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Heterodyne Receiver for the Origins Space Telescope Concept 2

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ABSTRACT

The Origins Space Telescope (OST) is a NASA study for a large satellite mission to be submitted to the 2020 Decadal Review. The proposed satellite has a fleet of instruments including the HEterodyne Receivers for OST (HERO). HERO is designed around the quest to follow the trail of water from the ISM to disks around protostars and planets. HERO will perform high-spectral resolution measurements with 2x9 pixel focal plane arrays at any frequency between 468GHz to 2,700GHz (617 to 111 µm). HERO builds on the successful Herschel/HIFI heritage, as well as recent technological innovations, allowing it to surpass any prior heterodyne instrument in terms of sensitivity and spectral coverage.

Keywords: heterodyne receivers, far-IR instrumentation, space mission, focal plane arrays, decadal survey

1. INTRODUCTION

The Origins Space Telescope (OST) is one of four science and technology definition studies selected by NASA for the 2020 Astronomy and Astrophysics Decadal survey. The OST is designed to address three major science questions: Are we alone in the Universe? How do planets become habitable? How do stars, galaxies, black holes, and the elements of life form from the cosmic dawn to today?[1]. To answer these questions the OST team proposes a large cooled space telescope for observations at near- to mid-IR wavelengths at unprecedented sensitivity[2] and has performed corresponding studies for two candidate concepts. Concept 1 uses a cooled 9.1m primary mirror[3] to feed five very versatile instruments. Concept 2 is a cooled, but smaller 5.9m primary mirror, optimized to achieve most of the key science goals of Concept 1 with four instruments.

Concept 2 of the OST is an on-axis telescope whose 5.9m primary mirror has a collecting area equivalent to that of JWST. To mimimize far-IR background radiation, the telescope is cooled to 4K by sunshields, a cold baffle and cryocoolers[4,5]. OST is designed to operate between 5µm and 600µm. The key science questions influenced the design of the four instruments, but each retains a degree of flexibility, and thus opening an immense discovery space: The **OST Survey Spectrometer[6] (**OSS, resolution $R \approx 300$ (for 25-580 µm) , $R \sim 40{,}000$ (at 112 µm/ λ for 25-580 µm) and R~325 000 (at 112 µm/ λ for 25-300 µm)) will provide imaging and spectroscopy over large extragalactic fields and study protoplanetary disks. The **Mid-Infrared Imager, Spectrometer and Coronagraph (MISC) [7]** instrument ($R \approx 300$) will conduct transit and emission spectroscopy of Jupiter to Earth-sized exoplanets with simultaneous wavelength coverage from 5-25 µm. MISC also has an imaging spectrometer (R~ 5 to 10) and imager, that doubles as a guide system for the observatory. OST's **Far-Infrared Imaging Polarimeter (FIP) [8]** conducts 50, 100, 250**,** and 500 µm imaging and polarimetry of wide extragalactic fields and star-forming regions in our Galaxy. The **HEterodyne Receiver for OST (**HERO, resolution R~10^5 -10^7 at wavelengths between 111 µm and 617 µm) measures the kinematics of gas in the interstellar medium and protoplanetary disks and solar system objects.

The HEterodyne Receiver for OST (HERO) performs high-spectral resolution measurements across continuous frequency range of 468GHz to 2,700GHz via a multi-band 2x9 pixel focal plane array (FPA) architecture. Its design utilises considerable heterodyne receiver heritage associated with both spaceborne and ground-based instrumentation and encompasses the latest research and development work in the field. Lightweight optics send the sky signal and the local oscillator to focal plane heterodyne arrays with 9 pixels in two polarizations. Broadband amplifier multiplier chains provide a necessary local oscillator (LO) reference system for all channels. The focal plane arrays are equipped with sensitive balanced superconductor-insulator-superconductor (SIS) and superconducting hot-electron bolometer (SHEB) mixers. Low-power, low-noise SiGe amplifiers amplify the signal at 4 and 35K, and low-power backends digitalize the spectra. A particular challenge for an advanced and powerful instrument of this type is to minimize payload power consumption and mass.

