A 1THz Receiver System at APEX

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***Abstract*— We present a two channel heterodyne receiver system operating simultaneously in the 300µm and 625µm atmospheric windows. For the design of the THz channel, we make use of the technological spin-off of HIFI, the heterodyne instrument on board of the HERSCHEL space telescope. The system concept includes a co-aligned 460GHz channel, to establish a pointing reference and to increase therefore the efficiency of the astronomical operation.**

I. Introduction

Successful ground based astronomical observations in the THz regime are depending on several important factors, the most dominant is the atmospheric transmission, that allows our view into space in a few windows only. The APEX telescope (Fig. 2) with its 12 meter dish, located at an altitude of 5100m in the high Chilean Andes is one of the few places where observations of such short wavelength are possible [1]. Under very good weather conditions an atmospheric transmission of up to 35% (Fig. 1) in the 300 micron window is possible, where statistics show that only in about 5% of the nights the atmosphere is transparent enough for reasonable THz measurements [2].

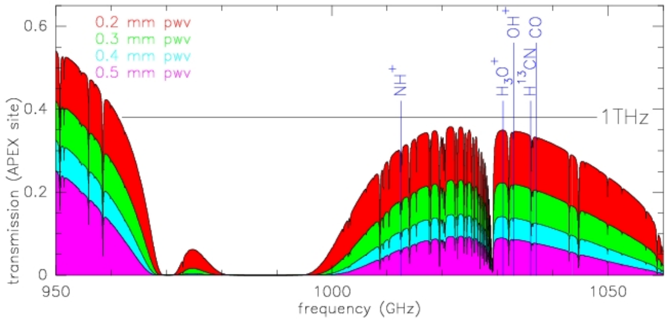


Fig. 1 The atmospheric transmission at APEX in the 300 micron window for different precipitable water vapor values and the RF tuning range of the 1THz Rx.

But not only the atmosphere plays an important role, the telescope itself with its surface accuracy, and pointing capabilities must be able to handle the rather small beams of THz receivers and produce good beam efficiencies on sky. In order to get all these uncertainties included, a robust calibration scheme must also be in place.

The design of the THz receiver fell into the late phase of satellite integration and testing of HIFI [3], which made it possible to use the technological spin-off in mixer and local oscillator (LO) development of band IV. Operating the 1THz RX at APEX will act as a valuable test bed, it allows to study the long term behavior of the used HIFI components, to gain further knowledge in handling spurious signals and to optimize the operation conditions of the used LO components [4].

A complex system as the 1THz receiver requires a modern infrastructure for operation, like fast data network, broad band IF and backend processing and fast telescope beam switching, all these requirements are provided by APEX.

The instrument was designed as a dual-frequency system. Both channels use SIS mixers, the 1THz channel operates a copy of HIFI band IV ([5],[6]) while the second channel, designed for pointing purposes, uses a 460GHz mixer from the de-commissioned CHAMP array [7]. Two different LO systems are installed. The state-of-the art band IV solid-state active multiplier chain, is feeding the 1THz mixer, while a GUNN oscillator followed by self biased multipliers builds up the 460GHz LO chain.

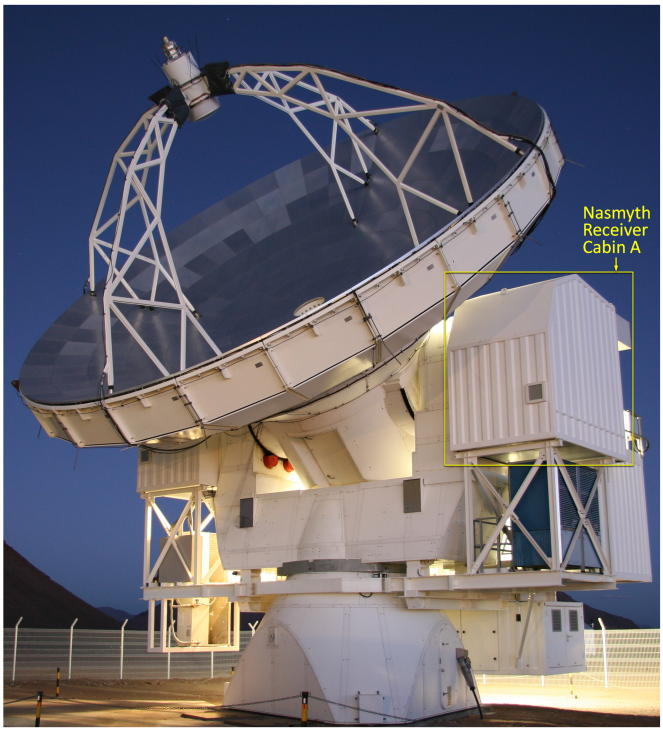


Fig. 2 The APEX telescope short after sunset – marked: Nasmyth receiver cabin A

With the ongoing development of local oscillator sources in the terahertz regime, demanding for high spectral purity, signal stability and sufficient output power, the receiver system also perfectly acts as a test bed for the photonic local oscillator developments at MPIfR [11].

