Heterodyne Receiver for Origins

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Abstract. The Heterodyne Receiver for Origins (HERO) is the first detailed study of a heterodyne focal plane array receiver for space applications. HERO gives the Origins Space Telescope the capability to observe at very high spectral resolution ($R = 10^7$) over an unprecedentedly large far-infrared (FIR) wavelengths range (111 to 617 μm) with high sensitivity, with simultaneous dual polarization and dual-frequency band operation. The design is based on prior successful heterodyne receivers, such as Heterodyne Instrument for the Far-Infrared /Herschel, but surpasses it by one to two orders of magnitude by exploiting the latest technological developments. Innovative components are used to keep the required satellite resources low and thus allowing for the first time a convincing design of a large format heterodyne array receiver for space. HERO on Origins is a unique tool to explore the FIR universe and extends the enormous potential of submillimeter astronomical spectroscopy into new areas of astronomical research. © *The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JATIS.7.1.011007]

1 Introduction

The Origins Space Telescope (Origins)[1–4] traces our cosmic history, from the formation of the first galaxies and the rise of metals to the development of habitable worlds and present-day life. Origins does this through exquisite sensitivity to infrared radiation from ions, atoms, dust, and molecules especially water in the form of vapor and ice. Origins observes extra-solar planetary atmospheres, protoplanetary disks, and large-area extragalactic fields in the wavelength range of 2.8 to 588 μm and is more than 1000 times more sensitive than its predecessors due to its large, cold (4.5 K) telescope and advanced instruments.

Origins has three baseline instruments—the Origins Survey Spectrometer (OSS),[5] a far-infrared (FIR) bolometer array with a grating, Fourier transform spectrometer, and a Fabry–Pérot; the Far-infrared Imager Polarimeter (FIP),[6] with two large FIR bolometer arrays at 50 and 250 μm, and the Mid-Infrared Spectrometer Camera Transit spectrometer (MISC-T),[7]

Table 1 Summary of the performance of HERO. HERO can carry out dual polarization and dual-frequency observations over a large frequency range, i.e., effectively using $2 \times 2 \times 9$ pixels at the same time. The receiver is ideally suited for very high spectral resolution observations of many molecular and atomic lines that are critical for answering the key science questions discussed above.

Band	Frequency (GHz)	Wavelength (μm)	Pixels	T_{rx} DSB (K)	Sensitivity (mK) in 1 h at $R = 10^6$, 1σ	Sensitivity (W) in 1h at $R = 10^6$, 1σ	Sensitivity ($W\,m^{-2}$) in 1 h, 5σ	Examples of spectral lines
1	486–756	617–397	2×9	50	2.6	$2.3 * 10^{-20}$	$4.5 * 10^{-21}$	H_2O, $H_2^{18}O$, HDO, and NH_3
2	756–1188	397–252	2×9	100	4.2	$5.7 * 10^{-20}$	$1.1 * 10^{-20}$	H_2O, $H_2^{18}O$, and H_3O^+
3	1188–1782	252–168	2×9	200	6.8	$1.4 * 10^{-19}$	$2.8 * 10^{-20}$	H_2O, $H_2^{18}O$, NH_3, and [NII]
4	1782–2700	168–111	2×9	300	8.4	$2.6 * 10^{-19}$	$5.2 * 10^{-20}$	HD, [OI], [NII], and [CII]

DBS = double side band, T_{rx} = receiver temperature.

an ultrastable mid-infrared (mid-IR) spectrometer. To fully exploit the capabilities of Origins, two upscope instruments have been designed: the Mid-Infrared Spectrometer and Camera: Wide Field Imager (MISC-WFI)[7] and the Heterodyne Receiver for Origins (HERO).

HERO's principal goal is to trace the trail of water[8–10] from the interstellar medium (ISM), through the different stages of star formation to (habitable) planets. HERO will measure the amount, location, and temperature of water and its isotopologues in the ISM, protostars, and protoplanatary disks. This science goal requires HERO to have extremely high spectral resolution of up to 10^7, to cover the major water lines and their isotopologues between 500 and 2700 GHz, and to have moderate instantaneous fields of view of a few arc minutes, sufficient to observe water in starless cores and protostars. This led the HERO team to design the first heterodyne focal plane array (FPA) receiver for a space mission. Table 1 summarizes HERO's capabilities. Figure 1 shows a block diagram of HERO. HERO has two sets of four frequency bands, one set for each linear polarization. Each frequency band has a small 3×3 pixel FPA.

Section 2 describes the instruments and its components in some detail. Section 3 puts HERO in the context of the Origins mission: it describes the resources HERO requires, the risks it carries, and shows the performance the receiver achieves, including comparison with prior missions. Section 4 discusses the technology roadmap. Section 5 briefly mentions an extension of HERO to be used as an element of the Event Horizon Telescope. The paper concludes with a summary and an outlook of the future.

2 Instrument Description

HERO uses the standard principle of a heterodyne receiver, in which the signal from the sky is mixed with a much stronger internally produced monochromatic reference signal called the local oscillator (LO). The beat signal is at the difference frequency, called the intermediate frequency (IF), which is amplified and spectrally analyzed. This beating of the two signals downconverts the sky signal to a lower frequency for amplification and makes very high spectral resolution measurements straightforward (spectral resolution up to 10^{11} have been demonstrated[11]). Extremely low noise mixers and first stage IF amplifiers are required for high sensitivity of such receivers and the tuning range of the mixers along with that of the LO determines the bandwidth of the receiver.

The design builds, in particular, on the experience from the receivers of the Atacama Large Millimeter Array (ALMA),[12] the German REceiver at THz (GREAT)/ 4GREAT/ up-GREAT[13,14] on the Stratospheric Observatory For Infrared Astronomy (SOFIA), and the Heterodyne
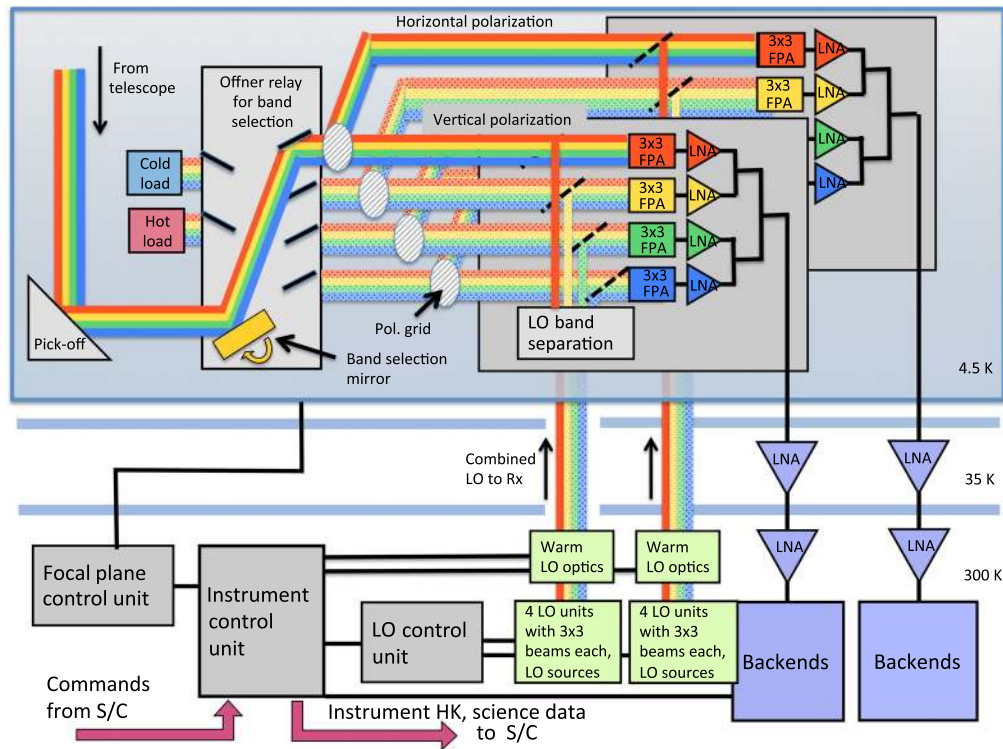
Fig. 1 Block diagram of HERO. The HERO instrument on Origins can observe and spectrally resolve the Universe over a wide submillimeter wavelength range in both linear polarizations simultaneously. HERO is a heterodyne receiver and has dual polarization 3×3 pixel focal plane heterodyne mixer arrays in four frequency bands.

Instrument for the Far-Infrared (HIFI)[15] on the Herschel satellite. The HERO design also takes the experience from the first ground and airplane-based FPAs[14,16–20] into account. HERO goes well beyond these earlier instruments by combining the largest frequency coverage of any heterodyne receiver and incorporates the first FPA design for space. The difficulty of cooling in space and the limited electrical power required us to look for innovative solutions for most of the receiver components. An earlier paper[21] describes the available technologies and justifies the choices we made for a preliminary version of HERO, here we describe the design submitted to the Decadal Review and the remaining challenges that need to be addressed with a technology roadmap.

