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Published in:

IEEE transactions on terahertz science and technology

DOI:

[10.1109/TTHZ.2018.2876093](https://doi.org/10.1109/TTHZ.2018.2876093)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2018

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Wiedner, M. C., Mehdi, I., Baryshev, A., Belitsky, V., Desmaris, V., DiGiorgio, A. M., Gallego, J-D., Gerin, M., Goldsmith, P., Helmich, F., Jellema, W., Laurens, A., Risacher, C., Cooray, A., & Meixner, M. (2018). A Proposed Heterodyne Receiver for the Origins Space Telescope. *IEEE transactions on terahertz science and technology*, 8(6), 558-571. <https://doi.org/10.1109/TTHZ.2018.2876093>

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A Proposed Heterodyne Receiver for the Origins Space Telescope

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(Invited Paper)

Abstract—The HETerodyne Receiver for the Origins Space Telescope (HERO) is a proposed design for a heterodyne focal plane array for a large space mission. The Origins Space Telescope (OST) is one of the four missions selected to be studied by NASA for the 2020 Astronomy and Astrophysics Decadal survey. HERO is designed to observe the trail of water from the interstellar medium (ISM) to disks around protostars. In Concept 1, HERO provides continuous frequency coverage from 468 to 2700 GHz in

five bands and a sixth band to cover 4700 GHz. Most bands include 2×64 pixels providing at least an order of magnitude higher mapping speeds than available with today's instruments. Receiver sensitivities are expected to be close to the quantum limit. HERO Concept 2, highly constrained by cost and denoted Little-HERO, includes four bands with continuous coverage from 486 to 2700 GHz and with focal plane arrays having only 2×9 pixels per band. Both of these THz receiver concepts will be described and the designs will be motivated by the science drivers, the space craft constraints and the latest technological developments. The HERO design builds on the highly successful Herschel/Heterodyne Instrument for the Far-Infrared, on Stratospheric Observatory for Far-Infrared Astronomy/upGREAT and many other heterodyne receivers, but surpasses these in terms of frequency coverage, array size and sensitivity, thanks to the latest technical advances. HERO can be considered an example of a new generation of heterodyne focal plane arrays for future space missions.

Index Terms—Array receivers, far-infrared (far-IR) space instruments, heterodyne instruments, heterodyne receivers, THz astronomy, THz detectors.

I. INTRODUCTION

THE building blocks of our universe are gas and dust that make up the interstellar medium (ISM). To understand the ISM and the processes that govern it, such as star formation, stellar death, turbulence, and gas flows, far-infrared (far-IR) observations are an invaluable tool. Direct detectors are ideally suited to observe the broadband continuum emission from the dust, while high-resolution spectroscopy is needed for tracing molecules in the gas. Heterodyne receivers that can easily achieve very high spectral resolution play an essential role in our study of the universe.

The first (sub)millimeter heterodyne receivers were installed on ground-based single dish telescopes and on interferometers. The success of these projects leads to airborne, balloon, and space missions, in order to access lines absorbed by the Earth atmosphere. (Sub)millimeter astronomy reached a golden era with the construction of the Atacama Large Millimeter Array [1], the first flights of the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) [2], and the launch of the Herschel Space Observatory [3]. These impressive projects led to rapid advances in heterodyne technology, technical innovations, and to

Manuscript received August 1, 2018; revised September 26, 2018 and October 9, 2018; accepted October 10, 2018. Date of publication October 15, 2018; date of current version December 11, 2018. This work was supported by the Centre National D'études Spatiales (a French Space Agency). (Corresponding author: Martina C. Wiedner.)

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Digital Object Identifier 10.1109/TTHZ.2018.2876093

excellent receivers. Since then, heterodyne receivers have been built for smaller observatories and balloon experiments. New receivers have also been developed for SOFIA and on ALMA.

It is now time to consider the future of far-IR astronomy. White papers have been written calling not for extremely sensitive bolometer arrays with thousands of pixels but also for heterodyne focal plane arrays (FPAs) [4]. Conferences and special sessions have been organized, e.g., the Nunspeet Meeting for Focal Plane Arrays (2016) or the far-IR session at the EWASS conference (2016). Ambitious new projects are being proposed, such as the large ground-based telescopes CCAT [5] and ATLAST [6], [7] and the satellite mission Millimetron [8]–[10]. NASA is submitting to the 2020 Decadal Review a study of a large mid- to far-IR satellite, the Origins Space Telescope (OST). These new projects call for a new era of instruments, including heterodyne FPAs.

This paper describes the proposed HETerodyne Receiver for the OST (HERO), as an example of a new generation heterodyne focal plane array receivers for space application. The paper gives a brief overview of previous heterodyne instruments and describes the state-of-the-art of receiver component, which are the bases for any new array receiver design. An introduction to the OST and its science goals is given to set the technical requirements and the design constraints for the HERO receiver. The main part of this paper is a detailed description of HERO for OST Concept 1, outlining the advanced technologies that will be necessary to provide drastic improvement of mapping speeds for heterodyne instruments. The more modest HERO for Concept 2, dubbed Little-HERO, is also described but in less detail since the general concepts are the same. The paper ends with a summary and outlook.

II. PREVIOUS INSTRUMENTS

Heterodyne receivers based on superconducting mixers have been installed in nearly all ground-based millimeter and sub-millimeter telescopes. These include the Institut de Radioastronomie Millimetrique 30-m telescope [11], the James Clerk Maxwell Telescope [12], the Caltech Submillimeter Observatory [13], the Atacama Pathfinder EXperiment [14], the ASTE Telescope [15], the Large Millimeter Telescope [16], as well as in interferometers such as the Berkeley Illinois Maryland Array [17], the Owens Valley Radio Observatory [18], and the Sub-Millimeter Array [19]. Recently, some of the observatories have been equipped with focal plane arrays (FPA). The largest FPA is currently the Supercam, with 64 pixels [20]. The CHAI 64 pixel receiver [21] for CCAT and a pathfinder for a kilopixel array KAPPA have been proposed [22]. A good summary of the FPAs is provided in [23] and [24].

