SEPIA345: a dual polarization 2SB cartridge receiver for APEX telescope: Design and Performance

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***Abstract*—A new receiver channel covering the 271-377 GHz frequency band has been installed into the SEPIA receiver at the APEX telescope. The receiver channel was designed and built in an ALMA-compatible cartridge layout. The receiver has a dual polarization layout with OMT and employs 2SB SIS mixers featuring an extended 4-12 GHz IF band, providing 32 GHz instantaneous IF bandwidth for two polarizations and two sidebands.**

Keywords—sub-mm receiver, SIS technology, dual-polarization

I. Introduction

The frequency band between 200-425 GHz has been marked as the highest priority for the new generation of ALMA receivers in the "ALMA 2030" roadmap document because of its most direct impact on the new ALMA science goals [1]. The upper part of this band, corresponding to the ALMA Band 7, has quite many astrophysical important molecular transitions. The new generation of state-of-the-art receivers has to provide a wide IF band, which opens the possibility of performing science observations more effectively.

The Atacama Pathfinder Experiment (APEX) telescope placed next to ALMA at the Chajnantor plateau in northern Chile has offered outstanding millimeter- and submillimeter-wavelength observing possibilities [2]. A major component of the current set of APEX facility receivers is provided by the Swedish ESO PI Instrument for the **A**PEX telescope (SEPIA), which is a multiband heterodyne instrument developed, designed, and built by the Group for Advanced Receiver Development (GARD), Onsala Space Observatory, Chalmers University of Technology, in collaboration with ESO [3]. This instrument features a cartridge layout that is fully compatible with ALMA technologies. The SEPIA instrument, therefore, provides a flexible platform for observations but also for testing different receivers.

One of three SEPIA receiver channels, the SEPIA345 receiver, operates over the frequency range of 271–377 GHz and was installed in 2020. The primary use of the receiver is to observe important molecular transitions (CO, CH_3OH, and N_2H^+) as part of the single-dish spectroscopic observing program of APEX. Moreover, the SEPIA345 receiver also expands APEX participation in Very Large Baseline Interferometry (VLBI) observations for the Event Horizon Telescope (EHT) from 230 GHz to 345 GHz. In April 2022 the SEPIA345 receiver channel was successfully used in EHT test observations at 345 GHz. The scientific importance of EHT telescopes such as APEX moving to a higher observing frequency is that this gives longer VLBI baselines in terms of wavelengths, allowing higher-resolution images to be made of Super Massive Black Holes in the center of galaxies [4].

In this paper, we present the SEPIA345 receiver channel that covers 271-377 GHz and provides the IF bandwidth of 4-12 GHz in 2SB and dual polarization configuration.

II. Receiver Design

The SEPIA instrument occupies one of the facility positions inside the Nasmyth cabin A at the APEX telescope. The optics design implements a frequency-independent illumination of the secondary for all SEPIA receiver channels (159–722 GHz) with an edge taper of about −12 dB [5]. To be able to provide beam coupling in the limited cabin space, the SEPIA optics has a total of ten mirrors, including five warm mirrors. As part of the receiver verification, measurements of the beam at several signal frequencies were performed in the lab as near-field scans over the cryostat windows. The calculated Gaussivity was found to be about 96%.

The SEPIA345 receiver is built for dual polarization operation and utilizes the 2SB receiver architecture, as

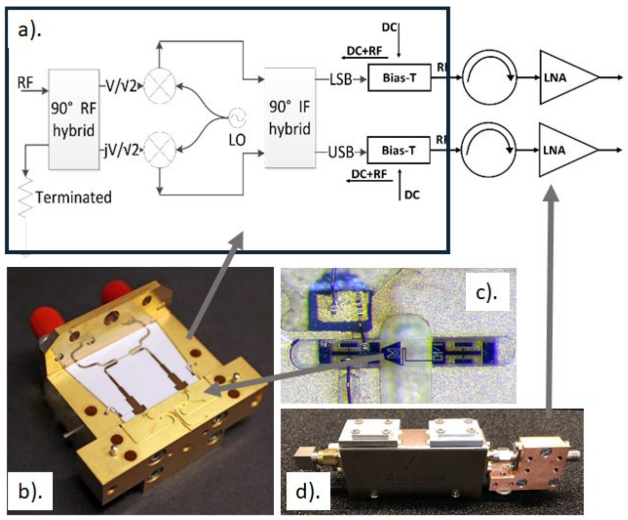

Fig. 1 SEPIA345 receiver channel. a). receiver layout; b). the part of the mixer block containing mixer- and IF circutries; c). SIS mixer layout d). IF assembly of one of the sidebands consisting of a cryogenic isolator and a low noise amplifier (LNA).