II. SYSTEM DESCRIPTION

In the following paragraphs we will outline the system layout, beginning with the local oscillator systems, followed then by details of the receiver cryostat and an overall system description.

A. 460GHz LO system

The 460GHz LO is a PLL locked GUNN oscillator in W-band, followed by a self-biased multiplier chain. There are no special environmental conditions to take into account, making the LO from a mechanical and electrical point of view rather comfortable to use. All required RF-signals are generated by commercial synthesizers. During telescope operation, the APEX control system [10] commands the synthesizers for the LO frequency and Doppler-shift correction. Therefore, frequency changes can be commanded remotely but require, depending on the covered span, a final re-tuning of the micrometers of GUNN and multiplier waveguide back-shorts to recover LO power.

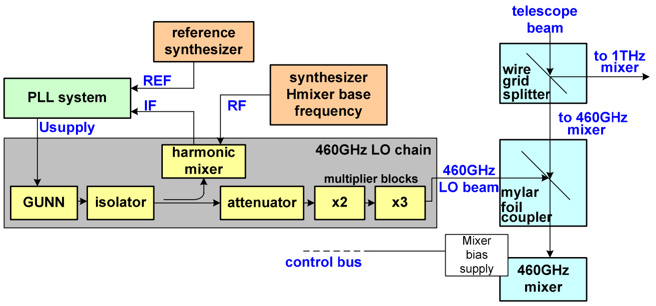


Fig. 3 Schematic of the 460GHz LO subsystem and the LO signal path to the 460GHz mixer

B. 1THz LO system

In contrast to the 460GHz LO layout, output power and foremost lifetime issues make it necessary to operate the 1THz LO chain cold. An additional cryostat increases the mechanical complexity of the system.

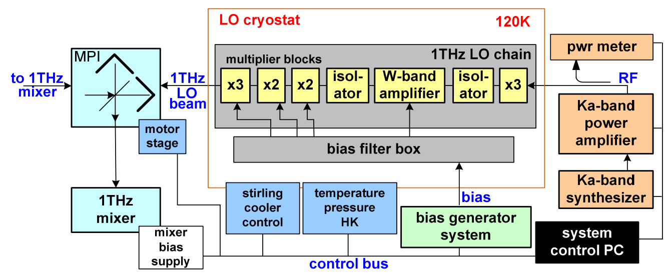


Fig. 4 Schematic of the 1THz LO subsystem and the LO signal injection path to the 1THz mixer

The solution is based on a very compact cryostat design that contains a bias filter box and the LO chain, stacked together in sandwich form. The typical LO chain DC power dissipation of about 3 to 4Watts demands for a cooling system with sufficient power to cool to 120K. In order to have sufficient cooling capacity to compensate for the heat dissipation inside the W-band amplifier, which changes with LO output power, we use a cooler that is capable of handling 6W@77K.

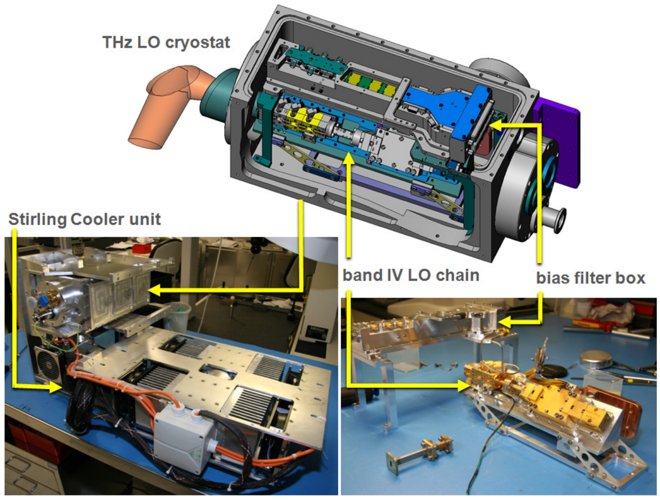


Fig. 5 The 1THz LO cryostat. Left: LO cryostat linked to the Stirling Cooler, the cooler with its radiator system takes most of the space. In the upper right corner is the opened cryostat visible and gives an impression of the very compact design achieved by placing the local oscillator chain and the bias filter box in a stacked way.