In this paper we describe the HERO instrument for Concept 2 of the Origins Space Telescope (sometimes referred to as "little HERO"). Section 2 introduces the main science questions that lead to the design of HERO. Section 3 derives the technical requirements from the science. Section 4 briefly reminds us of the heterodyne principle and its components. Section 5 gives a quick summary of previous heterodyne missions. Section 5 gives an overview of HERO for OST concept 2, whereas section 6 describes the components of HERO in more detail. The enabling technologies that allow HERO to surpass prior missions are discussed in section 7. HERO'S observing capabilities and modes are listed in section 8 and a summary of the instrument is given in the last section.

2. HERO SCIENCE DRIVERS

2.1 The Trail of Water

One of the 3 key science questions to be answered by the OST mission is: How do planets become habitable? It is believed that (liquid) water is a prerequisite for the appearance of life. But how does water get to terrestrial planets? To understand this, OST observes the trail of water from its earliest stages to its appearance on habitable planets. OST maps water's birth in the interstellar medium (ISM) and starless cores, traces the supply of water to young disks surrounding protostars, follow the water trail during the early stages of planet formation in protoplanetary disks and debris disks, and finally investigates the supply of water onto terrestrial planets via comets. In the early stages of the trail of water, the water is cold and only detectable at far-IR wavelengths, best studied by heterodyne receivers. Herschel/HIFI observations (at lower angular resolution and sensitivity) have already indicated that gas-phase water goes through large spatial and temporal abundance variations during the star forming process. High spectral resolution observations, resolving the shapes of the emission/absorption lines, lead to vital kinematic information including for instance the 'infall rate'. High spectral resolution observations are also necessary to distinguish between emission and absorption features seen at different velocities, which can often cancel out when observed at coarser spectral resolution. Models fitted to the observed line profiles towards protoplanetary disks allow retrieval of the distribution of the water on scales much finer than the spatial resolution of the telescope. The OSS instrument detects the associated spectral lines, and HERO will be used to velocity resolve the lines of the brighter objects.

2.2 Turbulence in the ISM

The energy density of the stellar radiation, cosmic rays, magnetic fields and turbulence are in rough equipartition in the interstellar medium (ISM). The dissipation of turbulence manifests itself by strong velocity gradients and localized energy inputs that contribute to the gas heating. As one of the main gas coolant, the [CII] fine structure line is a key tracer to probe the gas kinematics and thermal balance. The submillimeter spectral lines of carbon monoxide are also expected to trace the location of the hot spots due to the dissipation of turbulence and to provide a quantitative assessment of the energy exchange at play. High spectral resolution of $\leq$ 1 km/s is necessary to kinematically separate the various components in this energy cycle.

2.3 Cosmic Ray Flux in the Milky Way

The flux of low energy cosmic rays is an important source of ionization in the interstellar medium, that drives the formation of interstellar molecules and the coupling of the gas with magnetic fields. Results obtained from the Herschel Space Observatory, have confirmed the usefulness of new molecular ions as probes of the cosmic ray ionization rate, across a broad range of conditions, from ArH+ for the nearly purely atomic hydrogen, to OH+, H_2O+ and H_3O+ for increasing fractions of hydrogen in molecular form. The huge leap in sensitivity offered by OST enables a survey of absorption lines from these ions towards submillimeter continuum sources across the whole Milky Way and possibly nearby galaxies to image the distribution of the cosmic ray flux, and understand the mechanisms that govern the propagation of cosmic rays. High spectral resolution of about 1 km/s is needed to disentangle the various components from their kinematic signatures and resolve the intrinsic molecular line profiles.