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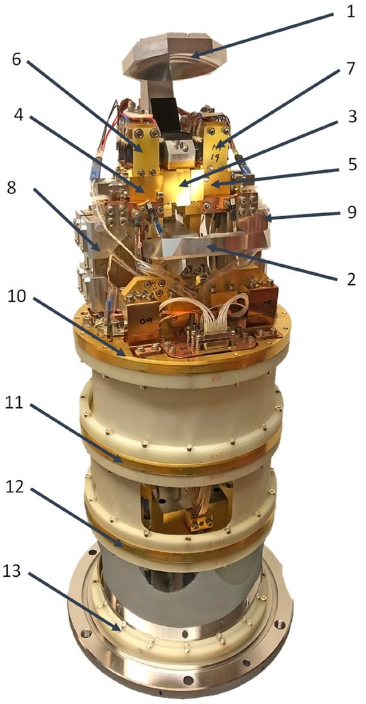

Fig.2 SEPIA345 Cold Cartridge Assembly (CCA) layout [6]. The follow-ing components are marked: 1- first cold mirror; 2 - second cold mir-ror; 3 - orthomode transducer (OMT); 4 - 2SB mixer block at Pol0; 5-2SB mixer block at Pol1; 6 - magnetic coil assembly at Pol0; 7 - magnetic coil assembly at Pol1; 8 - LSB and USB IF assemblies at Pol0; 9 - LSB and USB IF assemblies at Pol1; 10 - 4K plate; 11 - 15K plate; 12 - 110K plate; 13 - room temperature plate.

shown in Fig.1a. An orthomode transducer (OMT) is employed for polarization split. Since both polarizations share the same feed horn, they are co-aligned on the sky. Lab measurement results confirmed a cross-polarization lower than −25 dB over the entire operational band.

As any ALMA receiver channel, the SEPIA345 consists of a Cold Cartridge Assembly (CCA) and a Warm Cartridge Assembly (WCA). The WCA is the standard ALMA Band 7 WCA produced by NRAO. The SEPIA345 CCA was designed from scratch and consists of the cold optics with two elliptical mirrors, corrugated feed horn, OMT, 2SB mixer blocks, IF chains, and DC bias circuitry with the LO multipliers installed at 110 K of the CCA. Details of the CCA are presented in Fig.2 [6].

In the 2SB mixer block, we integrated two Superconductor-Isolator-Superconductor (SIS) mixer chips, along with the RF and IF circuitries. The bottom part of the 2SB mixer block is shown in Fig. 1b. As in the commonly used 2SB mixer configuration, the RF circuitry comprises a signal waveguide quadrature 3 dB hybrid and the LO injection directional couplers (with a coupling factor of -18dB). Mixer- and IF circuitries are also located inside each of the two mixer blocks. Waveguides' dimensions of 380x760μm demand the strict fabrication accuracy of the receiver components.

The mixer chips (shown in Fig. 1c) employ Nb/Al-AlO_x/Nb SIS in the twin-junction configuration [7] and have an area of 2.3 μm^2; the SIS junctions have been fabricated in-house and the mixer chip employs 65μm thick quartz substrates [8]. The twin-junction tuning circuitry with a single-step transformer compensates for the reactance of the junctions in the RF signal band of 270-375 GHz. The transformer is formed on 360 nm of SiO_2 sputtered on top of