After the successful operation of heterodyne receivers on the ground, airborne instruments were built (e.g., for the Kuiper Airborne Observatory [25]) for the Odin satellite [26] and the SWAS satellite [27].

The next generation space heterodyne instrument could not be conceived without the history of all these prior instruments. In particular, they will be able to leverage the technology being developed for the most recent airborne, balloon, and space instruments.

The GREAT instrument [28] had single-pixel receivers at 1.4, 1.9, 2.7, and 4.7 THz and flew on the SOFIA from 2011 to 2016. In 2015, the upGREAT array receivers started operation in two bands to allow observations of the major cooling lines of [CII] and OH (1.9–2.5 THz) and [OI] 4.7 THz [29], [30]. It has medium-sized arrays of 2×7 pixels and $1 \times$ pixels, respectively, to allow instantaneous observations of the sky at seven positions in two polarizations.

The balloon mission, STO-1 [31], has flown with 2×2 HEB mixer arrays at 1490 and 1900 GHz, and STO-2 [32], [33] with two pixel arrays at 1490 and 1900 GHz. STO-2 also included a pixel at 4700 GHz, but it was not operational due to technical difficulties. Another long duration balloon mission designed for the measurement of the far-IR fine structure lines has been approved by NASA and is being built. This mission, GUSTO [34], has three 8-pixel receivers, employing HEB mixers to measure ionized carbon, ionized nitrogen, and atomic oxygen from Antarctica. Launch is expected in 2021.

In space, the Heterodyne Instrument for the Far-Infrared (HIFI) [35], [36] operated successfully from 2009 to 2013 on the Herschel Space Observatory [3], one of ESA's cornerstone missions. It had seven frequency bands covering a large part of the 480–1910 GHz frequency range. HIFI used superconducting SIS and HEB mixers, and direct multiplication layout comprising amplifier-multiplier chains for the local oscillator.

III. STATE-OF-THE-ART COMPONENTS FOR HETERODYNE RECEIVERS

All heterodyne receivers require state-of-the-art components, where the mixer, the local oscillator (LO), the first amplifier, and the backends are the most critical elements. A space mission faces additional constraints, such as a necessity to limit the mass, volume, and to mitigate operational risk by flight qualifying hardware for space. The biggest challenges arise from the limited available cooling power at 4 K (typically < 100 mW) and the limited total mission power. For increased science throughput, it is desirable to have FPAs with a large number of pixels, thus forcing the design to incorporate innovative techniques and components with up to two orders of magnitude lower electrical power requirements.

A. Mixers

Superconductor insulator superconductor (SIS) mixers [36], [37] provide near-quantum noise limited performance at frequencies up to that of the superconducting band gap. The intermediate frequency (IF) bandwidth can easily reach 12 GHz and even higher with only modest increase in noise temperature. Current materials limit the frequency of operation to approximately 1.2 THz.

Hot electron bolometers (HEBs) are the most sensitive mixers above ~ 1.2 THz. Recently, considerable improvements in HEB receiver sensitivity have been made [38]–[40]. Traditional HEB mixers (Nb-based) are limited to around 3 GHz IF bandwidth. A recent work with novel superconducting materials, such as MgB_2 , shows promise that HEB mixers with 8 GHz IF bandwidth will be possible [41]–[43]. MgB_2 HEB mixers operate at a significantly higher critical temperature than Nb-based devices,

leading to higher Johnson noise contribution, as well as a higher required LO power. NbN HEB mixer development is progressing as well, with recent results by Krause [40] achieving an IF bandwidth of 7.5 GHz using NbN on GaN under-layer HEBs at around 1.3 THz. The large bandwidth is required at THz frequencies to be able to observe lines of ~ 500 km/s width.

B. Local Oscillator Sources

Local oscillators are a critical item, as they need to be tunable over a very wide frequency range, reach high frequencies (e.g., the important [OI] line at 4.7 THz), pump many pixels, and have low power consumption. Schottky diode-based frequency multiplier chains have made considerable progress recently [44]–[46]. By utilizing high-power GaN amplifiers at W-band and power-combining multiplication technology in the submillimeter-wave range, more than 1 mW of power has been demonstrated at 1.6 THz [47]–[49]. Although a fully operational all solid-state 4.7 THz source has not yet been demonstrated, most of the building blocks of such a source have been individually demonstrated and there is a clear and feasible path forward given additional engineering effort.

As an alternative, especially for the 4.7 THz channel, the quantum cascade laser (QCL) can be used [50]–[55]. Recent QCLs have a nearly Gaussian output beam and dissipate less power, so that a small commercial refrigerator can cool them. Continuous tunability may be achievable by using multimode QCL and a frequency-selective Fabry–Perot as well as a phase lock loop.

Technologies for signal synthesis have also advanced. CMOS-based synthesizers [56], [57] require much less power and are lighter than YIG- and DRO-based synthesizers.

C. Cryogenic Low Noise Amplifiers

Various low-noise cryogenic amplifier technologies exist, such as InP HEMTS, SiGe BiCMOS, and superconducting parametric amplifiers. For space missions, the amplifiers not only need to have very low noise, wide bandwidth, and high stability but should also have a very low power dissipation (~ 0.5 mW per IF chain) and a reasonably high technology readiness level (TRL) (≥ 5 in 2015). The technology needs to be mature enough to promise a successful mission.

To date, cryogenic SiGe heterojunction bipolar transistor amplifiers have demonstrated the lowest power dissipation (only 0.3 mW per chain) with good noise performance (5 K) albeit with an IF bandwidth of 1.8 [58] and 4 GHz [59]. This promising technology therefore requires further development to obtain a wider band, while keeping the power dissipation low, and a gain of at least 20 dB to avoid the degradation of the front end sensitivity.