2.4 Dust formation around Evolved Stars

Interstellar dust plays a key role in the physics and chemistry of the interstellar medium and star formation throughout cosmic time, and is routinely observed through interstellar extinction and in emission. Its origin is related to the late evolution of stars on the asymptotic giant branch (AGB) and supernovae (SNe). However, the dust-formation processes, their efficiency, and the detailed composition of dust around evolved stars remain major unknowns. To characterize the detailed chemical composition of dust around AGB stars and supernova progenitor red supergiants, we must determine the fundamental seeds of dust grains. High-resolution spectra of molecular emission and absorption lines in the range 0.5-1.9THz (160-640μm) enable the detection of molecular species that probe the regions where nucleation occurs. This includes high-excitation lines of abundant molecules as CO, SiO, HCN, and H_2O, but also spectra of less abundant molecules, such as Al-, Ti-, Fe-, Mg-, and Ca-bearing molecules, that could serve as nucleation seeds. High spectral resolution observations (<0.3km/s) are required to resolve the details of the velocity structure in the shocked innermost layers of the circumstellar environment, where the first dust seeds are formed.

2.5 Technical Requirements

The "Trail of Water" is a key science case, that has determined the design of HERO for OST Concept 2:

- very high spectral resolution observations to resolve line profiles to better than 0.3 km/s→ heterodyne receiver can easily reach $R = 10^6$
- frequency coverage to observe at least the ground state water lines between 557 and 1670 GHz and the HD line at 2675 GHz
- Instantaneous frequency (IF) bandwidth of more than 600km/s → IF bandwidth of at least 5.4 GHz
- relatively high sensitivity of $\sim 10^{19}$ W/m^2 in 1h, 0.3km/s, 5σ → cryogenically cooled mixers
- simultaneous (dual) frequency observations
- mapping of small areas around protostars → small focal plane array receivers

These requirements led to the definition of the HERO payload concept, which also allows the study of both high and lower priority science cases as listed above.

3. HETERODYNE PRINCIPLE

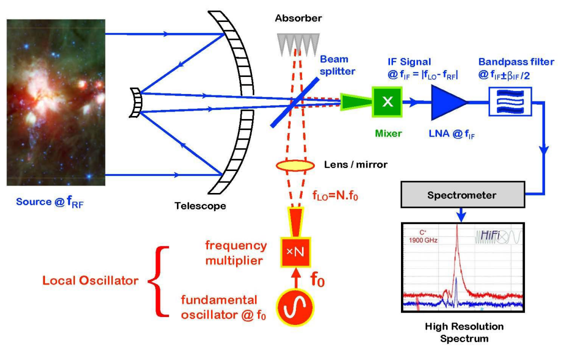

Figure 1: Schematic of a heterodyne receiver (figure by Alain Maestrini).

Heterodyne receivers are well suited for very high spectral resolution observations as well as for interferometry. Figure 1 illustrates a common heterodyne receiver: The signal from the sky at frequency ν_{sky} is collected by the primary mirror, focused, and directed to a mixer. An artificially created monochromatic signal, the local oscillator signal (LO), at the frequency ν_{LO} is overlaid onto the sky signal and also directed to the mixer. In the mixer, the beating of the two signals forms the intermediate frequency (IF) signal at $\nu_{IF} = |\nu_{LO =} \nu_{sky}|$. This IF signal is then amplified, filtered, and detected in a spectrometer. The adjustable LO frequency is positioned in close proximity to the sky frequency so that the IF signal is always at the same low frequency that can be easily amplified and detected. In essence, a heterodyne receiver consists of optics, a local oscillator (LO), a mixer, an IF chain, and a spectrometer.

4. HETERODYNE HERITAGE

Heterodyne receivers were invented nearly 100 years ago. In fact, every AM radio is a heterodyne receiver, with the difference that the IF signal is transformed into acoustic waves rather than detected by a spectrometer. Heterodyne receivers have been used in nearly all millimeter and submillimeter telescopes, e.g. the Institut de RAdioastronomie Millimétrique 30-m telescope, the James Clark Maxwell Telescope, the Caltech Submillimeter Observatory, the Atacama Pathfinder Experiment, the Large Millimeter Telescope, as well as in interferometers such as the Berkley Illinois Maryland Array, the Owens Valley Radio Observatory, the SubMillimeter Array and the Atacama Large Millimeter Array. In addition, heterodyne receivers are also used in many other fields, e.g. remote sensing and Earth observations, laboratory spectroscopy and even airport security scanners.