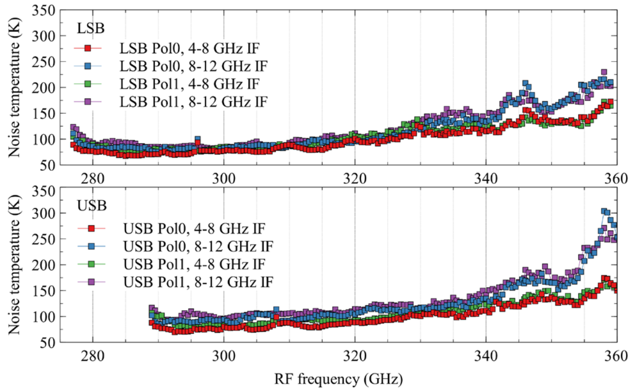

Fig.3 SSB receiver noise temperature measurements performed for each polarization and sideband averaged over each 4.0-GHz-wide FFTS IF sub-band. The temperature in the higher IF section (8–12 GHz) is illustrated with blue (Pol0) and violet squares (Pol1). The results in the inner segment (4–8 GHz) are shown with red (Pol0) and green squares (Pol1).

the RF choke, serving as a ground layer for the tuning circuitry. The extraction of the IF signal occurs at an additional port situated close to the SIS mixers and via a landing capacitor (Fig. 1c) and enhances the flatness of the IF response across the 4–12 GHz band.

The IF circuitry comprises two IF matching transformers, two bias-Ts, and an IF 90-degree hybrid integrated on the same 20 mils thick alumina substrate as depicted in Fig. 1b, enabling a broader IF bandwidth of 4-12 GHz for each sideband. Further amplification at IF is performed by low-noise cryogenic amplifiers (LNAs) preceded by 4–12 GHz isolators, as shown in Fig.1d. As a result, 16 GHz (2 × 8 GHz) of instantaneous IF bandwidth is reached per polarization.

The LO (283–365 GHz) is an integral part of the WCA produced by the National Radio Astronomy Observatory (NRAO) and uses a direct multiplication LO chain (x18), following a Yttrium Iron Garnet (YIG) oscillator. The last frequency multipliers (×3) for each polarization are mounted inside the CCA at the 110K stage. The YIG oscillator, LO chain components, as well as warm IF amplifiers are located in the Warm Cartridge Assembly (WCA), which is attached to the CCA. Amplified IF signal is processed further with the help of the APEX IF processor and the (Fast Fourier Transformer Spectrometer) FFTS. As a result, 4–12 GHz IF bandwidth for each side-band and polarization is divided into two 4-GHz-wide bands. The FFTS provides spectral resolution of up to 64000 channels per 4 GHz of input bandwidth.

III. Characterization of the Receiver at the Telescope

The technical verification of SEPIA345 at the APEX telescope took place in 2020. The science commissioning of the receiver band was then continuously performed until the middle of 2021.

The receiver noise temperatures were measured over the full RF band by tuning the LO in steps of 0.5 GHz with help of the facility calibration unit (FCU) following a standard COLD-HOT-SKY calibration procedure per sideband and polarization. Results of such measurements averaged over each 4-GHz-wide FFTS section are presented in Fig.3 [6].

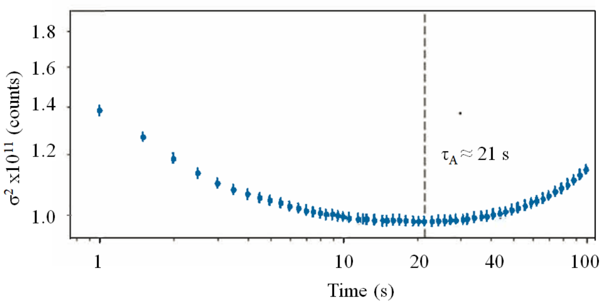

Fig.4 Example of total power Allan variance measurement performed for Pol0 LSB within a 125-MHz-wide sub-band in the 4–8 GHz FFTS segment at the LO frequency of 297 GHz.

The sideband rejection ratio (SBRR) plays an important role in the ability to perform high-quality science observations since these require as little contamination as possible in the signal band from lines in the image band. This is especially true for the single-dish observations. In the case of astronomical sources with high spectral line density, a poor SBRR may, for instance, hamper line identification. From our measurements, the average SBRR is as low as –18 dB. The Pol0 mixer demonstrates SBRR average values around –20 dB, while Pol1 channel average values lie around –15 dB [6]. These results are in line with measurements performed on-sky by observing the WB 947 source with strong and narrow CO J = 3 → 2 line [6]. In this experiment, the CO line was placed at different parts of the IF band, by retuning the LO. For each LO setting, the SBRR was evaluated by measuring the intensity ratio of the weakly appearing image line to the signal line.

