High-Resolution Receiver (HiRX) for the Single Aperture Large Telescope for Universe Studies (SALTUS)

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Abstract. The High-Resolution Receiver (HiRX) is one of two instruments of the Single Aperture Large Telescope for Universe Studies (SALTUS), a mission proposed to NASA's 2023 Astrophysics Probe Explorer. SALTUS employs a 14m aperture, leading to a 16-fold increase in collecting area and a factor of 4 increase in the angular resolution with respect to the Herschel Space Telescope. It will be radiatively cooled to $\leq$45 K and has a planned duration of >5 years. HiRX consists of four bands of cryogenic heterodyne receivers with a high sensitivity and high spectral resolution, being able to observe the gaseous components of objects across the far-IR. HiRX is going to detect water, HD and other relevant astrophysical lines while velocity resolving them. HiRX covers the following frequency ranges: Band 1 from 455 to 575 GHz, Band 2 from 1.1 to 2.1 THz, Band 3 from 2.475 to 2.875 THz, and Band 4 for both 4.744 and 5.35 THz. Bands 1 to 3 contain single, high-performance mixers. Band 4 consists of an array of seven hexagonally packed pixels, where the central pixel operates as a heterodyne mixer. Band 1 utilizes superconducting-insulator-superconducting mixers (SIS), whereas Band 2 to 4 use superconducting hot electron bolometers (HEB) mixers. The local oscillator (LO) system uses frequency-multiplier chains for Band 1 and 2, and quantum cascade lasers for band 3 and 4. Autocorrelator spectrometers are used to process the intermediate frequency (IF) signals from each science band, providing instantaneous frequency coverage of 4-8 GHz for Band 1 and 0.5-4 GHz for Band 2 to 4. SALTUS will also fly a chirp transform spectrometer system for high spectral resolution observations in Band 1.

Keywords: SALTUS, HiRX, Far-infrared, heterodyne, HEB, SIS, instrument

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1 Introduction

The observational goal of the Single Aperture Large Telescope for Universe Studies (SALTUS) is to probe the origin and evolution of galaxies, stars, and planets. In the far-infrared (far-IR) this requires both a large aperture to achieve the angular resolution required to beat the spatial confusion limit and sensitive detectors with sufficient resolution to disentangle the velocity fields along a given line of sight (LOS).

To meet these requirements the science payload of SALTUS consists of: 1) an optical system with a deployable, 14m primary reflector and corrective optics; 2) a four-band spectrometer of R=300 (SAFARI-*Lite*); 3) a four-band heterodyne receiver with R=10^5 to 10^7 (HiRX); and 4) a deployable sunshield that radiatively cools the telescope to $\leq$45K, see Fig. 1(a). The deployable, off-axis parabolic reflector, M1, collects light from celestial targets and conveys it to the cold corrector optics module (CCM). The CCM (see Fig. 1b) corrects wavefront error to provide diffraction limited performance between ~30 and 660µm and fast and slow beam steering over the 2.4 arcmin telescopic field of view (FOV). Upon exiting the CCM, the light enters the instrument module (IM) and proceeds to a flip mirror where it is directed to either SAFARI-*Lite* or HiRX, which share similar wavelength ranges. SAFARI-*Lite* is a moderate (R~200) resolution direct detection grating spectrometer. HiRX is a high resolution ($10^5 \leq R \leq 10^7$) heterodyne receiver system. Within each instrument there is a series of dichroics and polarizing grids that split the incoming signal into four frequency bands. The spectral range of the bands are different for SAFARI-*Lite* and HiRX. SAFARI-*Lite* utilizes kinetic inductance detectors (KIDs) in each of its bands, while HiRX employs superconducting hot electron bolometers (HEB) mixers in Bands 2 to 4 and superconducting-insulator-superconducting (SIS) mixers in Band 1. The detected signals are then processed by "backend" electronics in the warm instrument module (WIM). This approach permits a target to be observed simultaneously in all four bands of either SAFARI-Lite or HiRX.