The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI) is the latest (2009 - 2013) heterodyne receiver to be flown on a space telescope [9]. It had 7 frequency bands covering a frequency range of 480 to 1910 GHz. It used superconducting-insulating-superconducting (SIS) and superconducting hot electron bolometer (SHEB) mixers, and amplifier-multiplier chains for the local oscillator. The HERO design strongly builds on this very successful space instrument.

More recently, the UpGREAT receiver [10,11] on the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) has been built and is now flying. It has 2 bands to allow observations of the major cooling lines of [CII] and OH (1.9 THz - 2.7 THz) THz and [OI] 4.7THz. It has medium size arrays of 2 x 7 pixels, to allow instantaneous observations of the sky at 7 positions in 2 polarizations. The HERO design takes the high frequency experience of upGREAT into account. HERO also has small arrays, though these arrays are designed differently.

Advances in heterodyne receiver and spectrometer technology continue as a result of efforts ongoing at laboratories around the world. Many of the authors of this paper have been involved in these efforts and the results are incorporated into the HERO design.

5. THE HETERODYNE RECEIVER FOR OST (HERO)

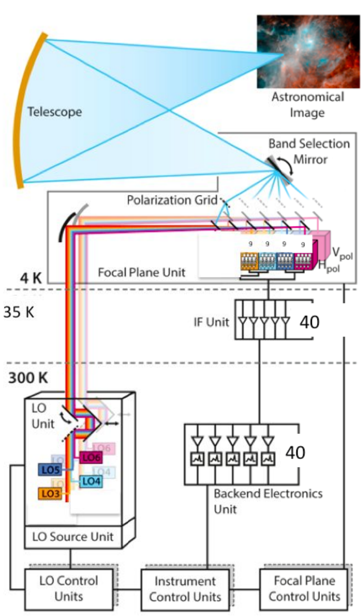

Figure 2 Schematics of the HERO receiver for the Origins Space Telescope Concept 2.

The HERO design is illustrated in Figure 2. The sky emission enters via the telescope and is directed towards one of 4 focal plane arrays (FPA), each covering a different frequency range. The reference / local oscillator (LO) signal is generated in the spacecraft bus and transmitted to the cold part of the telescope, superimposed onto the sky signal and also sent to the focal plane arrays. There are two focal plane arrays for each frequency band looking at the same location on the sky, one for horizontal, one for vertical polarization. Each focal plane array consists of 3x3 mixers, that combine the sky and the LO signal to create the IF signal at $\nu_{IF} = |\nu_{LO} = \nu_{sky}|$. Eight mixers of each focal plane array are balanced double sideband mixers. For sideband calibration purposes, one of the mixers of each focal plane array is a sideband separating (2SB) mixer, i.e. has a separate IF output for the lower and the upper sidebands. Thus each focal plane array has 10 IF channels. The first cryogenic low-noise amplifier stage is located close to the mixers to amplify weak IF signal. Subsequently, the IF channels of the different bands are combined to 40 channels, transmitted to amplifiers at 35K and then to the spacecraft. Here amplifiers and filters further increase the signal strength, and spectrometers digitize the signal, before sending it to the Instrument Control Unit and the spacecraft bus computer. Two further control units are responsible for monitoring and operating the heterodyne instrument: the LO Control Unit for the LO chains and the Focal Plane Control Unit for all components that are located at the 4K stage of the spacecraft bus, i.e. the band selection mirror, the mixers, the amplifiers and the calibration loads.