2.1 Instrument Overview

Figures 1 and 2 show the HERO receiver. HERO covers a frequency range of 486 to 2700 GHz in only four frequency bands, in two linear polarizations. A band selection mirror in the Offner Relay directs the sky signal to two of the 3×3 mixer FPA, one for each polarization. The LO signals are generated in the spacecraft bus and are sent to the mixers. Low noise amplifiers (LNA) operating at 4.5 K and 35 K amplify the IF signal. In the warm spacecraft bus, the IF signal is amplified further and digitized, and the backends carry out spectral analysis via fast Fourier transforms (FFT). The LO, instrument, and focal plane control units control all aspects of the operation of the receiver.

2.2 Optics

2.2.1 Design of optics

Figure 3 shows the optical ray trace of HERO and Fig. 4 details of the Offner Relay, the cold receiver optics with the cold LO optics and the warm LO optics. The Origins Space Telescope

| Sub-system	Component	Hero
Local oscillator	Synthesizer technology	CMOS or YIG-based W-band synthesizer + GaN. amps
	Multiplied LO	Cascaded multipl. + on-chip. power combining +a 3D integ.
	DC power/pixel	2 W
	Fractional bandwidth	45%
Cryogenic detectors	Mixer technology	SIS, HEB
	LNA technology	Low-power SiGe HBT
	Number of pixels	2 (polarizations) x 3 x 3
	DC power/pixel	0.5 mW
	Mixer. assembly	Waveguide
Backend	IF processing	GaAs HEMT ampl
	Spectrometer tech.	CMOS based SOC
	DC power/pixel	2 W
	IF bandwidth	8 GHz
Total DC power per pixel		3.5 W

Fig. 2 HERO is the first heterodyne array receiver designed for space. The schematic diagram shows a relatively simple design that provides the widest frequency coverage and the highest sensitivity of any heterodyne receiver. HERO uses sensitive state-of-the-art components with low power consumption and weight.

has a 5.9-m on-axis primary mirror. A secondary mirror (not visible) reflects the light, to a tertiary mirror, and finally to a small field steering mirror. Around the focal plane, each of the four instruments picks up the radiation from their corresponding field-of-view. The HERO pick-off mirror is slightly in front of the Origins field of view. It directs the light into an Offner relay (1 in Figs. 3 and 4), which has a movable mirror that can send the light to one of the four frequency bands. The cold receiver optics (2a) divides the sky signal into its two linear polarizations and reimages each onto a 3×3 focal plane mixer array.

There are eight LO chains 2 for each of the four frequency bands. To minimize coupling of the thermal radiation from the warm spacecraft bus to the cold Cryo-payload module (CPM), the eight LOs are combined into two beams in the warm LO optics (3): dichroics superimpose bands 1 on band 3 and band 2 on band 4, and polarization grids superimpose the vertical polarization of band 1 plus 3 with the horizontal polarization of band 1 plus 3 and the same for bands 2 and 4. (A design with four dichroics would be unable to provide continuous frequency coverage or have unacceptable losses.) The combined beams transfer the LO signals to the CPM, where the cold LO optics (2b) separates the LO beams into the four frequency bands and the two polarizations. A wire grid superimposes each LO signal onto a sky signal.

The LO and sky signals have orthogonal polarizations with respect to each other. Two mirrors and a lenslet array reimage the sky and the LO signals onto the focal plane mixer array. A set of 3×3 mixer feed horns captures the superimposed sky and the LO signal. A waveguide ortho-mode-transducer (OMT) at 45 degrees to both input signals divides the signals in sky plus LO and sky minus LO. These two signals are mixed and their outputs recombined. This method of superposition requires much less LO power than beam splitters, has no limitation on the IF bandwidth unlike Martin–Puplett interferometers, but there are some losses in the OMT.[22] The HERO mixers consist of superconducting tunnel junction [superconductor-isolator-super-conductor (SIS)] mixers or hot-electron bolometer (HEB) mixing junctions, depending on the target frequency band. A paper giving details of the HERO optics by Jellema is in preparation.
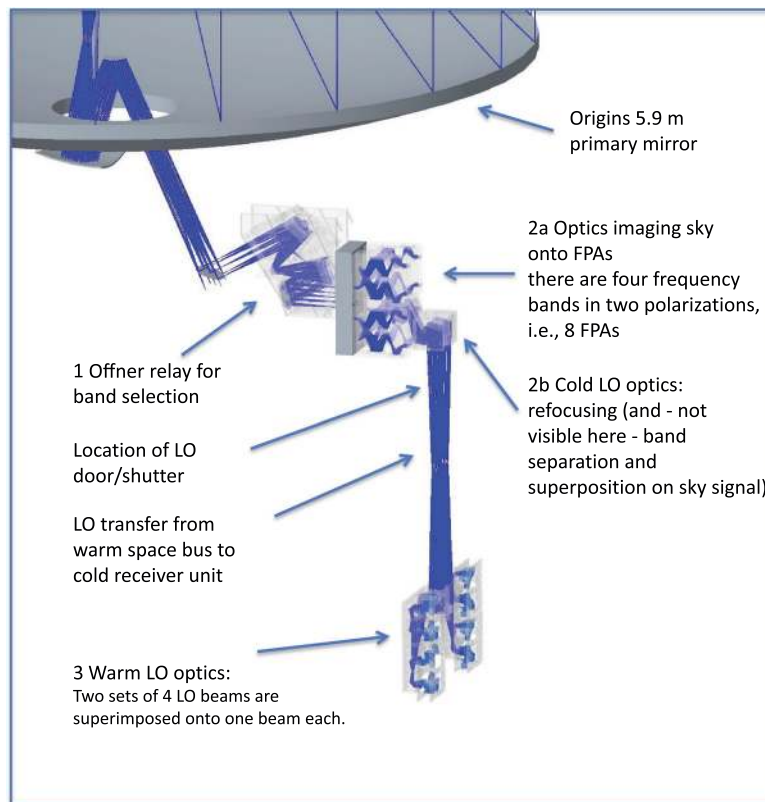
Fig. 3 Ray tracing of HERO optics. The signal from the sky is collected by the Origins antenna and redirected to the HERO instrument. The Offner relay mirror assures the band selection and sends the sky singal to one of the four frequency bands, where it is refocussed on two 3 × 3 FPAs, one for each polarization. The LO signal comes from the spacecraft bus at the botton of the picture. A set of four LO beams are superimposed onto one optics paths and send to the cold instrument bay, where the LOs are refocused, separated and sent to the FPAs.

2.2.2 Optical losses

HERO optics has a throughput of 95%, due to not perfect reflectivity and losses in the polarization grid, see Table 2. This calculation does not include the matching of the beams and truncation. We calculated the throughput of the HERO optics at its mid frequency of 1.6 tetrahertz (THz), see Table 2. The HERO mirrors are gold plated and at 4.5 K. Using the surface impedance Z at 80 K for gold, the emissivity is 0.146% at 1.6 THz (epsilon $= 4Z/Z_0$, with $Z_0 = 376.7 \ \Omega$). To account for slight surface roughness and misalignments, we doubled that number and used a mirror throughput of 99.7%. For a wire grid using $10 \ \mu$m wire at 35-μm spacing, Defrance[23] calculates at 1.4 THz a transmission of 99.8% at 0° and 99.7% at 45°, for the reflections the numbers are slightly lower at 99.1% and 98.3%, respectively. Jacob et al.[24] obtained a good agreement between their calculations with measurements at 640 GHz, where transmission and reflections were above 99% for nearly all grids tested. For the HERO calculations, we used the most pessimistic number of 98.3%. The lenslet array is an array of individual mirrors to refocus each beam onto the mixer array. We assumed a reflectivity of 99%, worse than that of a single mirror. The Offner relay with the pick-off mirror consists of five mirrors (see Fig. 4, insert 1) and has thus a throughput of 98.5%. The mixer optics (Fig 4, insert 2a) contains one wire grid, three mirrors, and the lenslet array and hence has a throughput of 96.4%. Together, the HERO optics has 95% throughput.