Stability is one of the most important receiver parameters. A standard method to characterize receiver stability is performing measurements of the Allan variance [9]. These measurements took place while the telescope was standing still (stowed). The cold load of the FCU was providing more stable conditions than the cabin ambient temperature while data was being collected over several hours. The total power Allan time was measured in small sub-bands combining consecutive FFTS channels, spanning a total bandwidth of 125 MHz per sub-band. In Fig. 4, we show the total power Allan variance that was obtained using the Pol0 USB within a 125-MHz-wide sub-band within the 4–8 GHz FFTS segment at the LO frequency of 297 GHz. This frequency is recommended for continuum observations as it is relatively free of atmospheric features. The spectroscopic Allan times are calculated by creating smaller sub-bands combining a few consecutive FFTS channels, spanning 1.0 MHz in total. Then, the signals of two of these 1.0 MHz sub-bands are subtracted, and their noise characteristics are inspected to have a more complete overview.

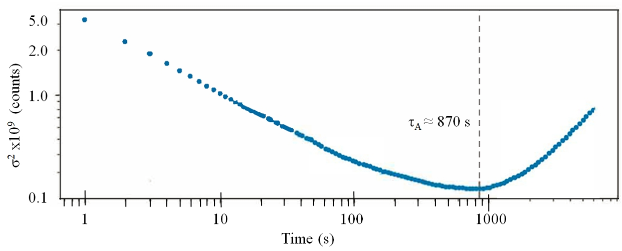

Fig.5 Example of a spectroscopic power Allan variance measurements at a signal frequency of 345 GHz. The FFTS response was recorded for more than 13 hours.

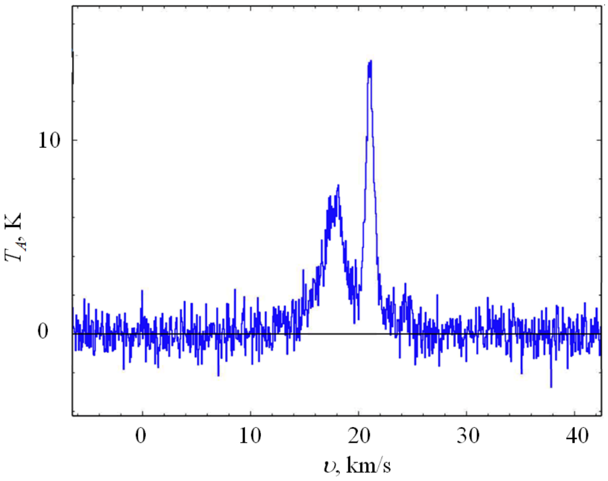

Fig.6 The observed H_2O 321 GHz maser spectrum towards the red supegiant VY CMa

An example of the spectroscopic Allan variance measurements is displayed in Fig. 5. These measurements were performed with Pol1 mixers at the 345 GHz USB in the 4–8 GHz FFTS IF section using the difference between two different 1.0-MHz-wide sub-bands, some 1.8 GHz apart. The Allan time is estimated to be larger than 850 s.

In a frame of science verification, among many other tests, observations of the water maser at 321 GHz toward VY CMa have been performed. The water maser emission originates from energy levels near 2000 K in excitation energy. It can be considered as a point source concerning the APEX beam size at 321 GHz. Fig.6 shows this water maser line.

IV. CONCLUSION

The SEPIA345 receiver channel, installed at the APEX telescope in February 2020, covers a signal band of 271–377 GHz. The dual polarization receiver employs 2SB SIS mixers and offers an instantaneous IF bandwidth of 4×8 GHz. The receiver has an average SBRR of –20 dB and –15 dB measured at the telescope for the Pol0 and Pol1 mixer channels, respectively. The receiver stability measurements demonstrate typical total power Allan times on average larger than 10 s in the 125 MHz effective noise bandwidth and better than 60 s spectroscopic Allan times in the 1 MHz effective noise bandwidth. The SEPIA345 receiver become one of the APEX facility instruments and is now available to all APEX observers.

V. REFERENCES

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