An alternative is using the well-established InP technology, which is being employed in numerous ground-based instruments, e.g., the most recent InPs for ALMA [60], and has been space qualified for HIFI/ Herschel [61]. InP cryogenic amplifiers with very good performance are now commercially available [62]. For optimal performance, they typically require around 5 mW of power per IF chain, although operation at reduced power while maintaining good performance has been described

[63], [64]. Further experiments are required to investigate their stability and reproducibility at such low power levels.

Parametric cryogenic amplifiers are capable of much lower power dissipation with noise performance approaching the quantum limit [65], [66], but they need microwave pumping which adds complexity. These devices are still to be demonstrated in practical ground-based radioastronomy receivers and are currently at a low TRL level.

D. Backends

Compact and low-power backend spectrometers have been a significant bottleneck for array receivers. Traditional approaches such as filter banks, AOS, and chirp-transform-spectrometers (CTS) are bulky and require a substantial amount of dc power (30–40 W). Recent focus has been on developing low-power solutions. FPGA/ASIC-based solutions are currently being developed by European consortiums, while ASIC-based system-on-chip (SoC) architectures are being developed in the United States with the purpose of providing low-power backends for array receivers. A 3 GHz bandwidth CMOS chip based on 65-nm technology has already been demonstrated [67], [68]. This single chip backend can support 4096 channels and requires only 1.65 W. Work is underway to develop a 6-GHz version.

For instruments on the ground, backends based on FPGA technology can be used [69], [70]. They show excellent performance and are the baseline for the new ALMA correlator.

These components provide us with a choice of building blocks for the next generation of heterodyne (array) receivers, including the proposed HERO.

IV. ORIGINS SPACE TELESCOPE

The OST is one of the four NASA-funded studies for a large space mission to be submitted to the 2020 Decadal Review survey. The top three science questions for OST [71] are listed as follows: How common are life bearing planets around dwarf stars? What is the trail of water from the ISM to habitable planets? How do galaxies form stars, make metals, and grow their central supermassive blackholes from reionization to today? To achieve these science goals a mid- to far-IR telescope was designed [72]. Some of the technical challenges in designing a large cryogenically cooled telescope have been presented [73]–[75]: a segmented primary reflector will be surrounded by multiple layers of sunshields and cooled with closed-cycle cryocoolers. Following two concepts of the OST have been suggested: Concept 1 is an ambitious mission that is based on a 9.1-m off-axis mirror cooled to 4 K. It has five instruments, including the HERO, covering a wavelength range of 5–660 μm . Concept 2 is a more modest mission, utilizing a 5.9-m telescope and has only four instruments [76]–[79], including Little-HERO. If selected, OST is expected to be launched in the mid-2030 s.

V. SCIENTIFIC MOTIVATION AND TECHNICAL REQUIREMENTS FOR (LITTLE) HERO

A. Scientific Motivation

A key science driver for HERO/OST is tracing the path of water from interstellar clouds to habitable planets (see Fig. 1).

Fig. 1. Artist conception of the phases of star birth beginning in the “prestellar” phase where a cloud of gas collapses (top left) into a still-forming star surrounded by disk near the size of our solar system and a collapsing envelope of material (top right). Over time the envelope dissipates, leaving being a young star and a disk that is beginning to form planets (bottom left) eventually leaving being a new planetary system (bottom right). (Image Credit: Bill Saxton, NRAO).

Water is an extraordinarily interesting molecule for astrophysics, astrochemistry, and astrobiology. Understanding how habitable planets came to have significant surface water requires knowing the full story of this molecule in evolution from interstellar cloud cores to (exo)planets. It starts with water formation in interstellar cloud cores on dust grain surfaces [80]. Once evaporated, water serves as an extremely important indicator of dynamical processes, in addition to its chemical role on and off the icy dust grains. Stars form in cores, which condense from interstellar clouds. A new star incorporates material from its placental core, much of which ends up in the star and its surrounding protoplanetary disk that evolves to form planets and smaller objects.

The trail of gaseous water can be studied by observing the emission and absorption lines of water and its isotopologues [81]. The low-lying transitions (at 557, 1661, and 1670 GHz for ortho- H_2^{16}O , 1113 and 988 GHz for para- H_2^{16}O , 548 GHz for H_2^{18}O , 552 GHz for H_2^{17}O , and 509 and 894 GHz for HDO) are particularly important as they trace water in the cold, early phases of cloud and protostellar evolution. High spectral resolution observations (<0.3 km/s) reveal detailed kinematics of the gas, thus giving insight into the origin of the water emission/absorption at finer spatial scales than the native resolution of the telescope and also giving accurate information on the infall motions. High spectral resolution ($R = 10^6$ – 10^7) is necessary to resolve extremely narrow (<1 km/s) features and obtain accurate line shapes for kinematic modeling and to identify absorption versus emission features. In interstellar cores, the water distribution is extended and spectral line maps are required to follow the spatial distribution of the physical and chemical conditions of the water. In protoplanetary disks where the gas motions follow a Keplerian rotation pattern, the line profile of the ground state water lines traces the location of the “snow line” where water condenses and forms ice mantles on

grains. The HD line at 2.7 THz is a unique tracer of the gas mass [82]. The radial distribution of the gas surface density can be derived from the spectrally resolved line profile.

Other science drivers of HERO/OST include the study of the turbulence of the ISM [83] and mapping the cosmic ray flux in the Milky Way [84], and a close look into the formation of the seeds for dust grains around evolved stars [85], [86].

B. Science Traceability and Technical Requirements

The design of the HERO receiver is based on the science traceability matrix established by the OST STD team, as documented in the interim report 17 [87]. The derived requirements for HERO are summarized as follows.