6. HERO COMPONENTS

6.1 Optics

Figure 3 below shows the optics of HERO surrounded by the mechanical components. The Origins Space Telescope Concept 2 has a 5.9 m on-axis primary mirror. The light is reflected to a secondary (not visible), then a tertiary mirror and a small field steering mirror. Around the focal plane, each of the 4 instruments picks up the radiation from their corresponding field-of-view. The HERO pick-off mirror (POM) is slightly in front of the OST field of view. It directs the light into an Offner relay, which has a movable mirror that can send the light to one of the 4 focal plane arrays or direct light from the hot or cold calibration load to the focal plane arrays. The radiation exiting the Offner array is split in polarization, overlaid with the LO signal and distributed to the individual mixers of the focal plane of the respective polarization.

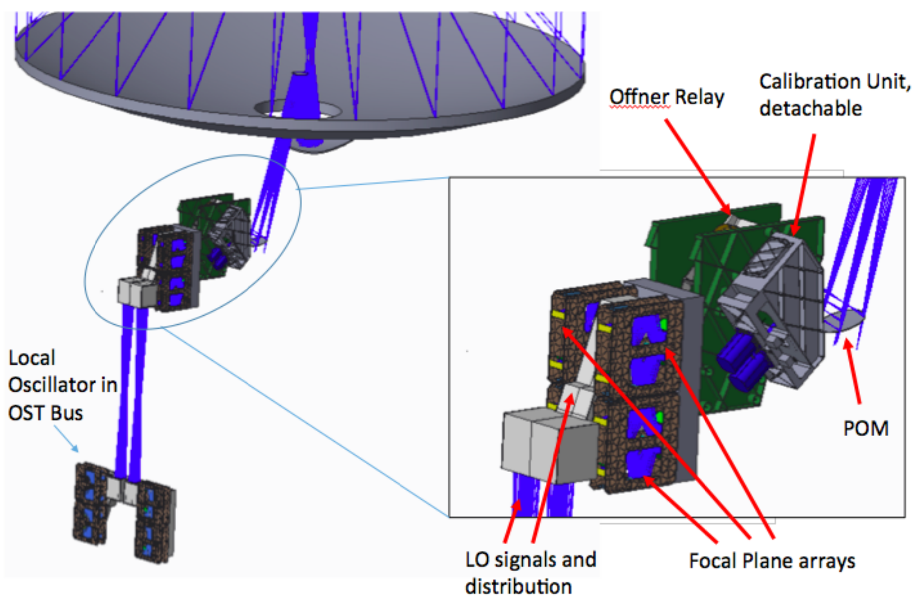

Figure 3 HERO optics on OST Concept 2.

There are eight LO chains (2 for each frequency band) that create the LO signal in the spacecraft bus (bottom left in the figure). To minimize any optics relaying the warm spacecraft bus with the cold Instrument Mounting Structure (IMS), the LOs of the different bands are superimposed onto 2 beams. These two beams send the LO signal to the IMS, where a LO demultiplexing unit separates the LOs and directs signals to each respective focal plane array.

LO and sky signal are superimposed in orthogonal polarizations, so that no signal is lost due to beam splitters. At the entrance of the mixer is a waveguide Ortho-Mode-Transducer (OMT) that separates the LO from the sky and directs the signals to the mixing junctions.

6.2 Mixer

HERO uses the most sensitive mixers currently available. These are SIS mixers, e.g. [12], for the frequency bands 486 - 756 GHz, and 756 - 1188 GHz, and SHEB mixers [13, 14, 15] for the bands 1188 - 1782 GHz and 1782 - 2700 GHz. The common OST closed-cycle cryocoolers cool the mixers to about 4K.

HERO has 8 focal plane arrays (FPA) (4 frequency bands with 2 polarizations each). Each FPA consists of 3x3 mixers in a square configuration. The beams have 2 x FWHM beam spacing on the sky, which is the closest spacing without considerable cross-talk between pixels. Eight mixers of each array are double sideband (DSB) balanced mixers, that enhanced the stability[16]. One mixer in each FPA is a sideband separating (2SB) mixer to allow sideband calibration of the DSB mixers. Each junction can be biased individually for optimal operation.