The heterodyne receivers of HiRX are sufficiently narrow band that they are detector noise-limited, obviating the need for cold optics [1]. However, due to their larger instantaneous bandwidth and sensitivity, the KID detectors of SAFARI-*Lite* are background noise-limited and, therefore, benefit from the radiative cooling of M1 and instrument fore-optics to low temperatures ($\leq$ 45K). Efficient radiative cooling is achieved by utilizing a 2-layer sunshield whose long axis is oriented perpendicular to the Sun-spacecraft line. M1 and the CCM are located on the shielded, "cold" side (CS) of the sunshield, while the WIM and spacecraft are on the "hot" side (HS) of the sunshield. A modified, James Webb Space Telescope (JWST) Mid-Infrared Instrument (MIRI) cryocooler [2] provides the required 5.25K cooling of the mixers and KID-precooler. Further cooling of the KIDs to ~100mK is achieved with an adiabatic demagnetization refrigerator (ADR). This paper describes the design and expected performance of HiRX. Another paper in this Special Section (Rolfsema et al. 2024) discusses SAFARI-*Lite.*

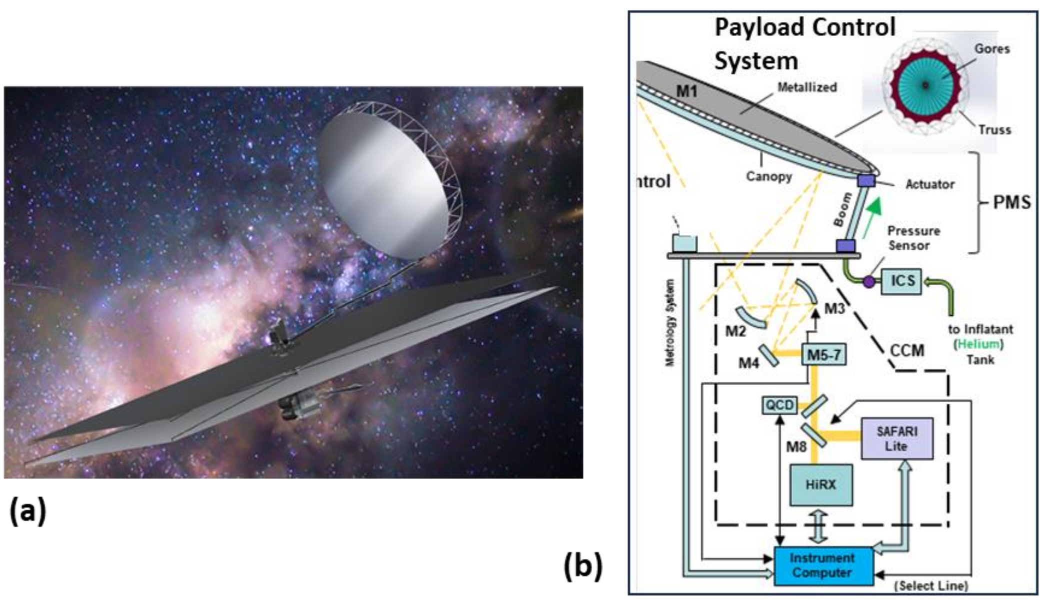

Fig. 1. a) SALTUS has a 14m aperture formed utilizing proven space deployable technology. A sunshield allows for radiative cooling to $\leq$45K. b) *SALTUS functional block diagram.*

2 HiRX System Overview

The SALTUS High Resolution Receiver (HiRX) employs a cryogenic superheterodyne receiver system with four frequency bands ranging from 455GHz (659µm) to 5.35THz (56µm). The receiver architecture is shown in Fig. 2. Bands 1, 2, and 3 contain single, high-performance pixels. Band 4 consists of an array of seven hexagonally packed pixels, where only the central pixel operates as a heterodyne mixer. The six pixels in the surrounding ring operate as direct detectors and are used for pointing and beam characterization. The receiver design is based on the instrument successfully flown on the GUSTO [3] Explorer balloon-borne mission (launched 12/31/2023) and in 2016 on the STO balloon-borne telescope [4].