The radiation is collected by corrugated feed horns. Munoz[25] estimates the loss of the feed horn to be -0.22 dB mainly due to losses in the walls of the waveguide, i.e., 95% throughput. Behind the feed horn is an OMT, which is expected to have about -0.3 dB loss, i.e., 6.7%.
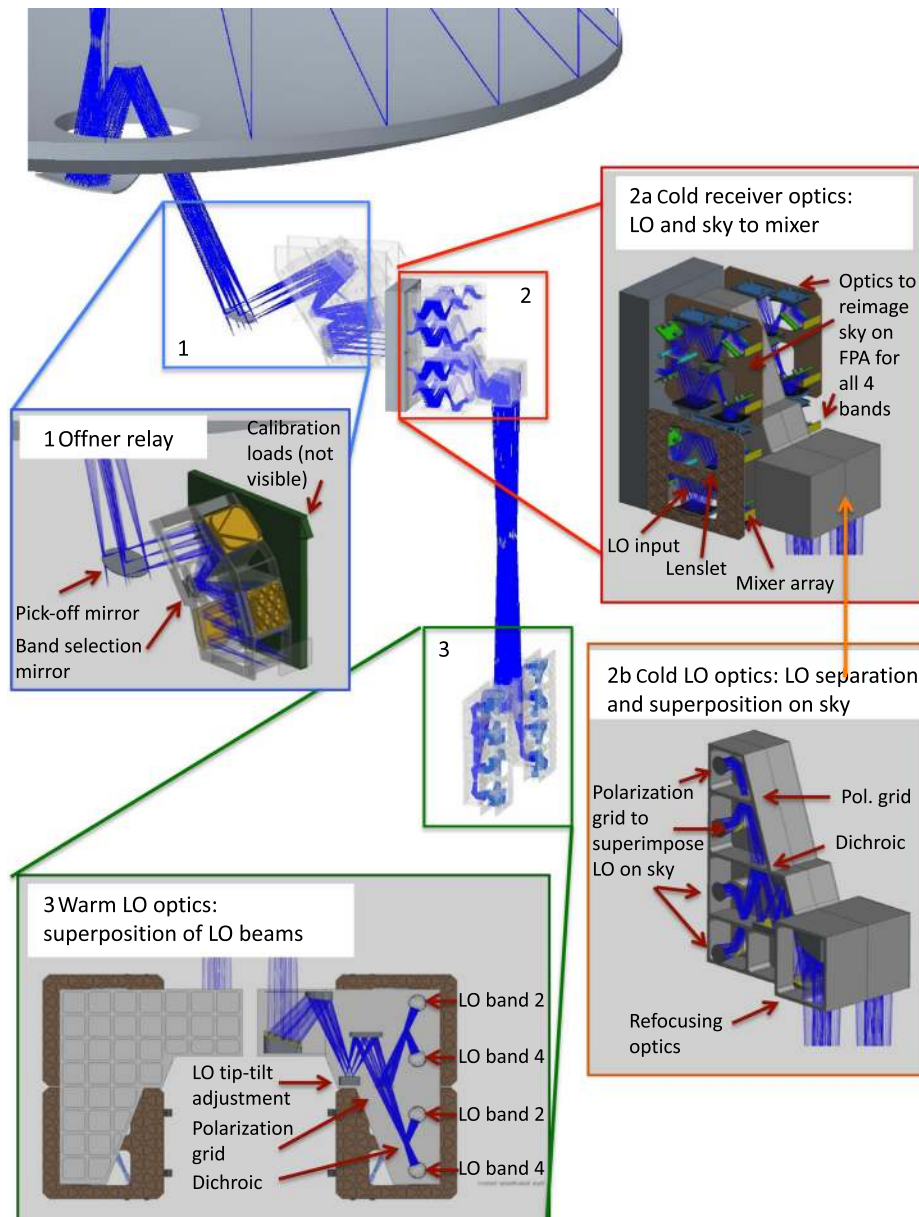
Fig. 4 HERO optics. Details of the Offner relay, the cold receiver optics with its cold LO optics and the warm LO optics.

Altogether, the optical losses and the losses in the feed horn and the OMT are expected to be 16%.

Estimating the final aperture efficiency requires a diffraction calculation to determine the coupling efficiency of the corrugated feed horn to the primary mirror, via the whole optics system.

2.2.3 *Challenges*

The greatest challenges of optics design are the wide bandwidth coverage of nearly three octaves, which requires a nearly frequency-independent design. A lenslet array in the cold receiver optics is used to map the sky, and the LO to fit the spacing of the mixers in the FPA. This component needs careful alignment, and optimization in the design phase.

Another challenge is the LO transmission from the warm spacecraft bus to the mixers, that are over 2 m away.
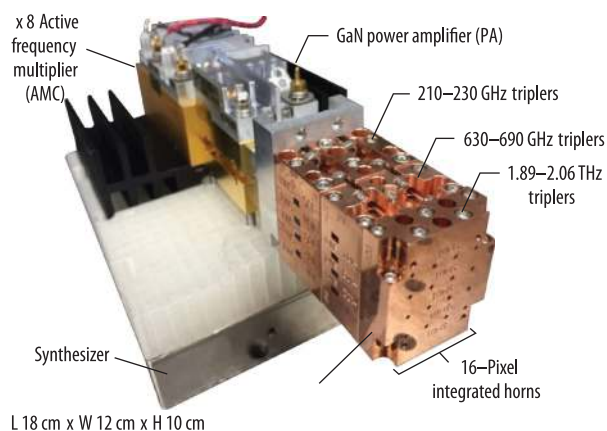
Table 2 HERO optical throughput.

Optical element	Specification	Optical throughput (%)
Mirror	Assumption: gold plated, 4.5 K (theoretical calculation × 2)	99.7
Wire grid	Assumption: 10 μm wire, 35-μm spacing, 45 deg angle	98.3
Lenslet array		99
Horn	Corrugated	95
OMT	Finline OMT	93.3
Offner relay	5 mirrors (see Fig. 4)	98.5
Mixer optics	Three mirrors, one wire grid, one lenslet array	96.4
Sum HERO optics	Offner relay, mixer optics	95
HERO optics plus horn and OMT	Offner relay, mixer optics, horn, and OMT	84

As mechanical stability between the warm spacecraft bus and the cold instrument cannot be guaranteed, the warm LO optics has a tip-tilt mirror (see Fig. 4, insert 3) that can be adjusted to maximize the LO power on the mixer.

In addition, the IR heat transfer needs to be kept minimal. In addition to superimposing the eight LOs onto two combined LO beams, these combined LO beams are kept as narrow as possible and the beam passes through 5 thermal blocking filters. These bandpass filters need to provide nearly lossless transmission of the LO signal, but block any out of band IR radiation efficiently. A single heat sink filter is able to block out of band radiation to −23 dB and thus the 5 filters reduce the heat load to 2.4 mW. An alternative solution would be low loss fiber-like waveguides for 500 to 2700 GHz, with a loss of <2 dB per m. Currently, these fibers do not exist yet; for an overview see, e.g., Humbert.[26]

2.3 *Local Oscillators*

Eight LO chains consisting of a combination of amplifier and multiplier stages multiply the frequency of a low noise W-band synthesizer signal to the required target LO frequency.[27,28] The LO signal is divided by waveguide power divider into nine outputs to match the mixer arrays, similar to the 16 beam example shown in Fig. 5.

x 8 Active frequency multiplier (AMC)
GaN power amplifier (PA)
210–230 GHz triplers
630–690 GHz triplers
1.89–2.06 THz triplers
Synthesizer
16–Pixel integrated horns
L 18 cm x W 12 cm x H 10 cm

Fig. 5 Compact multi-pixel electronically tunable LO systems have been demonstrated to 1.9 THz. The system shown here multiplies a ~9 GHz signal to ~70 GHz, amplifies it, then splits it into 16 signals and then further multiplies each to ~1.9 THz. The output is a 16 beam LO signal that can directly pump 16 mixers in a FPA. HERO has a similar chain with 9 outputs.

The HERO LOs have bandwidth of nearly 50% each to reduce the number of LOs and hence weight and volume in the spacecraft. Broadband amplifiers and multipliers are difficult to design, but multipliers for submillimeter LOs with 40% bandwidth have been already demonstrated, e.g., Virginia Diodes (VDI).[29] HERO requires extremely efficient multipliers as we have only allocated 2 W of DC power to each amplifier chain. The design of amplifier multiplier chains up to 2.7 THz with sufficient power to pump an array of mixers is difficult, but the prototype chains already exist for single-pixel applications, e.g., Mehdi et al.[27] for an overview, VDI[28] with 5 μW at 2.7 THz. An alternative approach for the LO source is the Quantum Cascade Laser (QCL).[30–33] These components have sufficient output power, but require cooling and generally have very limited tunability. Hübers[34], and Hübers et al.[35] have packaged a QCL with 0.6 mW output power in a compact cooler requiring 85 W input power. For continuous tuning, a multimode QCL with a frequency selecting Fabry–Pérot interferometer has been developed.[36]

2.4 Mixer

HERO uses the most sensitive mixers available. SIS mixers[37–39] are utilized in the FPAs at the two lower frequency bands 486 to 756 GHz, and 756 to 1188 GHz. HERO's SIS mixers will have noise temperatures of 2 hf/k (h = Planck constant, f = frequency, and k = Boltzmann constant), which has been already achieved for HIFI/Herschel[15] for band 1. HEB[40–43] mixers make up the FPAs for the bands 1188 to 1782 GHz and 1782 to 2700 GHz. The HEBs will have noise temperatures below 4 hf/k. Currently, the upGREAT[14] Instrument on SOFIA demonstrated the best noise temperatures of 700K double sideband (DSB) at 1.9 THz, and HEBs are continuously improving, with a 780 K receiver noise temperature (all components included) measured at 2.7 THz.[44] An overview of mixer noise temperatures is given in Fig. 6.

