The Origins Space Telescope and the HEterodyne Receiver for Origins (HERO)

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Abstract—**The Origins Space Telescope is one of four large mission concept studies carried out by NASA for the 2020 Decadal survey. Origins is a far-infrared telescope designed to understand the evolution of galaxies and black holes, to follow the trail of water from protostars to habitable planets and to search for biosignatures in the atmospheres of exoplanets. The Heterodyne Receiver for Origins (HERO) is the high spectral resolution receiver. It is the first heterodyne array receiver designed to fly on a satellite and an example for possible future focal plane arrays for space. HERO has focal plane arrays with nine pixels in two polarization. HERO covers a large frequency range between 486 and 2700 GHz in only 4 frequency bands, requiring local oscillators with fractional bandwidth of 45%. HERO uses the best superconducting mixers with noise temperatures between 1 and 3 hf/k and an intermediate bandwidth of 6 to 8 GHz. HERO can carry out dual polarization and dual-frequency observations. The major challenges for the HERO design are the low cooling power and the low electrical power available on a spacecraft, which impact the choice of the cryogenic amplifiers and backends. SiGe cryogenic amplifiers with a consumption of less than 0.5 mW, as well as CMOS spectrometers with a power consumption below 2W are the baseline for HERO. The development plan includes broadband (45%) multiplier-amplifier chains, low noise mixers (1-3 hf/k), low-power consuming (< 05.mW) cryogenic amplifiers and low-power consuming spectrometer backends (< 2W).**

Index Terms — **Astronomy, array receiver, terahertz, submillimeter, space technology**

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I. ORIGINS SPACE TELESCOPE

THE Origins Space Telescope [1][2] is one of four large mission studies NASA has carried out for submission to the 2020 Decadal Survey. Origins addresses three large questions: How does the universe work? How did we get here? and Are we alone? To answer these questions Origins observes the evolution of galaxies, the formation of dust and the feedback mechanisms of galaxies over cosmic time. Origins follows the trail of water from protostars, via planetary disks to debris disks, weighs disk masses and measures the D/H ratio of comets in order to understand how water, a prerequisite for life, arrives on planets. Last but not least Origins searches for markers of life by looking for biosignatures in temperate exoplanets with transparent atmospheres. All these observations require a very sensitive mid to far-infrared telescope in space. Origns has a 5.9 m antenna cooled to 4.5 K and has 3 principal instruments as well as 2 upscope instrument. The 3 principal instruments are 1) the Origins Spectral Surveyor (OSS) [3] that covers a wavelength range of 25 to 588 µm at resolving power of 300, 43000 or 325000; 2) the large field Far-infrared Imaging Polarimeter (FIP) [4] with a 50 and a 250 µm channel allowing polarimetry and 3) the Mid-Infrared Spectrometer Camera Transit (MISC-T) [5], an ultra-stable transit spectrometer for 2.8 to 20µm. The upscope options include the Heterodyne Receiver for Origins (HERO) described below and the Mid-Infrared Spectrometer Camera Imager (MISC-I)

[5] allowing spectral imaging in the mid-infrared between 5 and 28 µm.

II. HETERODYNE RECEIVER FOR ORIGINS (HERO)

A. Motivation

HERO complements the Origins instrument suit by providing extremely high spectral resolving power up to 10^7. The high resolving power enables line tomography where the observed spectra together with simple models allow us to deduce the distribution of gas at special scales much smaller than any telescope would allow.

HERO was designed for the trail of water science case. It has a moderate field of view with a footprint of 3x3 pixels and covers many water lines emitting between 586 and 2700 GHz. HERO can carry out dual-polarization and dual-frequency observations. The characteristics of HERO are given in Table 1.

TABLE 1
LITTLE-HERO DESIGN PARAMETERS (FOR OST CONCEPT 2)

Band	F_{min}	F_{max}	Pixel	Trx	Beam	T_{rms} [a]	Line Flux [b]
	GHz	GHz		K	"	mK	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

[a] Receiver noise for 1h integration at 10^6 resolution (0.3 km/s) using one polarization.

[b] Detectable line flux at 5 sigma, for 1h pointed integration (on+off source) in two polarizations, with a 5.9 m primary mirror as designed for OST Concept 2.