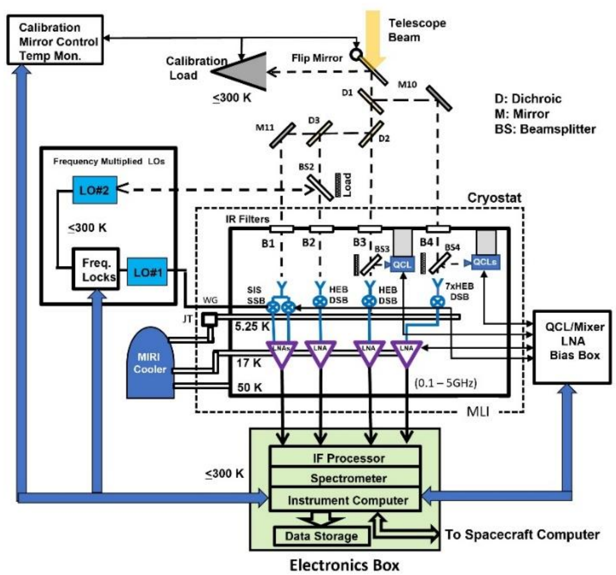

Fig. 2. HiRX Block Diagram. The green Backend Electronics Box is housed in the WIM on the hot side of the sunshield.

The beam enters the receiver system from the corrector system and is spectrally split by a series of dichroics into the four science bands. In Bands 2, 3, and 4, the local oscillator (LO) beams are coupled to their respective science beam using ~5% reflective dielectric beam splitters. Band 1 utilizes a waveguide coupler for this purpose. The Band 1 and 2 LO beams are produced by frequency-multiplied sources, while the Band 3 and 4 LO beams are each generated by a solidstate quantum cascade laser (QCL). The output frequency of the Band 3 or 4 LO is set by the associated QCL temperature and current bias. The QCLs are maintained at their target temperature by a 1.5 m^2 radiator external to the CCM and a resistive heater on the QCL die. The Band 2, 3, and 4 signal and LO beams propagate through the receiver cold-box into their respective front-end mixers. The mixers down-convert the science signals to intermediate frequencies (IF) of 4-8GHz (Band 1) or 0.5 - 4GHz (Bands 2 - 4) where cryogenic, low noise amplifiers (LNAs) and ambient temperature IF processors are used to boost and condition them before being passed to their respective spectrometers. The resulting spectra are then conveyed to the spacecraft for downlink. The total power output over the full IF bandwidth of each receiver (~4 GHz) is also provided to assist with calibration and pointing.

During calibration, the receiver beam is diverted to a calibration blackbody cone by actuating a flip mirror. The mixers/receivers are calibrated for ~5 seconds on the load at ~20 second intervals. The interval between calibrations is set by the stability time of the receivers.

The HiRX Instrument Electronics Box (IEB) contains the receiver bias control system, IF processor, spectrometers, and instrument computer. The instrument computer controls all receiver functions and transfers data to the spacecraft for storage until a scheduled downlink contact. The electronics and software for the SALTUS Receiver Electronics Box have heritage from the STO and GUSTO flight programs, and qualification for vacuum and wide temperature range has been completed, with vibe and radiation performance to be demonstrated prior to PDR. This focused demonstration program will establish technology readiness level (TRL) 6 for the HiRX electronics for the SALTUS environment. Table 1 provides a summary of SALTUS instrument performance parameters.

Table 1. HiRX Instrument Characteristics.

Receiver Properties	Band 1	Band 2	Band 3	Band 4 a/b
Frequency Range (GHz)	0.455 / 0.575	1.100 / 2.200	2.675	4.744 / 5.35
Wavelength Range (μm)	658.88 521.38	272.54 136.27	121.07 104.28	63.2 56.1
System Noise (DSB, K)	124	484	802	1555
Number of Pixels	1	1	1	7
Polarizations	Dual	Single	Single	Single
Mixer System	SIS SSB Waveguide	HEB DSB Spiral	HEB DSB Spiral	HEB DSB Spiral
Beam Size (arc-sec)	10	4	2	1
Spectrometer Type	ACS/FFT	ACS	ACS	ACS
Maximum IF Bandwidth (GHz)	4/0.75	3.5	3.5	3.5
Spectral Resolution (MHz)	5.37/0.1	5.37	5.37	5.37
Spectral Resolving Power	$10^5/10^7$	3×10^5	5×10^5	1×10^6
Velocity Resolution (km/s)	3.1/0.03	1.0	0.6	0.3
Point source spectroscopy ($5\ \sigma_{rms}$ -1hr)	0.018 K	0.063 K	0.671 K	0.095K