HERO has eight FPA (four frequency bands with two polarizations each). Each FPA consists of 3×3 mixers in a square configuration. The SIS mixers that require a magnetic field have a footprint of 10×10 mm^2, and the HEBs 5×5 mm^2. Projected onto the sky, the arrays have $2 \times$ full width half maximum beam spacing, which is the closest spacing that can be achieved without considerable cross-talk between pixels and low antenna efficiency. A similar FPA with 4×4 pixels is shown in Fig. 7.

Eight mixers of each array are DSB balanced mixers. The balanced mixer design is adopted to reduce the LO power required and to enhance the stability by suppressing LO amplitude modulation noise.[42] One mixer in each FPA is a sideband separating (2SB) mixer to allow sideband calibration of the DSB mixers. Each junction can be individually DC biased for optimal operation.

The baseline IF range is 0.5 to 6.5 GHz (goal of 0.5 to 8.5 GHz) so that the IF covers at least 670 km/s at the highest frequency, sufficient for observations of the inner Milky Way and of nearby galaxies. This IF bandwidth is typically not a problem for SIS mixers but is challenging for HEBs. A priori, NbN HEBs will be used, because NbTiN HEB mixers have narrower IF bandwidth (3 GHz), NbN HEBs need more LO power but have wider IF bandwidth.
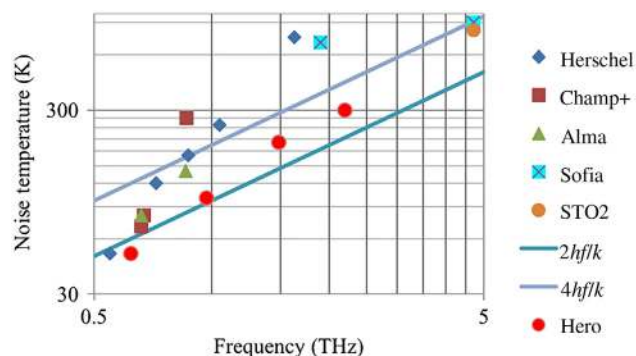
Fig. 6 DSB receiver noise temperature of different telescopes and the HERO goal. Below 1 THz the SIS mixers have nearly reached the requirement of 2 hf/k. HERO goal of 2 hf/k up to 1188GHz and 4 hf/k at higher frequencies. HEB mixers development is still required.
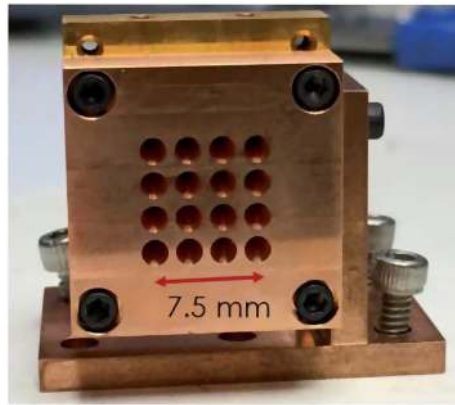
Fig. 7 A 16-element 1.9 THz mixer array with smooth-walled spline feed horns in a square grid configuration. The block, including circular-to-rectangular waveguide transitions and pockets to hold the hot-electron-bolometer mixers, was directly machined from copper.[45]

Recently, NbN HEB mixers on a GaN buffer-layer operating at ~1.3 THz with 7.5 GHz IF bandwidth have been demonstrated,[46] and efforts to increase the IF bandwidth are ongoing. An alternative are MgB_2 mixers[47] that have IF bandwidth of more than 8 GHz, however, they do not have the same sensitivity, yet (1400 K at 1600 THz), but progress is being made. The common Origins closed-cycle cryocoolers cool the mixers to about 4.5 K.

2.5 Intermediate Frequency and Backend

The IF signal at the output of the mixer is immediately amplified by ~20 dB by an LNA at 4.5 K physical temperature, then again by ~20 dB at a physical temperature of 35 K, and finally in the warm spacecraft bus. The first stage low-noise (<6 K), low-power SiGe cryogenic amplifiers[48–50] [Fig. 8(a)] are directly behind the mixer arrays and connected to the mixers by a short transmission line on a flexible Mylar bus.[52,53] Low power dissipation of the LNAs is essential to prevent the mixers from heating up and to minimize the cooling requirements. Bardin et al.[48] have recently demonstrated a state of the art SiGe amplifier integrated with a SIS mixer having an instantaneous bandwidth of 4 GHz and with power dissipation as low as 0.3 mW. An alternative are the mature InP High-Electron-Mobility Transistor (HEMT) amplifiers,[54] which have already been used on Herschel. Normally, InP amplifiers would require around 5-mW power per pixel, but tests operating at only 0.5 mW have shown only slightly higher noise temperatures.[55] If InP amplifiers operating with less than the nominal power are stable, they could serve as a backup alternative to SiGe.

Passive power combiners multiplex the IFs of different bands, such that the 2×9 pixels of any two frequency bands can be operated simultaneously. The multiplexing minimizes IF cables and back-ends, thus economizing on weight and thermal conduction. Coaxial cables carry 40 IF channels to the 35 K LNAs for further amplification, and then to the spacecraft bus. Miniaturized
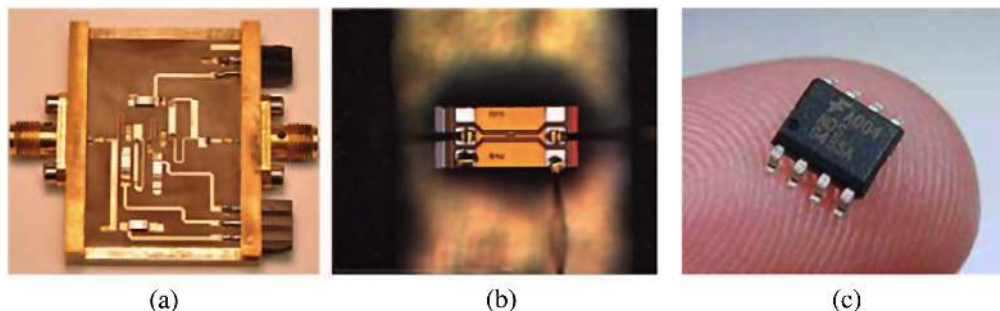
Fig. 8 (a) Low power SiGe cryogenic amplifiers.[50] (b) and (c) Extremely compact CMOS prototype amplifiers.[51]

integrated IF circuits[51] [Figs. 8(b) and 8(c)] further amplify, filter, and condition the signal for the backends.

HERO requires 40 low-power (∼1 W) spectrometers, each covering a bandwidth of 6 to 8 GHz. Complementary Metal Oxide Semiconductor (CMOS) Application-Specific Integrated Circuit (ASIC) backends as developed by Tang et al.[56,57] and others have very low power consumption, thousands of spectral channels and are rapidly advancing in bandwidth.[58,59] The spectrometers contain analog-to-digital converters, FFT processors, and data accumulators. They digitize to 3- or 4-bit resolution, sufficient for our application. Alternatively, HERO could use backends based on field-programmable gate array (FPGA) technology.[60,61] They show excellent performance, but their power consumption has to be lowered from currently around 70 W to about 2 W per spectrometer to be usable in HERO.

To increase the frequency resolution and minimize spectral leakage, HERO will use window functions in the spectrometer such as Blackman–Harris windows that reduce the side lobes to below −61 dB. The HERO spectrometer will take full advantage of prior experiments and knowledge, described e.g., by Klein et al.[62]

2.6 Control Electronics

There are three different control units, one for each subsystem to make testing before integration easier. The LO control unit monitors and controls the synthesizer and the LO Unit with the amplifier multiplier chains. The focal plane control unit monitors and controls all the components mounted at 4.5 K, in particular, the mixer bias, the amplifier bias, and the Offner relay mirror that is used to select between the different frequency bands. It also monitors and regulates the temperature of the calibration loads. The instrument control unit (ICU) monitors and controls the IF and the spectrometers. This unit also reads the data from the spectrometers and compresses it before passing it to the Origins bus computer for downlinking. The ICU is the interface between the Origins bus computer and the other control units of the HERO instrument.

The control units use state of the art onboard processors such as the GR740 rad-hard quad-core LEON4FT. They use spacewire as an interface between the units and MIL1553STDB as an interface to the spacecraft. All control units are mounted on the spacecraft bus in pairs, one operating unit and one redundant spare that is normally not operating.

