 7.3 Front-end electronics cooling requirements

The SIS and HEB mixers will need to be cooled to 4K or below (with dissipation powers of much less than a mW each), while the IF pre-amplifiers will need to be cooled to at least 20K (dissipation  $\sim$  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  $\sim$  10 mW per amplifier).

Table 5. Cooling Requirements for ESPRIT front-ends

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
20 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 the ESPRIT THz receivers is given in Table 5 for observations at one frequency with dual polarization (i.e. using two mixers per interferometer element). 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 space 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 2<sup>nd</sup> 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.

## **8. SYSTEM CONSIDERATIONS**

Heterodyne interferometers provide, due to the long coherence length, a large degree of freedom in positioning and moving the dishes in terms of the path difference. Thus, the proposed six-element free-flying interferometer can be configured in three dimensions, avoiding collision danger. However, to limit the complexity of the metrology for measuring the distance between elements, we consider having the elements in two planes with three mirrors in each plane as a viable baseline. An example of such a 3D configuration along with the instantaneous u-v coverage is shown in Figure 1. As pointed out before, our preference is for a distributed correlator in which each of the six elements houses its own correlator. Thus, the design for all six elements can be the same, which reduces costs, and has built-in redundancy. Furthermore, the power requirements are shared between the elements for the most notorious power-hungry element of the system.

The launch configuration for the elements is made small by folding the deployable boom secondary support structures into the cavities of the off-axis telescopes. Conceptual designs indicate that all six elements could be fitted into a cylinder 10–11 m high and four meter in diameter and could be launched on a single rocket.

### **8.1 The metrology subsystem**

The metrology subsystem will provide accurate information on the distances between satellites. In principle two distance measures per satellite are enough, but to obtain sufficient redundancy three metrology links will be required. An accuracy of approximately 1 to 5 micrometer in the distance determination is required. Positions should be recorded continuously, also during movements of the satellites. Most likely, the metrology subsystem will utilise an optical system based on laser beams. The information from the coarse positioning system (part of time and phase distribution subsystem) can be used for additional position clarification as well as for aiming the beams between the satellites. The metrology information is then used in the global central geometrical model (like in ALMA or SMA) to provide the fringe stopping phases. This accurate position information should be recorded with every data frame.

### **8.2 Navigation, pointing and propulsion**

The most stringent navigation requirements are for relative satellite movements to allow for fringe-stopping. Secondary are the requirements related to the low levels of thrust that are required for continuous on-the-fly operation as contrasted to the relatively large demand in satellite repositioning capabilities needed for the core operation of the interferometer, i.e. image quality. The high angular resolution places significant requirements on the pointing accuracy. However, these pointing requirements can be met using today's technology. One should note, that an inertial navigation system may be required which is likely accurate enough to reinforce the coarse GPS because of the stable space conditions.

### **8.3 Central control and earth communications**

Many of the satellite and observatory control functions are fulfilled by a main computer. Most of these functions are well understood as they apply to any satellite mission; however there are a few issues which deal specifically with the interferometer nature of ESPRIT. Firstly based on the coarse and fine metrology signals, the central computer should always know the relative positions of the satellites for use in the central geometrical model for the array, which is to be updated (continuously) during an observation. The phase corrections should be computed for each satellite relative to a common virtual phase centre. These phase corrections are then used to stop the fringes either in correlator or in LO subsystem. Since the metrology system has its own time cycle, the positions of satellites should be (continuously) interpolated between known points using a dynamic model of the array element movements and information on velocity and acceleration of the satellite (aided by extrapolation of past movements). The phase closure relations should also be used to constrain the element positions provided the signal to noise ratio is good enough.

## **9. SENSITIVITY CALCULATIONS**

The ESPRIT baseline design is for six interferometer elements and a diameter of at least 3.5 m for each element to achieve the desired sensitivity. Thus, the collecting area for each element is  $>10 \text{ m}^2$ . The use of small mixer arrays, if LO power and correlator capacity permitted, could compensate the small primary beam size. In using the ALMA sensitivity calculator [14]

ESPRIT sensitivity results were obtained which are given below in Table 6. With expected levels of molecular line brightness in the order of 10 K, we can expect from ESPRIT a large set of interesting observations.

Table 6. Sensitivity calculations for ALMA, and for ESPRIT with 6 telescopes with 3.5 m primaries and 15 baselines.

Parameters:	Units	ALMA	ESPRIT
Central Frequency (Wavelength)	GHz ( $\mu\text{m}$ )	650 (461)	3000 (100)
Velocity Resolution	km/s (MHz)	1 (2.2)	1 (10)
Angular Resolution	arcsec	0.1	0.1
Baseline	m	900	200
Jy per K ratio	mJy/K	3.4	74
Tsys	K	1326	1000
Cont. flux density	mJy	0.13	16.7
Cont. Brightness	K	0.04	0.2
Line flux density	mJy	8.07	333
Line brightness	K	2.33	4.5

Assumed integration times are 3600 secs.

## 10. CONCLUSION

We have presented a concept for a far-infrared space interferometer consisting of 6 free-flying elements, each with a 3.5m telescope, heterodyne receivers in the range 0.5 to 6 THz, and part of the distributed correlator. Such a space interferometer allows addressing fundamental question of modern astrophysics in the field of star and planet formation. Issues concerning the configuration, detectors, detector cooling, correlator, and the system were presented and discussed.

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