- 1) Very high spectral observations of 0.3 to 0.03 km/s, i.e., $R = \lambda/\Delta\lambda$ of 10^6 – 10^7 to trace the velocity structure of water in starless cores and young disk around protostars, for example.
- 2) A radio frequency (RF) observing range to cover at least the main water lines (557, 988, 1113, 1661, and 1670 GHz) and those of its isotopologues (509, 548, 552, and 894 GHz), together with the HD line (2675 GHz) is required for the water trail. The [CII] line (1901 GHz; 158 μm) is a valuable tracer of the rate of star formation and of the evolution of interstellar atomic diffuse to dense molecular clouds in which new stars form. The fine structure lines of [NII] at 1461 and 2459 GHz (205 and 122 mm) are required to probe ionized regions and measure the electron density there. [OI] at 4746 and 2060 GHz is a critical tracer of the photodissociation regions around massive young stars. OH, CH, CO, SiO, HCN, and Al–, Ti–, Fe–, Mg–, and Ca-bearing molecules and the key molecular ions ArH^+ , OH^+ , H_2O^+ , H_3O^+ , HCl^+ , and H_2Cl^+ (with major transition lines in the 500–3000 GHz range) are also desired to probe the cosmic ray ionization rate and the essential physical and chemical processes that determine the structure of the interstellar medium.
- 3) An instantaneous frequency bandwidth of 0.5–8.5 GHz is required. This is equivalent to ~ 500 km/s at 4.7 THz more at lower frequencies. At least 500 km/s bandwidth is desirable to cover the different velocities along the line of sight across a spiral arm.
- 4) Arrays of heterodyne receiver for efficient mapping, especially at the higher frequencies where the beams are smaller (~ 2 in $\times 2$ in for the trail of water).
- 5) 5 sigma sensitivities of at least 10^{-19} W/m² for 1 h integration time at $R = 10^6$ resolution.

C. Design Constraints

In addition to the design requirements derived from the science, there are also design constraints to limit the cost of the space craft, which are summarized in Table I.

VI. CONCEPT 1: HERO

These requirements led to the design of the HERO for OST Concept 1. The HERO architecture largely follows the classical

TABLE I
OST CONSTRAINTS FOR INSTRUMENT DESIGN

Properties	OST 1	OST 2
Mass	none	< 200 kg
Volume	none	< 2 m ³
Power	none	< 250 W
Heat dissipation ^a @ 4K	< 70 mW	< 35 mW
Heat dissipation ^a @ 20 / 35K	< 70 mW	< 35 mW
TRL in 2018	> 3	> 3
TRL in 2015	≥ 5	≥ 5

^aHeat dissipation only includes heat produced in the 4/20/35K elements; there is an additional allocation of 100 mW for OCT Concept 1, and 50 mW for Concept 2 of conductive and radiative heat (e.g., via cables and LO path) attributed but this time for all 5/4 instruments.

TABLE II
HERO DESIGN PARAMETERS (FOR OST CONCEPT 1)

Band	F _{min}	F _{max}	Pixel	Trx	Beam Size	T _{rms} ^a	Line Flux ^b
	GHz	GHz		K	''	mK	Wm ⁻²
1	468	648	2x16	40	14.6	2.0	2.1 E-21
2	648	900	2x16	80	10.5	3.4	4.9 E-21
3	900	1260	2x64	110	7.6	3.9	7.9 E-21
4	1242	1836	2x64	200	5.3	6.0	1.7 E-20
5	1836	2700	2x64	300	3.6	7.4	3.1 E-20
6	4536	4752	2x64	500	1.8	8.6	7.5 E-20

^aReceiver noise for 1 h integration at 10⁶ resolution (0.3 km/s) using one polarization.

^bDetectable line flux at 5 sigma, for 1 h pointed integration (ON+OFF source) in two polarizations, with a 9.1 m primary mirror as designed for OST Concept 1.

Fig. 2. HERO instrument architecture closely follows architectures of successful heterodyne instruments like HIFI. Novel coupling optics and advances in component technologies allows for mapping speeds that are orders of magnitude faster than HIFI. (Image Credit: Britt Griswold, NASA.)

design of heterodyne receivers used (HIFI, upGREAT, ALMA, and SUPERCAM). However, what sets HERO for OST Concept 1 apart is the usage of large focal plane arrays and the continuous frequency coverage from 468 to 2700 GHz. A functional block diagram of the instrument concept is shown in Fig. 2, and the expected performance is summarized in Table II.

The OST telescope captures the signal from the sky and sends it to one of the six receiver bands depending on the observing frequency requested. In the receiver module, the sky signal is divided into its two linear polarizations and each polarization is sent to one of the two focal plane arrays of mixers. The FPAs consist of 4×4 SIS mixers in the two lower frequency bands and 8×8 HEB mixers in the four higher bands. For each polarization, one of the six local oscillators in the spacecraft bus (lower left in the figure) creates a monochromatic reference signal that lies a few GHz away from the targeted sky frequency. Sky and LO signals are optically superimposed and are combined in the mixer to create the intermediate frequency signal. Cryogenic low-noise amplifiers placed directly behind the mixers amplify the weak IF signal. As only one focal plane array (in both polarizations) looks at the nominal position in the sky, the IF signals of the different bands are passively combined to 130 separate IF chains that are common for all frequency bands. The second stage low-noise amplifiers are at 20 K. Coaxial cables direct the signals to the warm spacecraft bus, where they are further amplified and prepared for the backends, which detect and digitize the spectra. The instrument control unit receives the data, compresses it, and sends it on for downlinking.

A. Optical Design

The broadband optics of HERO is designed to have a wavelength independent design and to be lightweight. It has four distinctive parts, described as follows.

1) *Fore-Optics*: The common fore-optics directs the sky signal to one of the receiver bands with the help of a two-axis Offner Relay [88], [89]. The fore-optics also contains a warm and a cold calibration load, as well as a polarization load, and a sideband calibration load.

2) *Receiver Module*: The receiver module optics employs polarization grids to split the incoming sky signal into its two linear polarizations and sends the beams to the respective focal plane arrays.