3 Thermal and Mechanical Design and Mechanisms

3.1 Thermal Design

The thermal design contains on one hand requirements for the instrument to operate correctly and on the other hand the requirement that the instrument's heat load on the satellite should be minimized. The HERO front-end is located in the CPM at 4.5 K, the LOs, back-end, and the control units in the warm (∼300 K) spacecraft bus. The CPM is cooled by four cryocoolers, which can each lift 50 mW of heat, i.e., there is only 200 mW cooling power available in the CPM for all instruments, mechanical structures, and thermal radiation.

The only components that require cryogenic temperatures for operation are the superconducting mixers. They only work below ∼6 K and have slightly better performance at lower temperatures. The mixer mounts have brass straps to two of the cold fingers of the ISM and hence are cooled to ∼4.5 K. A Mylar cable bus separates the mixers from the LNAs, which have significant heat dissipation of around 0.5 mW/amplifier. The second components that need to be cooled are the LNAs, which add less noise to the signal when cold. There is no strict temperature limit, so we have compromised between instrument performance and cooling demands on the satellite. The outcome is that the first stage LNAs with 20 dB gain are on the CPM at slightly above 4.5 K, the second stage with another 20 dB gain at 35 K, and the third stage with 60 dB gain in the warm spacecraft bus. The emissivity of reflective optics elements at submillimeter wavelengths is small (5%, see Table 2), and since the noise temperatures are 50 to 300 K, the temperature of the optics has only a small impact on the system noise temperatures.

The second design criterion is to keep the cooling demands of the satellite low. On the 4.5 K stage, the LNAs are the most important heat source. We have selected SiGe amplifiers,[48] which

can operate at around 0.3 mW for 20 dB gain, as opposed to InP LNAs[53] as used in HIFI/ Herschel, which had 5 mW power dissipation. All amplifiers not in use are turned off.

The passive heat load on the 4.5 K stage comes from three major sources: the warm calibration load, the two holes through which the LO beams pass, and the cable harness. We carefully designed a thermally suspended calibration load with a shutter that can be closed when HERO is not in operation. We minimized the IR radiation through the LO beam by adding five heat sunk bandpass filters that block all IR radiation except that in the observing range of HERO. The filters reduce the heat load to 2.4 mW per beam, i.e., 4.8 mW in total. In addition, the LO beams have a shutter that is closed when HERO is not in operation to minimize stray light to the other instruments. In the cable harness, the coaxial IF cables conduct the most heat. We have designed a passive multiplexing system on the 4.5 K stage so that only 40 IF signals for the $2 \times 2 \times (9 + 1)$ beams are carried back to the spacecraft bus (+1 because one mixer in each FPA is sideband separating and has a second IF signal). The cable harness is heat sunk on the 35 K stage.

The thermal design on the spacecraft bus is less critical, because the operating temperature range is larger between ∼200 K and 320 K, and heat can be removed by radiators. Nevertheless, we strive to use components with low power consumption, in particular spectrometers requiring only 2 W of power each, and efficient LO frequency multiplier chains. Alltogether HERO requires 205 W of power.

3.2 Mechanical Design

Figure 9 shows a computer-aided design (CAD) drawing of HERO with the mechanical components in gray, brown, and green, and the ray trace in blue. The Offner relay and the cold receiver optics including the cold LO optics fit in an envelope of $1.05 \times 1.47 \times 0.4$ m^3. The warm LO optics requires $1.37 \times 0.8 \times 0.21$ m^3. Given the large space of the CPM under the 5.9 m primary mirror HERO fits comfortably between the other instruments as can be seen in Fig. 10.
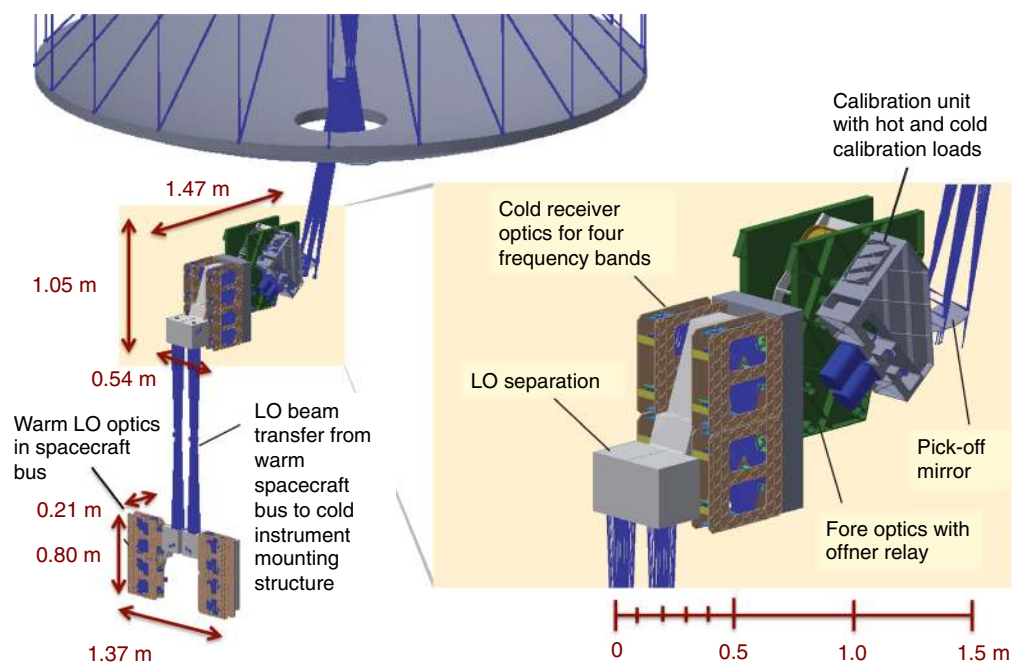
Fig. 9 CAD drawing of HERO with ray trace in blue. The Offner relay, the cold receiver optics, and the LO separation optics are at 4.5 K and are in the CPM below the primary mirror in the upper part of the figure on the left and in the enlarged drawing on the right. To minimize the cryogenic heat load, the LO signals are generated in the spacecraft bus. The warm LO optics (lower part of figure) superimpose the 8 LO signals onto two beams and transfer them from the warm spacecraft bus the cold CPM.
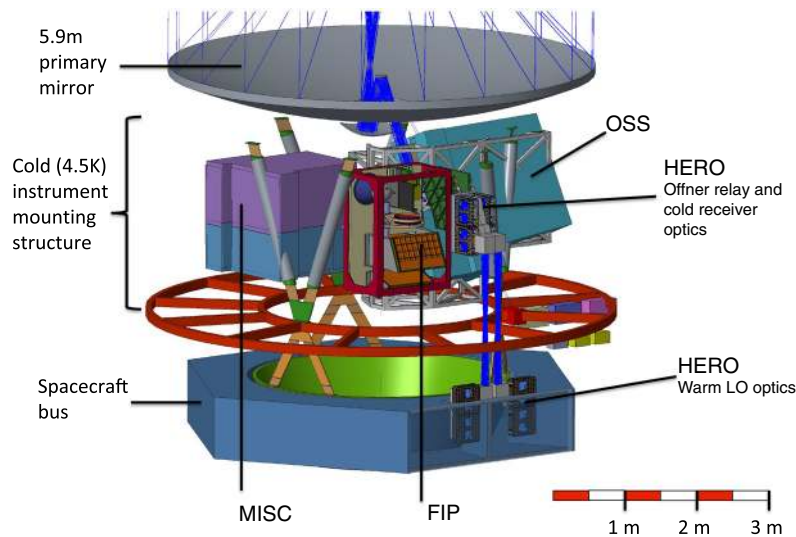
Fig. 10 HERO fits comfortably into the spacecraft between the other three instruments, MISC, FIP, and OSS.

Despite using lightweight mechanical structures, HERO still weighs ∼180 kg. The mirrors for the LO relay and their support structure are the biggest contributors weighing 40 kg.

3.3 Mechanisms

HERO has only four mechanisms (Table 3). The Offner Relay[63–66] directs the sky beam to the respective frequency array with the help of a band selection mirror (see Fig. 4, insert 1) that has two axis of rotation. The tip-tilt mirror (Fig. 4, insert 3) on the warm side of the LO relay compensates for any mechanical displacement between the warm spacecraft bus and the focal plane. Finally, the calibration load shutter and the LO door [location of LO door see Fig. 3, for the design see light tight shutter design for SPace Infrared telescope for Cosmology and Astrophysics (SPICA)[67]] can be closed when HERO is not in use to minimize heat transfer and to ensure a dark environment for the other instruments. All mechanisms are based on prior designs and are hence relatively low-risk.