The baseline intermediate frequency is 0.5 GHz to 6.5 GHz (goal of 0.5 GHz to 8.5 GHz), so that the IF covers at least 670 km/s at the highest frequency, sufficient for Galactic observations. This bandwidth is not a problem for SIS mixers, and a 7 GHz IF bandwidth has recently been demonstrated for SHEB mixers[17].

6.3 Local Oscillator

HERO uses a combination of power amplifiers and harmonic multipliers in each LO chain associated with the four frequency bands, e.g. [18]. (Quantum Cascade Laser are an alternative solution for the high frequency channel.) A low-phase noise synthesizer creates a W-band signal, which is amplified and multiplied to the required LO frequency. Waveguide splitters divide the signal into 9 signals, corresponding to the 9 mixers in the array. Each focal plane array has its own LO chain array.

The amplifier-multiplier chains are extremely wideband, with bandwidth around 50%. They are continuously tunable and have an output power of a few µ□ per pixel.

6.4 Intermediate Frequency Chain

The IF chain amplifies and filters the signal output from the mixer, and transfers it to the digital spectrometers. The IF chain has components at 4K, at 35K and in the warm spacecraft bus.

The first stage low-noise, low-power SiGe cryogenic amplifiers[19,20] are directly behind the mixer arrays and connected to the mixers by a flexible Mylar cable. Their low power consumption is essential to prevent the mixers from heating up and to minimize the cooling requirements.

Passive power combiners multiplex the IFs of different bands, such that the 2x9 pixels of any two frequency bands can be operated simultaneously. The multiplexing of the IF minimizes IF cables and back-ends, thus economizing on weight and thermal conduction. Coaxial cables carry 40 IF channels to the 35K low noise amplifiers for further amplification, and then to the spacecraft bus. Miniaturized integrated IF circuits further amplify, filters and conditions the signal for the backends.

6.5 Backends

HERO requires 40 low power (~1W) spectrometers, each 6 to 8 GHz wide. CMOS backends as developed by A. Tang have very low power consumption, thousands of spectral channels and are rapidly advancing in bandwidth [21]. The spectrometers contain analog-to-digital converters (ADC), fast Fourier transform (FFT) processors and data accumulators (ACC). They digitize to 3 or 4 bit resolution, sufficient for our application.

6.6 Control

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 4K, 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 OST bus computer for downlinking. The ICU is the interface between the OST bus computer and the other control units of the HERO instrument.

The control units use state of the art on board 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 dormant spare unit.

7. ENABLING TECHNOLOGIES

No focal plane array (FPA) heterodyne receiver has flown on a space mission, yet, neither any heterodyne receiver operating above 2 THz. The successful HIFI/Herschel mission paved the way for single pixel heterodyne receiver up to 1.9 THz. The novel components of HERO are the FPA, the SiGe amplifiers, the wideband LO and the CMOS backends.

The Focal Plane Arrays of HERO consist of 3x3 pixels. The 9 mixers are integrated in a single block with drilled smooth walled horns, similar to the work presented by Kawamura et al. [22]. The FPA employing SIS mixers have a pixel footprint of 10mm x 10mm, the HEB mixers that do not require magnetic coils have a smaller footprint of 5mm x 5mm per pixel. The sky and LO are input in the front, whereas the IF leaves the FPA at the back, thus allowing for any size of FPA. A fexible Mylar foil with stripline circuits printed on it [23] connects the FPA with a block of 9 amplifiers.

HERO employs low-noise, low-power SiGe amplifiers[19,20]. They have a power consumption of less than 1mW. The low power consumption is desirable to keep the 4K heat dissipation low, especially for FPA with many pixels. These SiGe amplifiers exist, but have currently a bandwidth of only a few GHz, slightly narrow for observations of broad lines at high frequencies. HERO aims for an IF bandwidth of at least 6 GHz, which will be ample for Galactic astronomy (670km/s at 2.7 THz).