3 HiRX Subsystems

In terahertz astronomy coherent receivers are used to translate the terahertz spectrum of interest to a lower intermediate frequency (IF) where a low noise amplifier (LNA) can be used to increase signal levels to the point where they can be digitized and processed into spectra. The down-conversion is achieved by multiplying the incoming signal of frequency, ν_S, with a locally produced tone of frequency, ν_{LO}, referred to as the local oscillator (LO). The multiplication occurs within a nonlinear device; the mixer. There are 3 types of mixers commonly used at terahertz frequencies; Schottky diode, super-conducting-insulator-superconducting (SIS), and hot electron bolometer (HEB). A plot comparing their noise temperatures as a function of frequency is provided in Fig. 3. The ranges of frequencies associated with Bands 1, 2, 3, and 4 are indicated. The plot shows the optimum type of mixer for Bands 2, 3, and 4 is an HEB and for Band 1 is an SIS [1].

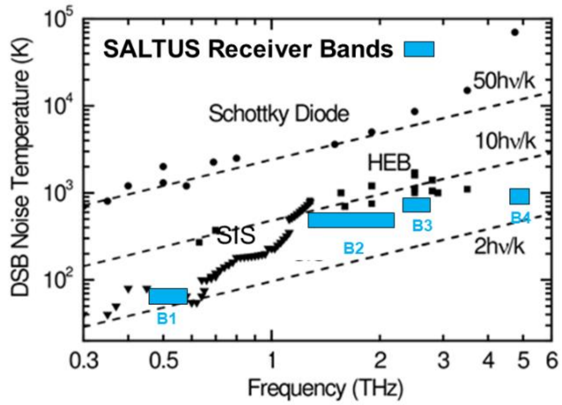

Fig. 3. Measured DSB noise temperatures for Schottky, SIS, and HEB receivers. Curves for 2, 10, and 50 times the quantum noise limit (for SSB operation) are overplotted [1]. SALTUS Bands 1, 2, 3, and 4 are shown in blue.

3.1 HEB Mixers

Band 2 (1.1-2.1 THz), Band 3 (2.475-2.875THz), and Band 4 (4.744/5.35THz) utilize the same cryogenic, quasi-optical, double sideband (DSB), hot-electron bolometer (HEB) mixer technology developed by SRON [5] that was flown on GUSTO and STO. In this approach, a silicon lens is used to focus incoming light on to a micron-sized niobium nitride bridge fabricated at the center of a planar spiral antenna (Fig. 4). The lower impedance afforded by silicon compared to free space effectively guides the incoming photons to the detector. Coax conveys the down-converted sky signal to a series of low-noise cryogenic and room-temperature microwave amplifiers. These HEB mixers have been shown to provide the sensitivity needed for the proposed science investigations (Fig. 4; [1]). The same quasi-optical HEB mixer can operate over the full SALTUS spectral range; the only difference being the design of the anti-reflection coating on the silicon lens used by the mixer in each band.

To aid in pointing and increase mapping speed, Band 4 utilizes a hexagonally packed, seven-pixel HEB array. When pointing, the Band 4 mixers are operated in bolometric mode with an NEP of $\sim 4.5 \times 10^{-12}\mathrm{W\ Hz}^{-\frac{1}{2}}$, suitable for continuum detection [6]. Once pointed, the central array pixel is operated in heterodyne mode, suitable for spectral line observations.