3.4 HERO Tests, Integration, Alignment, and Calibration

The Herschel/HIFI testing, integration, alignment, and calibration procedures (see PhD thesis by Jellema[68]) will be used for HERO. The HERO instrument team tests, calibrates, and

Table 3 HERO uses two proven mechanisms and two shutters.

Mechanism	Function	Accuracy	Heritage
Offner relay	Select frequency band, calibration load	1'30" accuracy, 15 deg range	Herschel/SPIRE[63]
Tip-tilt for LO	Mirror allowing to adjust Lo beam for mechanical drift between the space craft bus and the cold instrument unit	1" accuracy	Herschel/HIFI (focal plane chopper[64])
Calibration load shutter	Cover calibration load to minimize heat load	1 mm at 50-mm base rotational cover	Herschel/HIFI
LO door/shutter	Close optical connection between LO units in warm spacecraft bus and cold telescope	1 mm at 50-mm base rotational cover	Herschel/HIFI

Table 4 The HERO instrument summary.

HERO	Current best estimate
Mass	183 kg
Volume	1.28 m^3
Power	205 W
Heat dissipation[a] at 4.5 K	20 mW
Heat dissipation[a] at 35 K	40 mW
Date rate	5.1 kbit/s
TRL in 2020	$\geq$4
TRL in 2027	$\geq$6

[a]These numbers do not take the passive heat transfer through cables or mounting structures into account.

internally aligns the instrument in existing cryostats prior to delivery. Origins is designed such that each instrument can be removed separately for maintenance and upgrades. Consequently, the National Aeronautics and Space Administration (NASA) team can integrate the instruments in any order.

The usual procedures are used to calibrate HERO in flight: HERO has two internal calibration loads to calibrate the receiver response, one of the mixers in each array is sideband separating to allow a calibration of the sideband ratio of the DSB mixers, and calibration on astronomical continuum sources (such as planets) are used to obtain a bandpass and allow the determination of the optical coupling/ aperture efficiency. Observations of point sources are used to determine the main beam efficiency.

HERO has two calibration loads, a hot load at a few tens of K and a cold load at 4.5 K. The loads are made of stycast or a similar material that looks like a black body at THz frequencies. The loads are cone shaped to have many internal reflections and to avoid any backscattering into the receiver. To minimize any heating of the CPM, the loads have infrared filters. The filters are mounted at an angle to avoid reflection and standing waves. The loads also have a shutter that will be closed when HERO is not in operation.

3.5 Resource Requirements

Table 4 summarizes the resources required by HERO.

4 Performance

The HERO has near quantum-limited performance and has unrivaled sensitivity over a very large frequency range (see Fig. 11). It consists of small mixer arrays, observes in both polarizations simultaneously and allows dual-frequency observations. It uses very little power per pixel and is the first heterodyne array receiver designed for space. The size of the HERO FPAs are well matched to prestellar cores thus requiring generally only a single pointing. For point source observations, HERO is 5 to 20 times more sensitive than Herschel/HIFI, i.e., can observe a factor of 25 to 400 times faster. This is partly due to the large collecting area of the Origins 5.9-m primary mirror (versus 3.5 m for Herschel) and partly due to improved sensitivity especially of the HEB mixers (e.g., at 1.9 THz HERO has 300 K receiver temperature versus 1100 K for HIFI). We used an aperture efficiency of 0.8 for Origins, versus 0.65 for Herschel. When mapping extended sources convolved to the same beam size, HERO is 10 to 30 times more sensitive, i.e., 100 to 900 times faster than HIFI/Herschel. HERO can map so much faster because it has 9-pixel arrays, can do dual-frequency observations and has more sensitive mixers, especially at the high frequencies. Being on a satellite, the full FIR spectrum will be available to HERO,
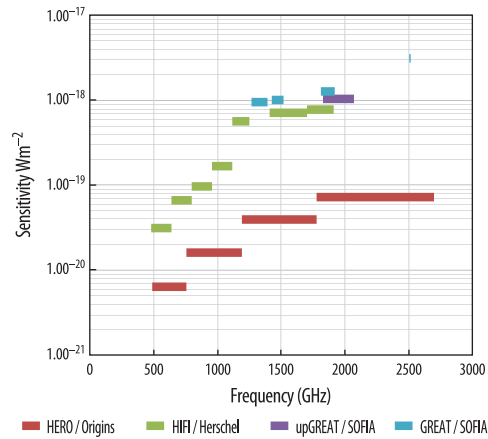
Fig. 11 HERO is more sensitive by an order of magnitude than any prior heterodyne instrument and has the widest frequency coverage of any instrument. It is worth noting that the sensitivity calculations for SOFIA assume a perfectly transparent atmosphere, which is not true close to the water lines.

whereas ground based telescopes and even SOFIA operate behind a more or less opaque curtain produced by atmospheric absorption.

5 Technology Roadmap

HERO builds on the current state-of-the-art receivers but surpasses them in different aspects of performance. For the current design, the latest and most promising Research and Development (R&D) results have been taken into account.

Table 5 gives an overview of prior missions, the HERO design and the technical readiness level (TRL) of the HERO components. Concerning the LO, multiplier amplifier chains have been used for HIFI/Herschel, however, the HERO LOs need to have wider relative bandwidth, higher efficiency to pump nine mixers and need to reach 2.7 THz versus 1.9 THz for HIFI; we hence consider that this proven technology has TRL 5. SIS, and HEB mixers have flown on HIFI/Herschel. HERO will have arrays of mixers, however these are essentially closely packed individual mixers, so no difficulty is expected. HERO will have more sensitive mixers, in particular more sensitive HEB mixers than HIFI/Herschel. More sensitive mixers are already used in up-GREAT on SOFIA, though some improvement is still needed for HERO. Up-GREAT has already demonstrated mixers in waveguide up to 4.7 THz, so this technology can be used for HERO up to 2.7 THz. Herschel has used InP LNAs, but Stratospheric TeraHertz Observatory (STO)[69] and GREAT have used SiGe; both worked well. For HERO we need the SiGe LNAs but with lower power consumption and space qualified (TRL 4). All missions have so far flown digital FFTs. CMOS-based system on chip (SOC) have been characterized and tested in the laboratory and have the required bandwidth and power, but they still need to be space qualified (TRL 5).

Table 6 lists the risks and mitigations that could be taken if these goals are not all met. In summary, HERO is a very low risk mission. In the design, we pushed current technologies further and used come innovative components. However, if any of these components should not be ready, there is always the HIFI/Herschel technology to fall back on. This would allow us to either built HERO with less pixels, or to build the HERO described here but with higher cooling power, electrical power, and mass budgets.

It is essential to carry out R&D work on components to ensure the HERO mission, we envisage. Figure 12 summarizes the technology roadmap for HERO.

6 EHT Extension

The concept of using the Origins Space Telescope (Origins) to study black hole physics on event horizon scales has recently been raised as a potential extension of the HERO science case.[70]

Table 5 Current state-of-the-art and HERO requirements.

Sub-system	Component	HIFI on Herschel	STO-2	GREAT/ 4GREAT/ upGREAT on SOFIA	HERO on Origins	TRL HERO
LO	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 (TRL = 5) + GaN. amps	5
	Multiplied LO technology	Cascaded GaAs frequency multipliers		Multipliers/ QCL for 4.7 THz	Cascaded multipliers (TRL = 7) + on-chip power combining (TRL = 4) + 3D integ. (TRL = 5)	
	Number of pixels per array	1	2	7	9	
	DC power/pixel	25 W	20 W	AMC: 14W QCL: 71 W	~1.5 W	
	Fractional Bandwidth	~12%	~1%	10%–33%	~45%	
Cryogenic detectors	Mixer technology	SIS, HEB	HEB	SIS, NbN HEB	SIS, HEB	9
	SIS sensitivity	$2-6\ hf/k$	—	$2-6\ hf/k$	$2\ hf/k$	5
	HEB sensitivity	$13-18\ hf/k$	$3{,}5\ hf/k$ lab only	$4-10\ hf/k$	$4\ hf/k$	4
	Mixer. assembly	Quasi-optical (QO)	QO	Waveguide	Waveguide	8
	Number of pixels	1	2	2×7	2×9	7
	LNA Technology	InP HEMT	SiGe HBT (heterojunction bipolar transistors)	SiGe, InP	Low-power SiGe HBT	4
	DC power/pixel	10 mW	4 mW	5 mW	0.5 mW	
Backend	IF processing	GaAs HEMT amplifiers				
	Spectrometer tech.	FFT FPG	FFT	FFT	CMOS-based SoC	9
	DC power/pixel	10 W	10 W	35 W	2 W	5
	IF bandwidth	1.5 GHz	1.5 GHz	0.2–4 GHz	6 GHz, goal 8 GHz	5
Total DC power per pixel		35 W	35 W	49–106 W	3.5 W	5

Table 6 Development goals, risks and mitigations. HERO is a very low risk instrument as it is based on a long heritage of successful heterodyne instrument and R&D development. Should some of the developments not reach the goals, there are always safe fallback options that still allow for a powerful though degraded instrument.