3) *Warm LO Optics*: The LO optics bring the LO signals created at the spacecraft bus to the ~ 8 m distant receiver modules. In order to minimize the LO channels, the 12 LOs are superimposed onto following two channels: channel A, containing bands 1 H, 2 V, 3 H, 4 V, 5 H, and 6 V, and channel B with the same bands in the opposite polarization. The warm LO optics also contain a path length compensation scheme, as

well as a tip-tilt mirror to compensate for any relative motion between the spacecraft bus and the mixer modules in view of the long optical path. The optics has been designed in such a way that the required tip-tilt and path length regulations are easily achievable with standard motors. The path length compensation scheme is very challenging and needs a careful design.

4) *Cold LO Optics*: The cold LO optics demultiplexes the LO channels into its six frequency bands using the same diplexers and grid layout but in inverted order when compared to the warm LO optics. The cold LO optics then sends the LO for each band to the respective receiver module. A lenslet array adjusts the spacing of the LO multiple beams (that are the output of the amplifier multiplier chains) to fit that of the mixer pixels. A polarization grid is used to overlay this multibeam LO with the sky signal. The advantages of using a polarization grid are simplicity, when compared to a Martin–Puplett interferometer, and reduced LO losses, when compared to a Mylar beam splitter. The disadvantage is that the mixers need to have an orthomode transducer to separate and then mix LO and the sky signal.

The LO optics, as proposed here, is a feasible and traditional approach to bring the LO signal created into the warm space craft to the cold mixers. It is not, however, a very elegant solution, because it is heavy and voluminous due to the mirrors and requires Mylar bandpass filters being installed at each sunshield to limit the IR flux from the warm space craft to the 4 K instrument module.

There are basically following two alternative approaches: first, to look for THz “cables” or second, to create the LO signal close to the mixers.

- 1) It has been suggested that dielectric waveguide could be used as a “cable” for THz signals. There are three classes of dielectric waveguide, such as solid-core, hollow-core, and porous-core waveguides. Of these, the hollow-core waveguides have the least losses, but they are rigid (diameter of a few millimeters) and they have relatively narrow transmission windows [90], [91]. Reflections within the waveguide need to be understood, as well as losses where the waveguide is mounted. These waveguides deserve to be looked at more carefully.
- 2) An alternative would be to produce the LO signal in the cold space craft, with the constraint that no more than 0.5 mW heat input per channel at 4 K are allowed. At the same time an LO output power of about 5 μ W per pixel is needed, i.e., this requires an efficiency around 1%. Approaches include the following: first, having the last multiplication stages at 4 K; second, sending up two IR/optical signals via an optical fiber and creating the THz LO signal using photomixers [92]; or third, using a flux flow oscillators [93], [94] to create the LO signal within the mixer. In the former two solutions, the heat dissipation is critical: A typical multiplier input around 70 GHz is a few hundred mW with an output around 1 THz of a few tens of μ W, i.e., efficiency of the order of 0.01%. The best photo mixers have efficiencies of 0.1% [92]. In both cases, the heat dissipation at 4 K would be too large. The third solution requires phase lock loops, etc., and only marginally simplifies the set-up. However, it is worthwhile

to look into these alternative approaches again during a phase A study.

B. Mixers

HERO uses the most sensitive superconducting mixers available, i.e., either SIS or HEB mixers. The frequency up to which SIS are used will be re-evaluated in phase A according to the latest developments. We have not selected MgB_2 mixers because they are currently slightly less sensitive than mixers fabricated from other materials. Further, the advantage of operating up to 20 K cannot be exploited for OST, as the instrument accommodation module is at 4 K.

The mixers employ horns that are followed by orthomode transducers to separate the LO from the sky signal, as suggested by Belitsky [95]. All mixers have two junctions and are balanced to reduce the LO power requirements and to enhance stability by suppressing LO AM noise [96]. One mixer of each array is sideband separating (2SB); the others are double sideband (DSB) mixers. The 2SB mixer is used to help calibrate the sideband ratio of the DSB mixers. We did not select 2SB mixers everywhere in the array, because for most of the science drivers the lines are sparse (either in the upper or the lower sideband, and because we want to limit the required IF power).

C. Focal Plane Arrays

To obtain continuous frequency coverage between 468 and 2700 GHz, and 4536 and 4752 GHz, HERO for OST Concept 1 is divided into six frequency bands, where the number of bands is determined by baselining LO chain bandwidths around 30%. Each band has focal plane arrays in two polarizations. The two lower bands (468–648 and 648–900 GHz) have FPAs with 4×4 SIS mixers, while the higher four bands have 8×8 HEB mixers. The SIS mixer has a footprint of $10 \times 10 \text{ mm}^2$ (to accommodate the magnet), whereas the HEB footprint is $5 \times 5 \text{ mm}^2$. The mixers are arranged on a square grid with $2F\lambda$ spacing at the lowest frequency, such that the beams on the sky are as close as possible without having significant crosstalk. The square configuration was chosen for simpler manufacturing that has been pioneered by large submillimeter arrays [20]–[22]. FPAs will consist of split blocks for multiple mixers, with smooth-walled conical horns formed directly in the block.

The optical matching of the horn arrays to the required focal plane sampling scheme will be established by lenslet arrays, which are part of the notional mixer and LO module optics [97], [98].

D. Local Oscillator

The LO sources for HERO need to be broadband and provide sufficient power to pump 64 pixels at up to 4.7 THz. As the sky and LO are superimposed in orthogonal polarization, there are (nearly) no losses due to the beam splitter and an LO power of $\sim 3 \mu\text{W}/\text{pixel}$ will be sufficient. To cover the wide bandwidth of HERO, there will be six different optimized frequency multiplier chains. A low-phase-noise synthesizer creates a reference signal in W-band that is amplified by high-power GaN amplifiers.

Power combining multiplication techniques are used to increase the LO power while bringing the LO signal to the requested frequency. Optically, the output of the LO chains matches the focal plane array. There will be blocks with 16 LO outputs for the lower frequencies and with 64 LO outputs for the higher frequencies, which is very similar to the 16 pixel prototype by Kawamura [99]. There are two LO chains for each band, one per polarization. We have not chosen a single beam LO output followed by a Fourier grating/Daman gratings to split the LO into multiple beams because Fourier gratings have only small RF bandwidth, which is much less than the 30% we require.