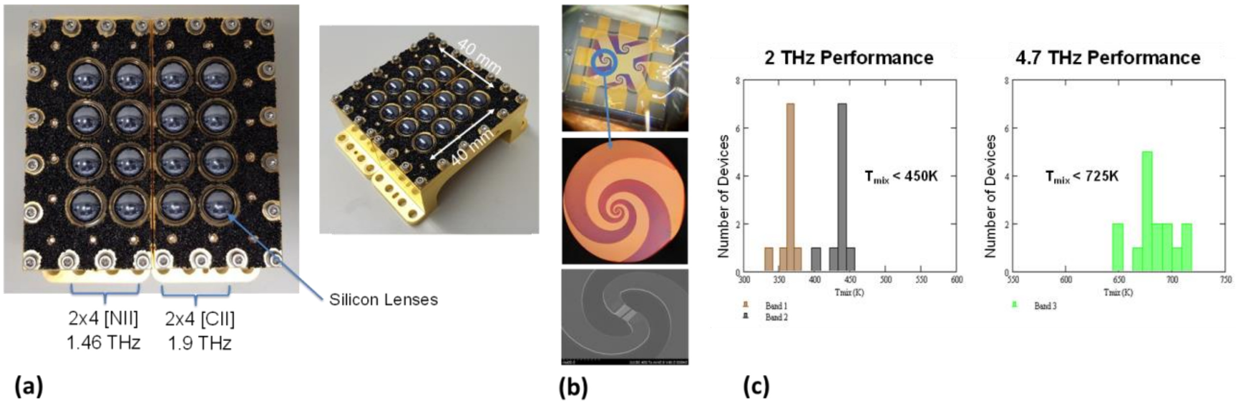

Fig. 4*. GUSTO HEB Mixer Arrays. (a) 2x4 quasi-optical HEB mixer arrays composed of AR coated silicon lenses with (b) substrate mounted spiral antennas. c) Measured mixer noise performance. Very similar broadband, low noise mixers will be utilized in HiRX, but with 30% improved performance below 2 THz [7].*

3.2 SIS Mixers

As indicated by Fig. 3, at frequencies below 0.6THz, an SIS mixer can provide 3-5 times greater sensitivity than an HEB mixer, which makes it the choice for SALTUS Band 1 (455-575GHz). For optimum performance a dual polarization, single sideband separating waveguide mixer architecture is employed [1]. In this implementation, a corrugated feedhorn conveys the incoming signal to an orthomode transducer which splits it into horizontal and vertical polarized components. These components then travel through waveguide to two independent, single sideband separating (SSB) mixers. Each SSB mixer provides a separate down-converted IF signal for each of its sidebands, reducing the possibility of spectral confusion, and lowering noise temperatures within each sideband.

The Band 1 mixer design is scaled and optimized from the successful Atacama Large Millimeter Array (ALMA) Band 8 mixer [8]. Extensive modelling of the mixer at the University of Arizona (UA) indicates a single sideband noise temperature of ~130K will be obtained over a 4 GHz IF bandwidth throughout the frequency range of Band 1.

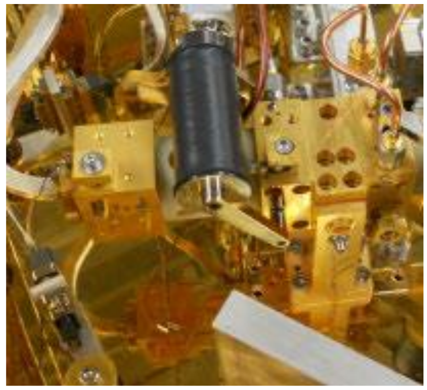

Fig. 5. ALMA Band 8 SIS mixer [8]. This successful design has been scaled to operate for use in Band 1 of SALTUS.

3.3 Local Oscillators (LOs)

The Band 1 and 2 LOs are frequency multiplied sources provided by Virginia Diodes Inc. (VDI) (Fig. 6a). The multipliers themselves are housed in a common LO box in the CCM. For thermal isolation, the microwave synthesizers and power amps that drive the multipliers are in a separate box in the upper half of the Core structure. To cover the full 1.1-2.2THz range, the Band 2 LO consists of two active LO chains; one for the lower half and a second for the upper half of the band. The Band 2 beams are quasi-optically coupled into its mixer via a polarizing grid and a dielectric beam splitter.

The Band 3 and 4 LOs are quantum cascade lasers (QCLs) fabricated by MIT (Fig. 6b). Band 3 targets the 2.7THz HD 1-0 line and only requires one QCL. Band 4 has two QCLs, one targeting the 4.7 THz [OI] line and the second targeting the HD 2-1 line. The QCLs operate at ~60K and are located within 20cm of the mixers. The output of the two Band 4 QCLs are diplexed using a polarizing grid before being coupled into the central Band 4 mixer via a dielectric beamsplitter. Only one of the two Band 4 QCLs is on at any given time.

Both VDI and MIT provided similar LO units for GUSTO, and a demonstration of TRL 6 for the SALTUS flight environment will be performed prior to PDR with the instrument electronics.