Item	Goal	Risk	Mitigation	Consequence
LO	45% fractional bandwidth with 10 micro W/pixel and 0.5 W/pixel	Band width (BW) not obtained with sufficient output power	(i) More power input or (ii) More LO bands	More satellite resources required: (i) power (ii) weight and power
			Two kinds of LOs will be developed. QCLs have more output power	For QCL need frequency selection, PLL and extra cooler → more engineering effort
Mixers	2-3 hf/k with 6 (goal 8) GHz BW	(i) Sensitivity not reached	Two mixer types are developed SIS and HEB, the better can be used	Longer observing time
		(ii) BW not reached for HEB mixers	Use SIS mixers as much as possible	For very wide lines use two spectra, which requires very careful calibration
	Compact arrays	Less compact	Use individual mixers	Slightly more volume required
Spectrometers	6 (goal 8) GHz BW, at 1 W/pixel, 8196 channels	SOC ASIC not radiation hard	Put in radiation shielding box	Equipment heavier
		Stability or BW selection cannot be reached	There are two spectrometers types developed: Autocorrelators can reach these specs	Autocorrelators are likely to be heavier and consume more power, might need to have less backends, in worst case no dual-frequency observations → increase in observing time in the same cases
Low noise amplifiers	2K noise, 6 (goal 8) GHz BW, 0.5 mW power dissipation	Lower BW and low power dissipation cannot be obtained at the same time	Two kinds of LNAs are developed: (i) SiGe, which have low power dissipation, but currently not the bandwidth (ii) InP have BW but at higher power	Use InP LNAs, require more cooling or reduce backends, in worst case no dual-frequency observations → increase in observing time in some cases
Optics	Wide bandwidth and excellent performance	Performance degrades over BW	(i) Increase number of frequency bands (ii) Slightly less sensitive receivers	(i) Increase in mass and volume of Rx (ii) Slightly longer observing time

		2019	2020	2021	2022	2023	2024	2025	2026	2027
								TRL 5	EM	TRL 6
Optics	Lenslet arrays, filters, calib source, etc				Develop broadband design →		Envir./qual. testing →			
Mixers	SIS and hot electron bolometer	Single pixel with required sensitivity and frequency coverage, search for materials for high freq. SIS →		Single pixel with sensitivity and IF BW	Array proof of concept, balanced mixers	Envir. test	Qual. test	Characterization in relevant environment	Subsystem level integration	System level testing
Local Oscillator	Schottky multipliers	Single pixel with fractional BW →			Array proof of concept					
	QCL		Powerful and efficient source, large and continuous coverage, high operating temp →		Development of mode selection optics, PLL, beam divider	Efficient and long distance (few m) LO and mxier coupling scheme	Down select. envir./qual. testing			
	Parametric multipliers		Single pixel with output power	Single pixel with BW	Array proof of concept					
IF	LNAs				Low noise, wideband and low DC power →		Down select. envir./qual. testing			
Backends	SoC ASIC		Bandwidth, DC power, calibration →			Envir./qual. testing and down selection →				
	Autocorrelators		Bandwidth, DC power →							

Fig. 12 The development schedule ensures a low-risk technology development roadmap for HERO.

Preliminary science concept exploration shows much promise and merits further study. The unprecedented angular resolution resulting from the combination of Origins with existing ground-based submillimeter/millimeter telescope arrays would increase the number of spatially resolvable black holes by a factor of 10^6, permit the study of these black holes across all cosmic history, and enable new tests of general relativity by unveiling the photon ring substructure in the nearest black holes. Expanding the HERO instrument to be an interferometric station will require adding broadband single pixel receivers at 86, 230, 345, and 690 GHz, a very accurate time reference, fast on-board data processing, and a fast downlink. A top-level examination of these requirements has not revealed any insurmountable obstacles to achieving this goal.

7 Conclusion

The HERO is the first heterodyne FPA designed for space. It builds on the solid foundations of prior heterodyne receivers and in particular on the successful Herschel/HIFI instrument. HERO incorporates the latest mixer developments to reach unprecedented sensitivity. Using innovative components and a compact design, HERO demands only relatively modest resources of the satellite. HERO also surpasses any prior instrument in terms of wavelength coverage and observing efficiency; it allows dual polarization and simultaneous dual-frequency observations with four 9-pixel arrays. HERO will help to map the trail of water from the ISM to habitable worlds. With its unique capacities HERO opens a new window onto the physics and chemistry of the ISM and invites observers to explore the still largely unknown FIR Universe.

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References

1. M. Meixner and A. Cooray, "Origins Space Telescope," https://asd.gsfc.nasa.gov/firs/ (2020).
2. M. Meixner and A. Cooray, "Origins Space Telescope," https://origins.ipac.caltech.edu/.
3. C. Battersby et al. "The Origins Space Telescope," *Nat. Astron.* **2**, 596–599 (2018).
4. D. Leisawitz et al., "The Origins Space Telescope: baseline mission concept," *J. Astron. Telesc. Instrum. Syst.* **7**(1), 011002 (2021).
5. C. M. Bradford et al., "The Origins Survey Spectrometer (OSS): revealing the hearts of distant galaxies and forming planetary systems with far-IR spectroscopy," *J. Astron. Telesc. Instrum. Syst.* **7**(1) (2021).
6. J. Staguhn et al., "The Origins far-infrared imager and polarimeter (FIP)," *J. Astron. Telesc. Instrum. Syst.* **7**(1) (2021).
7. I. Sakon et al., "The Origins mid-infrared spectrometer camera (MISC) baseline and upscope," *J. Astron. Telesc. Instrum. Syst.* **7**(1) (2021).
8. E. F. van Dishoeck, E. Herbst, and D. A. Neufeld, "Interstellar water chemistry: from laboratory to observations," *Chem. Rev.* **113**(12), 9043–9085 (2013).
9. E. A. Bergin and E. F. van Dishoeck "Water in star- and planet-forming regions," *Philos. Trans. R. Soc. A* (**370**), 2778–2802 (2012).
10. E. A. Bergin et al., "An old disk still capable of forming a planetary system," *Nature* **493**, 644–646 (2013).
11. S. Schiller et al., "Ultra-narrow-linewidth continuous-wave THz sources based on multiplier chains," *Appl. Phys. B* **95**(1), 55 (2009).
12. "ALMA," http://www.almaobservatory.org/en/home/.
13. R. Guesten et al., "Performance and science opportunities with the upGREAT spectrometer onboard of SOFIA," *EAS Publ. Ser.* **75–76**, 427–432 (2015).
14. C. Risacher et al., "The upGREAT 1.9 THz multi-pixel high resolution spectrometer for the SOFIA observatory," *Aatron. Astrophys.* **595**, A34 (2016).
15. T. de Graauw et al., "The Herschel-heterodyne instrument for the far-infrared (HIFI)," *Astron. Astrphys.* **518**, L6 –L12 (2010).
16. U. Graf et al., "Terahertz heterodyne array receivers for astronomy," *J. Infrared, Millimeter, Terahertz Waves* **36**(10), 896–921 (2015).
17. P. Goldsmith, "Sub-Millimeter heterodyne focal-plane arrays for high-resolution astronomical spectroscopy," *Radio Sci. Bull.* **362**, 53 (2017).
18. C. Groppi et al. "Test and integration results from SuperCam: a 64-pixel array receiver for the 350 GHz atmospheric window," *Proc. SPIE* **7741**, 77410X (2010).
19. C. E. Groppi et al., "The kilopixel array pathfinder project (KAPPa), a 16 pixel integrated heterodyne focal plane array," *Proc. SPIE* **8452**, 84520Y (2012).
20. U. Graf, "Heterodyne array receiver development at Kosma," in *Atacama Large-Aperture Submm/mm Telescope (AtLAST), held 17-19 January, 2018 at ESO-HQ*, Garching b. München, p. 9 (2018). http://www.eso.org/sci/meetings/2018/AtLAST2018.html, id.9 DOI: 10.5281/zenodo.1158854.
21. M. C. Wiedner et al., "Proposed heterodyne receiver for the Origins Space Telescope," *IEEE Trans. Terahertz Sci. Technol.* **8**(6), 558–571 (2019).
22. C. Groppi et al., "A broadband finline ortho-mode transducer for terahertz applications," in *Proc. ISSTT*, pp. 314–320 (2004). https://www.nrao.edu/meetings/isstt/proceed/2004-Proceedings.pdf.
23. F. Defrance, "Instrumentation of a 2.6 THz heterodyne receiver," PhD, https://tel.archives-ouvertes.fr/tel-01314133 (2015).