As a backup solution, a quantum cascade laser (QCL) LO design could be used, especially for the 4.7-THz channel. The QCL is currently a backup solution, because continuous tunability is difficult to be achieved. The tunability over a broad RF bandwidth can be obtained by using multimode QCL with a Fabry–Perot grating for mode selection, together with a reference signal and a PLL. This is a rather complex system. For space application, low power space-qualified coolers are also needed for the QCL.

E. IF Chain

The IF processing unit (including the first IF amplifier) forms a significant subsystem and covers 0.5–8.5 GHz. The IF is at 0.5–8.5 GHz because the HEB mixers have better performance at low IF frequencies. An important challenge is the limited available cooling power of about 0.5 mW at 4 K and 0.5 mW at 20 K per pixel. A gain of at least 20 dB is required at 4 K to increase the noise by less than 10%. For HERO, we selected SiGe low-noise amplifiers [58], [100], [101] as a baseline, as they have demonstrated good performance with an extremely low dissipation of ~ 0.3 mW. This technology has recently made significant progress, but it still requires some development to increase the bandwidth from currently 4 GHz to the required 8 GHz while keeping the power dissipation low. Space qualification of cryogenic SiGe amplifiers is also pending. An alternative is to run InP HEMTs at low bias values. Tests are currently being carried out to confirm that the stability is not affected when these amplifiers are run at suboptimal power. We have not selected parametric amplifiers because they still have too low TRL levels.

To minimize any heating of the mixers, the 4-K amplifiers are housed in an independent block at 4 K and connected by short flexible strip line or Kapton cables [102], [103] to the focal plane arrays. The second stage SiGe amplifiers are heat sunk to the 20 K cooling stage. In the baseline configuration, the gain and noise temperature of these amplifiers are better than 20 dB and 6 K, respectively, while dissipating less than 0.5 mW at 4 and 20 K.

After the first amplification, the IF chains of the different frequency bands are multiplexed onto one set of 130 IF chains (2×64 pixels + 2×1 for the two-sideband mixer). The multiplexing gives a distinct advantage as it reduces the number of components (amplifiers, cables, and backends), as well as the heat load through the IF cables.

The IF is further amplified at 300 K and conditioned for the spectrometer. Each pixel needs to be treated individually

and, given the large number of pixels, each chain is as simple as possible. Due to their large size, the use of connectorized components is not favorable. Therefore, for each channel the whole IF is built on one complementary metal-oxide semiconductor (CMOS) chip that is $\sim 1.5 \times \sim 1.5$ mm² and consumes ~ 160 mW of power. A CMOS prototype provides the following functionalities: band pass filtering, amplification, equalization, power attenuation, and downconversion. It can also include power monitoring and on-board auto-level control if desired [104].

F. Backends

HERO requires 130 low-power backends, each with 8 GHz bandwidth. To achieve a resolution of 10^6 – 10^7 , 1000 channels are needed to be configured to cover more or less of the IF bandwidth, depending on the observing frequency. This translates into a resolution bandwidth between 4.7 MHz (for OI at 0.3 km/s resolution) and 50 kHz (for the 557 GHz water line at 0.03 km/s). We allocate 1 W power consumption to each 8-GHz backend. This can only be achieved with low digitization levels, but a level of 4 bits (for ALMA) is sufficient.

As a baseline, HERO will use CMOS-based spectrometers, which are advancing quickly with the telecommunication industry and are predicted to reach the required bandwidth and power within a few years. Current versions have 6 GHz bandwidth, are extremely lightweight (< 120 g), and require little power (< 1 W) per backend [67], [68].

An autocorrelation spectrometer is another viable option, as it has been used already in space missions (ODIN) [105], balloon mission TELIS [106], and low-power ASIC versions are becoming available. For HERO, it is essential that backend power consumption is reduced from about 40 W to less than 2 W per 8 GHz IF.

G. Control Electronics

HERO has three control units to allow easy testing of sub-units. The LO control unit commands the frequency synthesizer and the LO chains. The focal plane control unit commands and powers all components mounted on the 4 K stage, namely, the Offner Relay with its two-dimensional (2-D) steering mirror, the mixers, and the first-stage amplifiers. The instrument control unit (ICU) is the overall control unit of HERO with spacewire connections to the other units. In addition, it is responsible for the IF chain and the backends and collects and compresses the data. The ICU connects to the spacecraft computer via MIL1553STDB. All control units will use next generation space-qualified processors.

H. Mechanisms

For high reliability and a low failure rate, HERO uses a minimum number of mechanisms: The Offner relay has a two-axis (cryo-) mechanism/actuator to direct the sky signal to the corresponding focal plane array. This mechanism is essential and the one-axis version has proven reliable on Herschel/Spire [89] and a two-axis version on METIS [107]–[109]. To reduce any

thermal radiation and stray light, the calibration loads, as well as the LO entrance beam, have shutters that will be closed when HERO is not in operation. Both the hot and cold calibration loads are identical, so that if one does not work, they can be exchanged and the cold load runs passively at the surrounding temperature of 4 K. The LO shutter is designed to be highly reliable (98%/96% for 5/10 years lifetime) and fail-safe. The warm LO optics has path-length compensation optics and a tip-tilt mirror to compensate for any variations in relative location of the HERO mixers, with respect to the spacecraft. Should these mechanisms fail, the stability of the receivers will be lower, but it will still work unless the relative positions have changed drastically.

I. Redundancy

There will be one additional control unit of each type as a spare (external redundancy).

The LOs, mixers, and IF chains have internal redundancy: Each frequency band has two polarizations. Should an entire LO chain or focal plane array fail, observations can still be carried out with the receiver/LO of the other polarization, albeit at reduced efficiency. The array receivers are also internally redundant: Neighboring pixels can compensate for any broken pixel (mixer, LO, and IF).