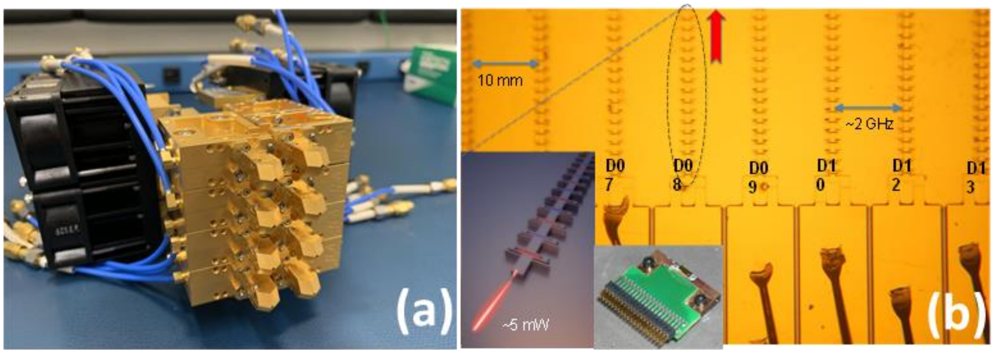

Fig. 6. *(a) GUSTO 2x4 1.9 THz LO array. The array consists of 8 chains of synthesizer driven varactor multipliers with output feedhorns. [9] (b) GUSTO 4.7 THz LO QCL. A series of 8 QCLs each offset in frequency by ~8 GHz are formed on a single wafer. FTS measurements are made to determine the QCL closest to the science target frequency. When operated at ~65K, the output power of a single QCL is ~5 mW. [10]*

3.4 IF Spectrometers

To meet instrument requirements, each of the IF outputs from the mixers and LNAs must be processed efficiently into spectra with per-channel resolving powers ($\lambda/\Delta\lambda$) as high as 10^7. SALTUS will utilize the same LNA design developed for GUSTO. These requirements are met utilizing autocorrelator spectrometers (ACS) with 5MHz resolution for Bands 1-4, with the addition of chirp transform spectrometers (CTS) for use with Band 1. Requirements for the ACS are identical to those of the 1.9 THz spectrometer to be flown on GUSTO [3]. The GUSTO ACS was built by Omnisys Inc. and can simultaneously process up to eight IF outputs (Fig 7). The high-resolution CTS spectrometer system used to process the four IF outputs of the dual polarization, single separating of Band 1 receiver are being contributed by the German Space Agency (DLR) and are based on a heritage design being flown on the ESA JUICE mission [11] (Fig. 8).

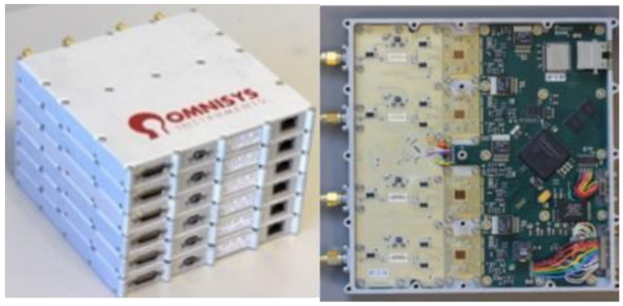

Fig. 7. GUSTO Autocorrelator spectrometer. Within its 2.5 kg/160x160x160 mm package the unit can process 120 GHz of spectral data at a total power dissipation of ~75W. [3]

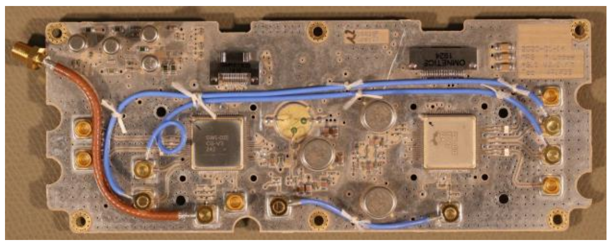

Fig. 8. ASIC board of SWI-CTS with chirp generator (CGV3) and digital preprocessor (PPV3). [11]

4 Summary

The observational goals of SALTUS are to probe the origin and destiny of the universe and explore the evolution of galaxies, stars, and planets. For far-IR studies of star and planet formation, these goals require both a large aperture to achieve the necessary angular resolution and heterodyne receiver systems, such as HiRX, with high spectral resolution to disentangle velocity fields along a given line of sight (LOS). For example, *Herschel* was only able to detect a handful of protoplanetary disks in HD due to its 3.5m aperture. With HiRX on SALTUS, it will be possible to not only detect, but spectrally resolve a number of protoplanetary disks, allowing a direct measurement of the radial mass distribution; thereby providing much needed constraints to theories of planet formation. HiRX leverages directly from the development of the flight instruments for the *GUSTO* and *STO* balloon-borne missions, as well as instruments for *Herschel* and *JUICE*. As an illustration of the power of this proven technical approach, Fig. 9 shows a *GUSTO* first-light spectrum of the 1.9 THz [CII] line taken towards the star forming region of Eta Carina in under 2 sec of integration time. Fig. 10 shows the first extragalactic GUSTO spectrum taken towards the 30 Dor region in the Large Magellanic Cloud (LMC) in 15 sec of integration.