24. K. Jacob, M. Kotiranta, and A. Murk, "Transmission and reflection characterization of polarizing beam splitters at submillimeter wavelengths," *IEEE Trans. Terahertz Sci. Technol.* **9**(3), 272–281 (2019).

25. P. Munoz, "Waveguide heterodyne mixers at THz-frequencies—superconducting hot electron bolometers on 2 micron Si_3N_4 membranes for GREAT and CONDOR," Ph.D. thesis, Universitaet zu Koeln (2006).

26. G. Humbert, "Optical fibers in terahertz domain," in *Handbook of Optical Fibers*, G. D. Peng, Ed., Springer, Singapore (2019).

27. I. Mehdi et al., "THz diode technology: status, prospects, and applications," in *Proc. IEEE* **105**(6), 990–1007 (2017).

28. T. W. Crowe et al., "Higher power terahertz sources based on diode multipliers," in *42nd Int. Conf. Infrared, Millimeter, and Terahertz Waves*, Cancun, pp. 1–1 (2017).

29. https://www.vadiodes.com/en/frequency-multipliers.

30. H.-W. Huebers et al., "High resolution terahertz spectroscopy with quantum cascade lasers," *J. Infrared, Millimeter, and Terahertz Waves* **34**(5–6), 325–341 (2013).

31. B. Mirzaei, "Quantum cascade lasers as super terahertz local oscillators for astronomy," Ph.D. dissertation, TU Delft, Delft, The Netherlands (2018). https://repository.tudelft.nl/islandora/object/uuid:cce70e43-8730-45e2-b645-2f8c0884b9b4?collection=research.

32. B. S. Williams et al., "Terahertz quantum-cascade metasurface VECSELs," *Proc. SPIE* **10123**, 1012311 (2017).

33. N. van Marrewijk et al., "Frequency locking and monitoring based on bi-directional terahertz radiation of a 3rd-order distributed feedback quantum cascade laser," *J. Infrared, Millimeter, and Terahertz Waves* **36**(12), 1210–1220 (2015).

34. Huebers, private communication.

35. H.-W. Hübers et al., "Compact and efficient 4.7-THz local oscillator with a GaAs/AlAs quantum-cascade laser," in *29th IEEE Int. Symp. Space Terahertz Technol.* (2018).

36. D. Wirtz, G. Sonnabend, and R. Schieder, "THIS: a tuneable heterodyne infrared spectrometer," *Spectrochim. Acta Part A: Mol. Biomol. Spectrosc.* **58**(11), 2457–2463 (2002).

37. A. R. Kerr et al, "The genesis of SIS mixers—the legacy of John Tucker in radioastronomy," in *IEEE MTT-S Int. Microwave Symp.*, Phoenix, Arizona (2015).

38. A. Hedden et al., "Upgrading the SMA 600 GHz receivers," in *Proc. ISSTT*, pp. 428–432 (2010).

39. A. M. Baryshev et al., "The ALMA band 9 receiver—design, construction, characterization, and first light," *Astron. Astrophys.* **577**, A129 (2015).

40. K. Zhou et al., "Noise temperature and IF bandwidth of a 1.4 THz superconducting HEB mixer," in *Proc. URSI Asia-Pac. Radio Sci. Conf.*, pp. 2010–2012 (2016).

41. M. Hajenius et al., "Optimized sensitivity of NbN hot electron bolometer mixers by annealing," *IEEE Trans. Appl. Supercond.* **17**(2), 399–402 (2007).

42. D. Meledin et al, "A 1.3-THz balanced waveguide HEB mixer for the APEX telescope," *IEEE Trans. Microwave Theory Tech.* **57**(1), 89–98 (2009)

43. J. Kawamura et al., "1.9 THz 4-pixel heterodyne array receiver," in *27th Int. Symp. Space Terahertz Technol.*, Nanjing (2016).

44. Y. Delorme et al., "A quasi-optical NbN HEB mixer with 800 K DSB noise temperature at 2.5 THz," in *ISSTT Proc.* (*2011*). https://www.nrao.edu/meetings/isstt/2011.shtml.

45. J. Kawamura et al., "Development of a16 pixel monolithic 1.9 THz waveguide superconducting hot-electron bolometer mixer," in *ISSTT Conf.*, Cpologne (2017).

46. S. Krause et al., "Noise and IF gain bandwidth of a balanced waveguide NbN/GaN hot electron bolometer mixer operating at 1.3 THz," *IEEE Trans. Terahertz Sci. Technol.* **8**(3), 365–371 (2018).

47. E. Novoselov and S. Cherednichenko, "Low noise terahertz MgB_2 hot-electron bolometer mixers with an 11 GHz bandwidth," *Appl. Phys. Lett.* **110**(3), 032601 (2017)

48. J. C. Bardin, S. Montazeri, and S.-W. Chang, "Silicon germanium cryogenic low noise amplifiers," *J. Phys.: Conf. Ser Conf. Series* **834**, 012007 (2017).

49. S. Montazeri et al., "A wide-band high-gain compact SIS receiver utilizing a 300 μW SiGe IF LNA," *IEEE Trans. Appl. Supercond.* **27**(4), 1500605 (2017).

50. S. Montazeri et al., "Ultra-low-power cryogenic SiGe low-noise amplifiers: theory and demonstration," *IEEE Trans. Microwave Theory Tech.* **64**(1), 178–187 (2016).

51. E. Zailer, L. Belostotski, and R. Plume, "8-GHz, 6.6-mW LC-VCO with small die area and FOM of 204 dBc/Hz at 1-MHz Offset," *IEEE Microwave Wireless Comp. Lett.* **26**(11), 936–938 (2016).

52. A. I. Harris et al., "Cryogenic microstripline-on-Kapton microwave interconnects," *Rev. Sci. Instrum.* **83**, 086105 (2012).

53. P. McGarey et al., "A 16-channel flex circuit for cryogenic microwave signal transmission," *Proc. SPIE* **9153**, 91532F (2014)

54. I. Lopez-Fernandez et al., "Wideband ultra-low noise cryogenic InP IF amplifiers for the Herschel mission radiometers," *Proc. SPIE* **4855**, 489–500 (2003).

55. Schleeh, private communication.

56. A. Tang et al., "DDFS and $\Sigma\Delta$ approaches for fractional frequency synthesis in terahertz instruments," in *IEEE Trans. Terahertz Sci. Technol.* **8**(4), 410–417 (2018).

57. A. Tang et al., "A 177–205 GHz 249 mW CMOS-based integer-N frequency synthesizer module for planetary exploration," *IEEE Trans. Terahertz Sci. Technol.* **8**(2), 251–254 (2018).

58. Y. Zhang et al., "A 2.6 GS/s spectrometer system in 65 nm CMOS for spaceborne telescopic sensing," in *IEEE Int. Symp. Circuits and Syst.*, Florence, pp. 1–4 (2018).

59. Y. Kim et al., "A 1.5W 3 GHz back-end processor in 65 m CMOS for sub-millimeter-wave heterodyne receiver arrays," in *Int. Symp. Space Terahertz Technol.* (2018).

60. B. Klein et al., "High-resolution wide-band fast-Fourier transform spectrometers," *Astron. Astrophys.* **542**, L3 (2012).

61. http://www.omnisys.se/product/fft-spectrometer/.

62. B. Klein et al., "A new generation of spectrometers for radio astronomy: fast Fourier transform spectrometer," *Proc. SPIE* **6275**, 627511 (2006).

63. I. Pain et al., "SPIRE beam steering mirror: a cryogenic 2 axis mechanism for the Herschel Space Observatory," *Proc. SPIE* **4850**, 619–627 (2003).

64. R. Huisman et al., "Cryogenic mechatronic design of the HIFI focal plane chopper," *J. Mechatron.* **21**(8), 1259–1271 (2011).

65. S. Paalvast et al., "Development and characterization of a 2D precision cryogenic chopper for METIS," *Proc. SPIE* **9151**, 91510D (2014).

66. R. Huisman et al., "High-performance motion control of the METIS cold chopper mechanism," *IEEE/ASME Trans. Mechatron.* **21**(5) (2016)

67. M. Eigenmann et al., "Conceptual phase A design of a cryogenic shutter mechanism for the SAFARI flight instrument," *Proc. SPIE* **8450**, 84504G (2012).

68. W. Jellema, "Optical design and performance verification of Herschel-HIFI," Ph.D. University of Groningen, https://www.rug.nl/research/portal/en/publications/optical-design-and-performance-verification-of-herschelhifi%2824e22068-b3ba-45d9-b72b-503e951b193f%29.html (2015).

69. C. Walker et al., "The stratospheric THz observatory (STO)," *Proc. SPIE* **7733**, 77330N (2010).

70. D. W. Pesce et al., "Extremely long-baseline interferometry with the Origins Space Telescope," Astro 2020 APC White Paper, astro-ph, asXiv:1909.01408.

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