Since most of the LO chain's components are actively biased, 7 voltage supplies and additional monitoring of the currents are required to safely operate the chain. We make use of the HIFI LO operation philosophy and strategy, from software as well as from hardware side [8],[9]. Fig. 4 gives a schematic of the 1THz LO subsystem components. The heart of it is the band IV HIFI local oscillator chain. A commercial synthesizer generates the fundamental frequency in Ka-band which is amplified to drive a Ka- to W-band frequency tripler. Output power leveling of the LO chain is achieved by regulating the drain voltage of the second stage of the W-band amplifier. Starting from a safe, low drain voltage with almost no LO chain output power, the drain bias is ramped up to the setting where the mixer is pumped at its optimum level or to the maximum allowed drain voltage value. The Ka-band RF power level, the frequency setting and also the current and voltage housekeeping of the LO chain are monitored. In case that a parameter moves out of predefined ranges, the system takes appropriate measures to bring it back into the safe range or to stop the frequency tuning and set the drain bias voltage or Ka-band drive power to a safe state. The chain produces a peak power level of about 200µW, with a lower limit of ca. 40µW over the range 967GHz to 1042GHz.

C. The Receiver System

Fig. 6 gives insights into the system configuration. On the cryostat cover plate the warm optic components and both local oscillator systems are mounted. The incoming telescope beam is split by a wire grid into the two signal paths. For the 460GHz channel, we couple the LO signal to the mixer by use of a 10% Mylar foil coupler. On the 1THz side a Martin-Puplett interferometer, used as a diplexer, serves for the LO injection.