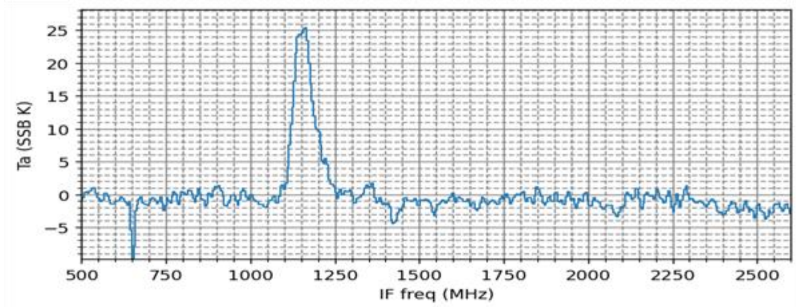

Fig. 9. *GUSTO First Light [CII] spectrum toward Eta Carina. This spectrum was obtained in under 2 sec on a 0.9m telescope using the same technical approach to be employed on SALTUS.*

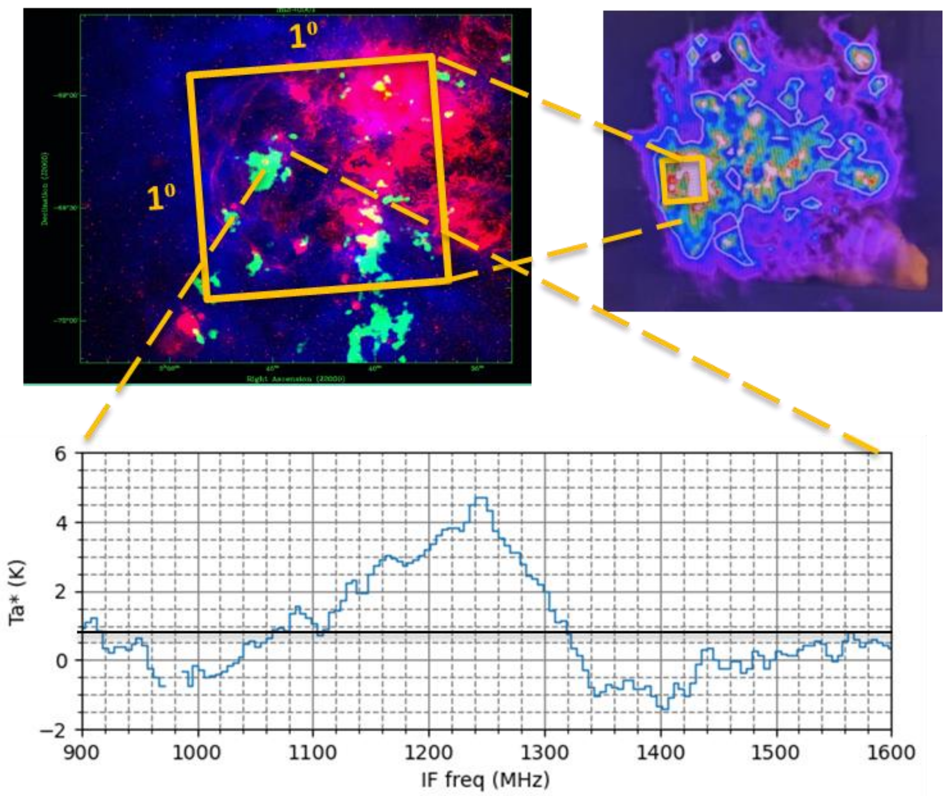

Fig. 10. *First Extragalactic GUSTO spectrum [CII] towards the 30 Dor in LMC obtained with 15 sec integration.*

Data Availability Statement

The data that support the findings of this article can be made available upon request to the corresponding authors.

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