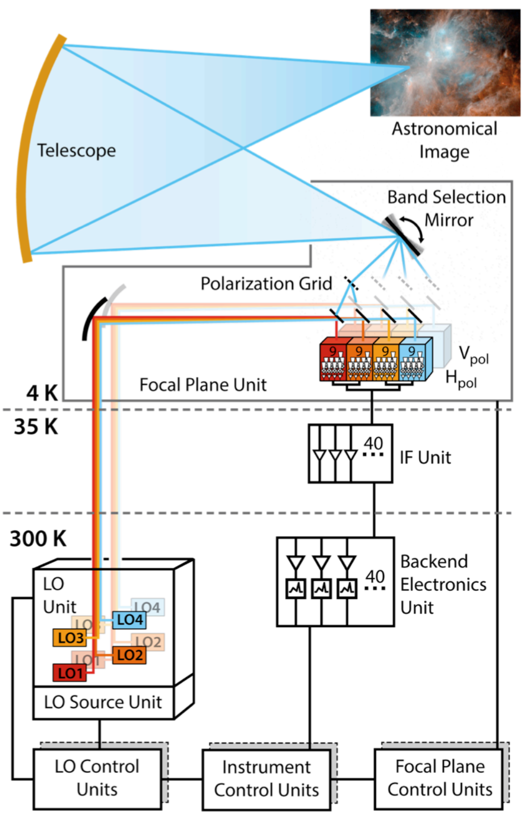

Figure 1: HERO instrument architecture closely follows architectures of successful heterodyne instruments like HIFI. Novel coupling optics and advances in component technologies allows for mapping speeds that are orders of magnitude faster than HIFI. (Image Credit: Britt Griswold, NASA.)

B. Instrument Design

The HERO design is shown in Figure 1.

The design follows the standard heterodyne layout, but is specifically adapted for space. In order to reduce the weight each frequency band is ~45% wide and HERO covers the entire frequency range of 586 to 27000 GHz in only 4 bands. HERO also uses low-power components, in particular the cryogenic low noise amplifiers only consume 0.5 mW, a tenth of those of Herschel, and the backends consume less then 2 W for 6 GHz to 8 THz bandwidth about 1/35th of the backends commonly in use. In spite of these savings the sensitivity is close to quantum limit and the intermediate frequency (IF) bandwidth is at least 6 GHz (goal 8 GHz). These substantial reductions of weight and power enable the design of the first heterodyne focal plane array for space application.

C. Components

Optics: A low loss and compact design with very high fractional bandwidth has been achieved for HERO. Figure 2 shows the cold optics.

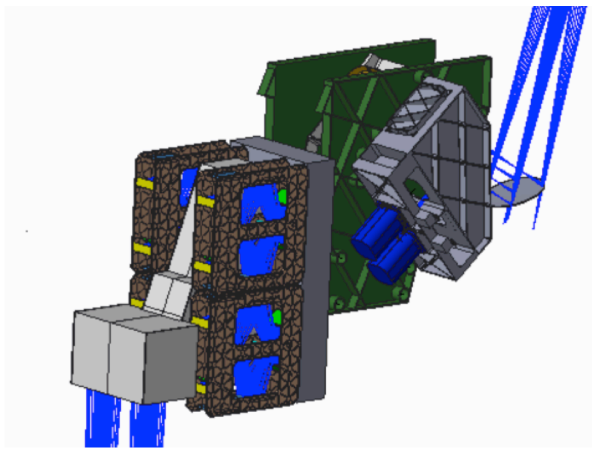

Figure 2: The compact design of the cold optics for HERO fits easily in the Origins space craft.

Radiation from the sky arrives from the top right. A pick-off mirror directs it to the HERO instrument. The Offner Relay (between the green plates) will direct either the light from the sky or from the internal calibration loads (blue cylinders on right) to one of the four bands. Within the bands the light from the sky / calibration loads will be split in polarization and superimposed with the local oscillator (LO) reference signal coming from the warm space craft (bottom left). After superposition of LO and sky with a wire grid, ellipsoidal mirrors refocus the beam and a lenslet array matches it to the mixer array.

To minimize infrared radiation coming from the space craft bus via the LO beam 1) the LO beams are superimposed and only two beams pass through the sun shields and 2) infrared bandpass filters are inserted in the beam blocking all radiation except at that of the LOs.

Local Oscillators: Local oscillators (LO) are a critical item, as they need to be tunable over a very wide frequency range, reach high frequencies (for HERO up to 2.7 THz), pump many pixels, and have low power consumption. Schottky diode-based frequency multiplier chains have made considerable progress recently [6][7] and are the baseline for the HERO design. 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. The LO signal is split in waveguide to 3x3 beams to match the focal plane mixer array. HERO has two LO chains for each frequency band, one for each polarization.

An alternative to the multiplier-amplifier chains are quantum cascade lasers. They have the advantage of having high output power, but require cooling and are more difficult to tune over a wide bandwidth. However, considerable progress has been made [8][11].

Mixers: HERO uses the most sensitive mixers: Superconducting Insolating Superconducting (SIS) mixers for the two lower frequency channels and Hot Electron Bolometer (HEB) mixers for the two upper frequency channels. SIS mixers have already reached a noise levels around 2 hf/k and intermediate frequency bandwidth of 8 GHz required for HERO. HEB mixers still have slightly higher noise and lower IF bandwidth, but rapid progress is made and bandwidth of 7.5 GHz have been reported [14], as well as noise temperatures of 3.3 hf/k [9].