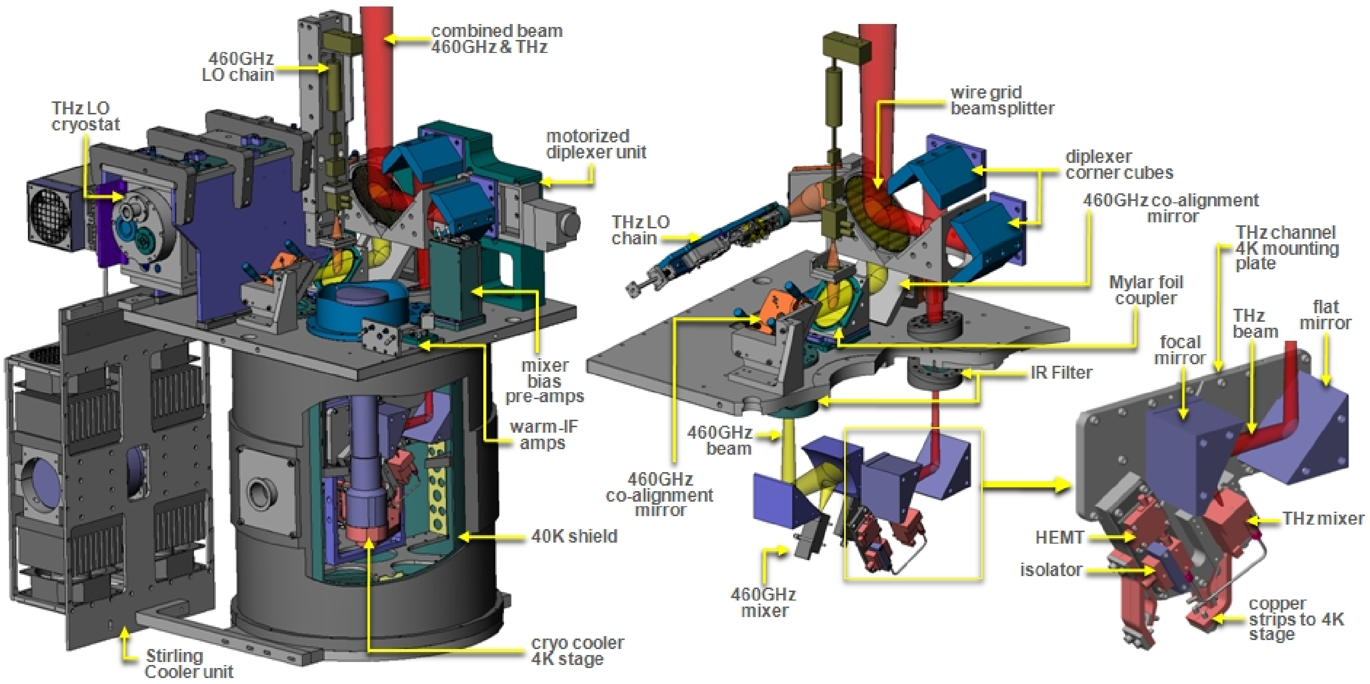


Fig. 6 CAD pictures of the receiver cryostat, generated with the 3D mechanical design software. Left: full integrated system; middle: beam paths with optical components; right: THz channel 4K mounting plate

Although the output power of the solid-state chain is comparably high, we use the Martin-Puplett Interferometer to allow integration of weak LO sources (e.g. the photonic LO source [11]).

For frequency tunings, the moveable arm of the interferometer is motorized to adjust for the correct optical path-length difference with a resolution of 0.1 micron. For the THz beam no adjustable optical elements are foreseen, here we make use of the strict mechanical tolerances achievable in our workshop. In order to co-align the 460GHz pointing channel to the THz beam, two adjustable flat mirrors with micrometer screw drives allow for a tilt and offset move.

We use a 2 stage cryocooler, providing a 40K and 4K temperature level. The cooler`s 40K stage is connected to a thermal shield to minimize the radiative thermal load at the 4K stage. Thermally connected to this temperature stage, there are two mounting plates, one for the 460GHz channel and the other for the 1THz channel (Fig. 6 right). Basically these are precision manufactured aluminum plates that carry the mixer, a low noise and high gain HEMT amplifier and two aluminum made mirrors. To improve the signal matching between mixer and HEMT amplifier an RF isolator, useable under cryogenic temperatures and thermally linked to 4K, is additionally inserted in the 1THz IF path. We gained a low thermal resistance path between the channel mounting plates and the 4K stage of the cryocooler by using packets of copper strips, resulting in an operational temperature of the mixer of 3.9K.

The first optical element behind the mixer is an aspheric mirror, followed by a flat mirror to direct the beam towards the warm optic plate. Infrared stray radiation in the beam path is blocked by IR-filters on the 40K and 4K stage. This reduced the mixer's physical temperature by ~0.4K but also introduces optical loss of 6%. Both cryostat windows use Mylar foils of appropriate thickness to minimize for Fabry-Perot effects.

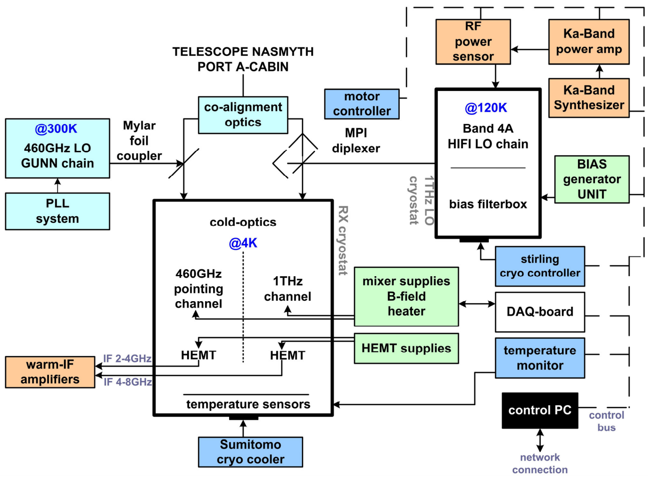


Fig. 7 Schematic of the full system layout

A major benefit of the receiver system is its capability of full remote operation. The control PC connects via a standard instrument bus to the relevant devices and keeps track of important housekeeping parameters on a periodic time base. Tuning requests are accepted via network UDP socket protocol from the APEX telescope control system (APECS).

III. Test Activities

A. *Receiver Tests*

The system was thoroughly characterized in our laboratory prior to its shipment to APEX. Optimum operation of the receiver is achieved by using look-up tables, where relevant data for the optimum LO bias voltages, synthesizer power level, diplexer position are stored as a function of frequency. Therefore, a single frequency entry contains more than fifteen parameters. Between two frequency entries, a linear interpolation scheme is in place, but an adequate distribution in frequency is required to get good receiver performance. Fig. 8 gives a simplified overview of the test setup.