In order to be able to observe at any frequency between 468GHz to 2,700GHz (617 to 111 μm), HERO requires local oscillators that cover this entire frequency range. HERO has frequency multiplier chains similar to those developed by e.g. Mehdi and his group [24]. These Schottky-diode based frequency multiplier chains have made continuous progress over the years and currently produce several μW of power at 2.7 THz, e.g. [25], sufficient to pump SIS or HEB mixers. These local oscillators can be tuned continuously. To economize in component mass, the HERO LO is divided in only 4 frequency bands, each having about 50% bandwidth, which is challenging to achieve.

Currently most heterodyne receivers use digital FFT spectrometers. These are excellent, but have a high power consumption of tens of Watts for a few GHz bandwidth. For space applications we desire low-power spectrometers. Recently, very low power CMOS backends[21] have been developed. The latest design[26] for late 2018 has a bandwidth of 6 GHz, requires only 1.65 W and weighs only 120g. The spectrometer is very close to the HERO requirements and needs to be tested for space applications.

8. HERO PERFORMANCE AND OBSERVING MODES

8.1 HERO performance

Table 1. HERO fact sheet summarizing the expected performance of HERO for OST Concept 2. The sensitivities are calculated for 1 focal plane array (for unpolarized sources the sensitivity increases by 1/sqrt 2) and for 1h on source time (a factor of 1.3 to 2 needs to be added for overheads due to off-source reference measurements). The sensitivity calculations take into account the 25m^2 collecting area of the OST Concept 2 primary mirror, assuming an aperture efficiency of 0.8.

Band	Frequency (GHz)	Wavelength (μm)	Pixels	T_{rx} DSB (K)	Sensitivity (mK) in 1h at R = 10^6, 1σ	Sensitivity (W) in 1h at R= 10^6, 1σ	Sensitivity (W m^{-2}) in 1h, 5σ	Examples of spectral lines
1	486 - 756	617 - 397	2x9	50	2.6	$2.3*10^{-20}$	$4.5*10^{-21}$	H_2O, $H_2{}^{18}O$, HDO, NH_3
2	756 - 1188	397 - 252	2x9	100	4.2	$5.7*10^{-20}$	$1.1*10^{-20}$	H_2O, $H_2{}^{18}O$, H_3O^+
3	1188- 1782	252 - 168	2x9	200	6.8	$1.4*10^{-19}$	$2.8*10^{-20}$	H_2O, $H_2{}^{18}O$, NH_3, [NII]
4	1782- 2700	168 - 111	2x9	300	8.4	$2.6*10^{-19}$	$5.2*10^{-20}$	HD, [OI], [NII], [CII]

The table 1 summarizes the performance of HERO. 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.

8.2 HERO observing modes

The OST guide systems allow HERO to carry out pointed observations, where the satellite is held at one selected position in the sky, small rasters (essentially a serious of pointed observations that allow to fill the imaged sky at 2 times Nyquist sampling) and on the fly mapping, where the telescope scans a region of the sky.

HERO receiver generally observes both orthogonal linear polarizations at the same frequency simultaneously. The receiver can also carry out dual-frequency observations, each in two polarizations, so that 4 focal plane arrays take data at any given time.

9. SUMMARY AND CONCLUSION

The HEterodyne Receiver for Ost takes advantage of all prior heterodyne receivers, in particular of the experience gained with HIFI/Herschel and upGREAT/SOFIA. By also making use of more recent technical advances, HERO will be able to surpass these former instruments, as it will cover a larger and continuous frequency range of 486 GHz to 2,700 GHz (617 µm to 111 µm) with focal plane arrays of 2x9 pixels. Its refined architecture minimizes the power required per pixel, and offers higher sensitivity and wider IF bandwidth. HERO on the Origins Telescope will lead to the “Renaissance of Submillimeter Astronomical Spectroscopy” from space. In particular, it will allow identification of the path of water from the ISM to protoplanetary disks and planets, it will characterize and quantify the turbulence of the ISM, trace cosmic rays, and the formation of dust around evolved stars.

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