The mixers employ horns that are followed by orthomode transducers to separate the LO from the sky signal, as suggested by Belitsky [12]. All mixers have two junctions and are balanced to reduce the LO power requirements and to enhance stability by suppressing LO AM noise [13]. 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.

Intermediate Frequency Chain: In order to be able to observe lines that are up to 500km/s wide, the HERO requires a bandwidth of at least 6 GHz with a goal of 8 GHz.

The weak IF signal from the mixers is first amplified directly behind the mixers, a second time at 35K and then before the spectrometers at around 300K. The cryogenic amplifiers are allocated only 0.5 mW while they need to be low noise (< 5K) and wideband (> 6 GHz). Currently, SiGe [15][16][17] amplifiers are the most promising candidates. They consume only 0.3mW albeit with only 4 GHz of bandwidth and further development is required.

An alternative are the well established InP amplifiers [18][19]. They are usually operated with 5mW power, but still show good performance at reduced power [20][21].

Backends: HERO requires 36 backends to allow dual polarization and dual frequency operation with 9 pixel focal plane arrays. The excellent Digital Fourier Transform Spectrometers (DFTS) commonly used in ground based telescopes consume around 70W, unfortunately too much for a space mission.

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 six GHz bandwidth, are extremely lightweight (<120 g), and require little power (< 1W) per backend [22][23].

An autocorrelation spectrometer (ACS) is another viable option, as it has been used already in space missions (ODIN) [24], balloon mission TELIS [25], and low power ASIC versions are becoming available. For HERO, it is essential that backend power consumption is reduced from about 40W to less than 2 W per 8 GHz IF.

Control Electronics:

HERO has three control 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 4K stage and 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. HERO flies two units of each control unit for redundancy.

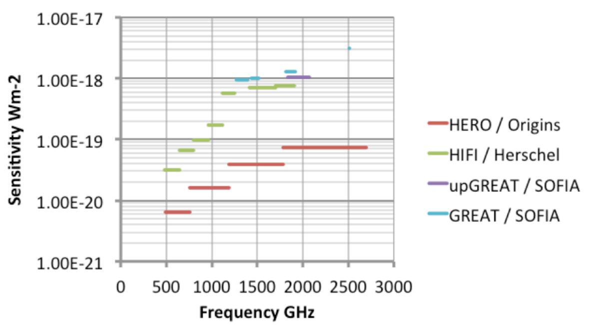

Figure 3: HERO is more than ten times as sensitive as the best current and past airborne heterodyne receivers. With its nine pixels, dual polarization and dual frequency modes HERO is also an efficient mapping instrument..

III. Enabling Technologies and Required Developments

The enabling technologies are the LOs, the mixers, the amplifiers and the spectrometers. The LOs need to be very broadband with a fractional bandwidth up to 45%, to allow covering a large frequency range with few bands, i.e. save weight. HERO requires near quantum limited mixers with less than 1 to 3 hf/k. SIS mixers already have noise temperatures around 2hf/k, but some development is needed to reduce the noise and increase the IF bandwidth of HEB misers. In order to be able to cool heterodyne arrays in space, we have only attributed 0.5 mW of power for each amplifier with about 25dB of gain. It is also critical to reduce the power consumption of the spectrometric backend to about 2W per 8 GHz. For HERO the components need to be Technology Readiness Level (TRL) 5 by 2025 and TRL 6 by 2027. Table 2 shows the technology development plan.

		2019	2020	2021	2022	2023	2024	2025	2026	2027
								TRL 5	EM	TRL 6
Optics	Lenslet arrays, filters, calib source, etc				Develop braodband design		Envirn/Qual testing	Characterization in relevant environment	Subsystem level integration	System level 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			
Local Oscillator	Schottky Multipliers	Single pixel with fractional BW			Array proof of concept	Efficient and long distance (few m) LO and mixer coupling scheme	Down select. Envirn/Qual testing			
	QCL		Powerful and efficient source, large and continuous coverage, high operating temp		Development of mode selection optics, PLL, beam divider					
	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. Envirn/Qual testing			
Backends	SoC ASIC		Bandwidth, DC power, calibration			Envir/Qual testing and Down selection				
	Autocorrelators		Bandwidth, DC power							

Table 2 Technology Development.

IV. Conclusion

Origins is a very powerful far-IR satellite concept that will revolutionize our understanding of the universe. With its 5.9 m cooled dish it is much more sensitive than any prior mission and will help us to understand the evolution of galaxies and the trail of water to planets, as well as search for biosignatures of exoplanets.

HERO is the first focal plane array designed for space. It is expected to have a performance that is more than ten times more sensitive than any current heterodyne receiver (Figure 3). HERO allows efficient mapping at high spectral resolution with its 9 pixel arrays, the dual polarization and the dual frequency modes.

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