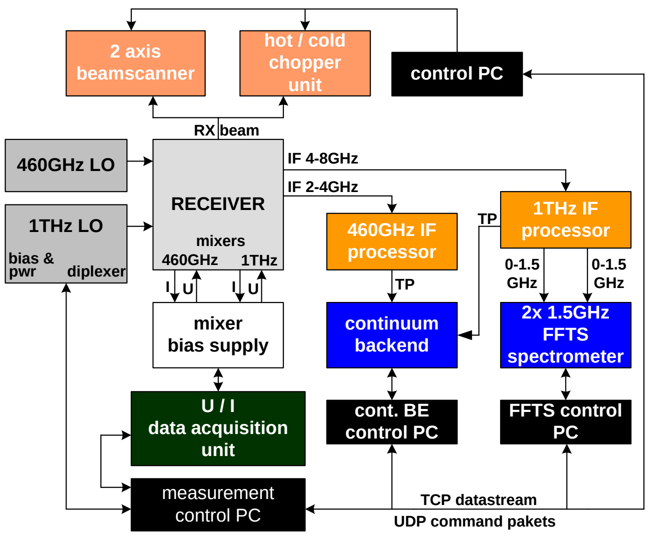


Fig. 8 Laboratory Test Setup

B. *Receiver Noise Performance*

The receiver noise has been measured with the y-factor method using 290K and 78K absorber loads. A typical measurement is shown in Fig. 9. For the un-pumped device, the total power vs. mixer bias in the shot noise region yields an IF noise temperature T_{IF} = 16K. From the hot – and cold traces at the optimum bias point, we derive a total conversion loss L = 2.9, resulting in an upper limit of 45K contribution of the IF to the total noise temperature T_{Rx} = 454K. A successive break-down of the system noise is given in Table 1: Starting from the y-factor measurement at 2.8GHz IF bandwidth, we get 430K at the IF center, explained by the increase of diplexer filter losses at offsets from the IF center. We then substract the various optical contributions and end up with 292K in front of the mixer. Assuming L_{mixer}=1, T_{mixer} would be less or equal 276K, which nicely fits to the mixer's EIDP.

Loss Component	**Loss [%,K]**	**$T_{ambient}$ [K]**	**T_{Noise} [K]**
y-Factor (2.8GHz IF)			455 K
Diplexer Filter Curve	25 K	290 K	430 K
70cm air	50 K	290 K	380 K
Diplexer insertion	1%	290 K	373 K
Window	10%	290 K	312 K
IR Filter	3%	50 K	301 K
IR Filter	3%	6 K	292 K
Mixer	0%	4 K	276 K

TABLE 1 RECEIVER NOISE CONTRIBUTIONS FROM VARIOUS COMPONENTS

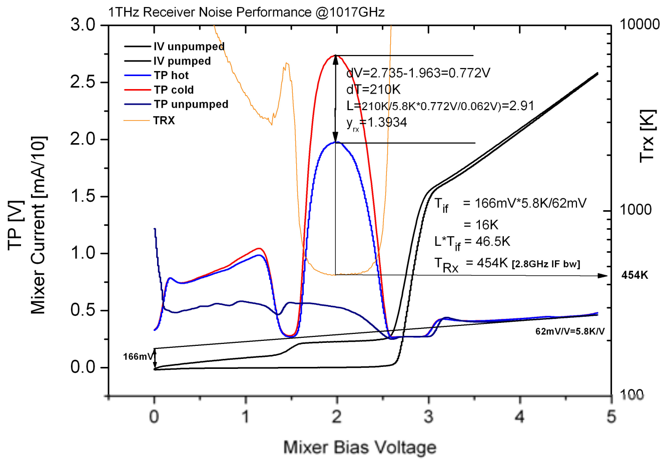


Fig. 9: Receiver noise measurement at 1017GHz. The total power signal contains the IF signal bandwidth of 2.8GHz

D. *Local Oscillator Noise*

As mentioned above, the total power signal refers to the 2.8 GHz wide IF. Fig. 10 shows T_{Rx} vs. IF band frequency and reveals the LO diplexer's filter characteristic pass-band. The black curve of this figure represents the receiver noise temperature for a 120K blackbody[1] LO (physical LO temperature), whereas the red curve has been calculated assuming an equivalent temperature of 350K to fit to the measured $T_{Rx.}$ A comparison shows that obviously a significant noise contribution apart from the LO physical temperature is generated by the LO in the range 4.6 - 7.4 GHz offset to its carrier. We have compared this to the HIFI band 4a noise measurements, taken during the HIFI commissioning phase and got to a very similar result.