The only part of HERO that is not redundant is the 2-D chopper on the Offner relay. It will have redundant actuators and encoders. In case all actuators fail, it will stop in a well-defined position, so that by repointing the spacecraft, the instrument can still observe, though with some loss of function and performance (internal calibration loads will not be observable and calibration will need to be carried out on astronomical objects).

J. HERO Observing Modes and Performance

In HERO's standard observing mode, the astronomer selects any frequency and observations in the corresponding band are carried out in the two polarizations, whose footprints are superimposed in the sky. Dual frequency observations with two different frequencies in the same band are easily possible. In this case, the two LOs will have different frequencies. One frequency will be observed in one polarization and the second frequency in the other polarization. During dual frequency observations with target frequencies in two different bands, the FPAs look at different parts of the sky (separated by a few arcminutes). This is not a problem when mapping large regions. For point source observations, one FPA looks at the source, while the other at the off-position and vice versa.

In terms of telescope motion, pointed observations, raster mapping, i.e., several pointed observations to Nyquist sample the footprint of the array receivers, and on-the-fly mapping are offered.

K. Calibration

The science requires a calibration accuracy of about 10%, with a goal of 3%. This is similar to Herschel/HIFI and, at this stage of the design, HERO calibration is based on the

Fig. 3. Sensitivities for HERO and Little-HERO in comparison with Herschel/HIFI and SOFIA/(up)GREAT. The sensitivities are calculated for 1 h ON+OFF source integration time, 5 sigma detection, and a resolution of 10^6 .

HIFI/Herschel experience. The observatory allows for position switching for ON-OFF source subtraction, but frequency switching is also implemented in HERO. Calibration methods include gain calibration by looking at the internal hot and cold load, together with aperture efficiency and main beam efficiency determinations, by observing astronomical objects such as planets and quasars.

The sideband ratio of the DSB mixers is calibrated in the laboratory prior to flight, but it can be checked by switching an internal reference signal to the two sidebands. This can also be done through the use of convenient lines with known intensities and calibrating their strength with the sideband-separating mixer present in each FPA. The established signal strength can be used to calibrate the sideband ratio of the DSB mixers.

Though line polarization measurements are very low on the science priority list, HERO has an internal polarization load to allow calibration of polarization measurements. These loads consist of a pair of orthogonally polarized blackbodies employing linear photolithographic polarizing grids.

L. HERO Performance

HERO will have state-of-the-art performance at about twice the quantum limit (see Table II). State-of-the-art mixers, the large collecting area of the OST Concept 1 telescope of 9.1 m, and the complete lack of atmospheric absorption all make HERO a very powerful heterodyne receiver (see Figs. 3 and 4).

VII. CONCEPT 2: LITTLE-HERO

NASA requested two conceptual studies of all four missions studied. Concept 1 is driven entirely by science, whereas Concept 2 has a cost cap and is only designed around the most important science topics. The OST team is still working on Concept 2. In this concept, the number of instruments was reduced to four and each instrument team was asked to reduce mass and power requirements in order to achieve a lower cost and lower development and operation risk. The HERO team was asked to reduce instrument mass to below 200 kg and the power

Fig. 4. Resolving power of OST instrument suite (for Concept 2). HERO enables high spectral resolution observations over a large portion of the far-IR (THz frequency range).

TABLE III
LITTLE-HERO DESIGN PARAMETERS (FOR OST CONCEPT 2)

Band	F _{min} GHz	F _{max} GHz	Pixel	Trx K	Beam Size "	T _{rms} ^a mK	Line Flux ^b Wm ⁻²
1	486	756	2x9	50	20.3	2.6	6.4 E-21
2	756	1188	2x9	100	12.9	4.2	1.6 E-20
3	1188	1782	2x9	200	8.5	6.8	4.0 E-20
4	1782	2700	2x9	300	5.6	8.4	7.3 E-20

^aReceiver noise for 1 h integration at 10⁶ resolution (0.3 km/s) using one polarization.

^bDetectable line flux at 5 sigma, for 1 h pointed integration (ON+OFF source) in two polarizations, with a 5.9 m primary mirror as designed for OST Concept 2.

consumption to below 250 W while dissipating less than 35 mW at 4 K (see Table I). The STDT also decided that for Concept 2, the primary mirror diameter would be reduced to 5.9 m.

The major change for little-HERO was to eliminate the 4.7 THz channel and to reduce the number of pixels per band to 2 × 9. To compensate somewhat for the loss of spatial pixels, Little-HERO allows dual-frequency observations. Little-HERO has a frequency coverage of 486–2700 GHz (no 4.7-THz channel). Current multiplier fractional bandwidths have been limited to around 15%. However, recent results obtained with ultrawide band multiplier MMICs have shown bandwidths approaching 40% in the 200–300 GHz range, and it can be expected that in future, multiplied LO chains will be able to provide this [110]. By baselining LO technology with approximately 40% instantaneous bandwidth, the desired frequency range can be achieved in four bands, as shown in Table III. By reducing the number of bands, the corresponding components for the optical design are also reduced. Little-HERO is described in more detail in [79]. The ray tracing and the mechanical design of little HERO are shown in Fig. 5.

Fig. 5. Little-HERO on OST Concept 2. Little-HERO has four bands each with 2 × 9 pixels, covering 486–2700 GHz. It is lighter and consumes less power than HERO for OST Concept 1. The optical design was carried out by W. Jellema (SRON) and R. Hills (MRAO), and the mechanical design was from B. Bruno (Paris Obs), G. Aitink-Kroes (SRON), M. Eggens (SRON), and G. Keizer (SRON).

TABLE IV
TECHNOLOGIES USED IN HETERODYNE RECEIVERS

Sub-system	Component	HIFI	STO-2	GREAT/ 4GREAT/ upGREAT	HERO
Local Oscillator	Synthesizer Technology	YIG-based Ka-Band+Active Frequency Multipliers + GaAs W-band power amps		VCO-based oscillators from VDI	CMOS or YIG-based W-band synthesizer + GaN. amps
	Multiplied LO	Cascaded GaAs frequency multipliers		Multipliers/QCL for 4.7 THz	Cascaded Multipl. + On-chip. Power Combining +. 3D integ.
	Number of Pixels	1	2	2	2x64
	DC power/pixel	25 W	20 W	AMC: 14W QCL: 71 W	~1.5 W
Cryogenic Detectors	Fractional Bandwidth	~12 %	~1 %	~10 %	~42 %
	Mixer Technology	SIS, HEB	HEB	SIS; NbN HEB	SIS, HEB
	LNA Technology	InP HEMT	SiGe HBT	SiGe, InP	Low-power SiGe HBT
	Number of pixels	1	2	2x7	up to 2x64
Backend	DC power/pixel	10 mW	4 mW	5 mW	0.5 mW
	Mixer Assembly	Quasi-optical (QO)	QO	Waveguide	Waveguide
	IF Processing Spectrometer Tech.	GaAs HEMT amplifiers			
	DC Power/pixel	FFT FPG	FFT	FFT	CMOS based SoC
Total DC power per pixel	IF Bandwidth	10 W	10 W	35 W	2W
		1.5 GHz	1.5 GHz	0.2-4 GHz	8 GHz
Total DC power per pixel		35 W	35 W	49 - 106 W	3.5 W

VIII. SUMMARY AND CONCLUSION

The HERO is the product of a detailed study of a new generation of heterodyne receivers for space applications. HERO builds strongly on the successful HIFI/Herschel instrument, on upGREAT/SOFIA, as well as on other balloon- and ground-based missions. Given the constraints of a space mission, particular care was taken in the design study to minimize mass, volume, weight, power, and cooling requirements. HERO/little HERO incorporates the newest technologies and makes use of innovative concepts letting it surpass any prior heterodyne instrument (see Table IV). HERO is a significant step forward to large focal plane arrays on space missions and opens a new era of high-resolution astronomy.

HERO/little-HERO complements the OST instrument suite by providing the very high spectral resolution to extract critical kinematic information from THz ionic, atomic, and molecular spectral lines. HERO on the OST is a unique facility, which opens a wide THz window into space, allowing for unprecedented discoveries. It will greatly enhance our knowledge of the trail of water from the interstellar medium to planet forming disks. HERO/OST will significantly increase our understanding of the impact of turbulence and cosmic ray fluxes on the ISM and star formation, and will pin down the birth of dust grains in the rich molecular environment of evolved stars.

ACKNOWLEDGMENT

The work presented in this paper is, by nature, a collaborative effort between several dozens individuals. The authors would like to acknowledge the assistance provided by the HERO concept science team as well as the HERO technical team, and also the assistance provided by the OST STDT, especially M. Meixner, A. Cooray, G. Melnick, T. Bergen, D. Leisawitz, J. Staguhn, and J. Zumuidzinis for their support and guidance. We would also like to thank the NASA Goddard engineers from the OST for defining envelopes and targets for HERO to be placed within the OST, in particular G. Martins, E. Amatucci, J. Corsetti, M. DiPirro and R. Carter. The optical design for Little-HERO was carried out by W. Jellema (SRON) and R. Hills (MRAO), the mechanical design was from B. Bruno (Paris Obs), G. Aitink-Kroes (SRON), M. Eggens (SRON), and G. Keizer (SRON). This work was carried out in part at the Jet Propulsion Laboratory, which is operated for NASA by the California Institute of Technology. The CNES supported this work both with staff and a grant.

The **Origins Space Telescope Study Team** has carried out the definition and the study of the Origins Space Telescope. It is headed by **Margaret Meixner** (chair), **Asantha Cooray** (Chair), David Leisawitz (Study Scientist), and Ruth Carter (Manager). The Science and Technology Definitions Team consists of Lee Armus, Cara Battersby, James Bauer, Edwin Bergin, Matt Bradford, Kimberly Ennico, Jonathan Fortney, Tiffany Kataria, Gary Melnick, Stefanie Milam, Desika Narayanan, Deborah Padgett, Klaus Pontoppidan, Alexandra Pope, Thomas Roellig, Karin Sandstrom, Kevin Stevenson, Kate Su, Joaquin Vieira, Edward Wright, and Jonas Zmudzinis as well as the nonvoting members Kartik Sheth, Dominic Benford, Johannes

Staguhn, Eric Mamajek, Susan Neff, Sean Carey, Denis Burgarella, Elvire DeBeck, Maryvonne Gerin, Frank Helmich, Itsuki Sakon, Douglas Scott, Martina Wiedner, and Harvey Moseley. A large team of NASA engineers has carried out the technical design, and industrial partners have advised the teams during the study.

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André Laurens joined Centre National d'Études Spatiales (CNES), Toulouse, France, in the early 1980s and has contributed to many space missions, mainly working on satellite image processing, spacecraft control and command, balloonborne astrophysics, and atmospheric chemistry experiments. He is currently a Space Systems Expert with PASO, the CNES Early Mission Studies Team, and a Coordinator of space sciences studies. He is involved in many future mission studies conducted by CNES in this area.

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Since 1998, he has been at various radio astronomy observatories developing novel instrumentation and supporting observations. Among those are the IRAM 30-m telescope in Granada, Spain, the Chalmers University of Technology with the Onsala Observatory, Sweden, the Apex Telescope with the European Southern Observatory, and the HIFI instrument with the Herschel Observatory. Since 2011, he has been with the Max Planck Institut für Radioastronomie, Bonn, Germany, and is the Project Manager responsible for the development of the upGREAT array receivers for the SOFIA NASA/DLR airborne observatory. He is now the Head of the receiver Front End Group, IRAM.

Asantha Cooray, photograph and biography not available at the time of publication.

Margaret Meixner, photograph and biography not available at the time of publication.