To eliminate the uncertainty in knowing the exact blackbody temperature of the cooled LO chain, we repeated this test operating the LO at room temperature. Fig. 11 shows the measured T_{Rx} and two traces, red and black, representing the calculated T_{Rx} for 460K and 290K black body temperature loads at the diplexer LO port. We conclude that the local oscillator signal noise in this configuration is 170K higher than its physical temperature, confirming the above considerations for the cooled LO.

Tuning the LO diplexer to the appropriate path-length difference gets more critical the more LO noise is in excess at the diplexer's LO port. The significant impact of a detuned diplexer on the receiver performance is shown in Fig. 12. Adjusting the tuning mirror position in steps of 6 microns immediately increases the noise temperature, and detuning it more, reveals an excess noise feature at about 600MHz below the IF center. We obviously make use of the diplexer's property, to act as a filter of LO noise in the signal frequency range. Regardless of the sign of the detuning, the noise feature appears at the same IF frequency, because the mixer is a DSB mixer and the LO noise is symmetric wrt. to the

[1] We define the LO physical blackbody temperature of 120K as a lower limit for the noise contribution. A more realistic value would be 150K, as the chain front-side absorber is IR heated. The thermal noise of the window at 290K adds another 30K.

carrier. The only difference appears to be that the higher LO frequency tuning (negative detuning) favored an optical standing wave manifested in an IF ripple. An outmost important conclusion is that only a very precise model to predict the interferometer's mirror adjustment over the whole RF range can ensure an optimum noise suppression by this filter, when it is operated remotely at the telescope-site.

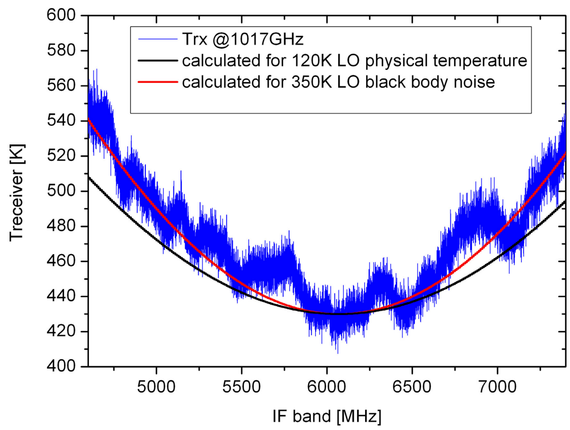


Fig. 10: Measured receiver noise vs. IF band frequency, showing the noise contribution of the local oscillator diplexer pass-band. The black curve indicates the expected noise by the local oscillator port at a physical temperature of 120K, the red curve fits to the measured data assuming 350K LO port load, indicating excess noise of the solid state local oscillator chain.

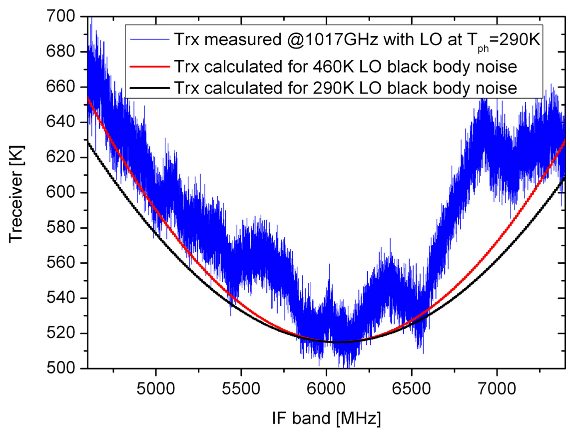


Fig. 11 Measured receiver noise vs. IF band frequency with LO chain operated at room temperature. The black curve represents the calculated noise temperature assuming 290K for the LO, whereas the red curve, assuming 460K, fits to the data. The LO noise is 170K higher than its physical temperature.

C. Beam Measurements

We used a computer controlled two axis motorized moving stage to move a chopped cold load aperture in front of the receiver's field of view and monitored the total power signals of both receiver channels in parallel. Beside the verification of the telescope beam waist (size and position), the co-alignment of both channels is of outmost importance. Only an excellent relative pointing accuracy can ensure that the 460GHz channel guides the 1THz system in tracking the weak astronomical source with a 6 arcsecond footprint on sky at 1THz.

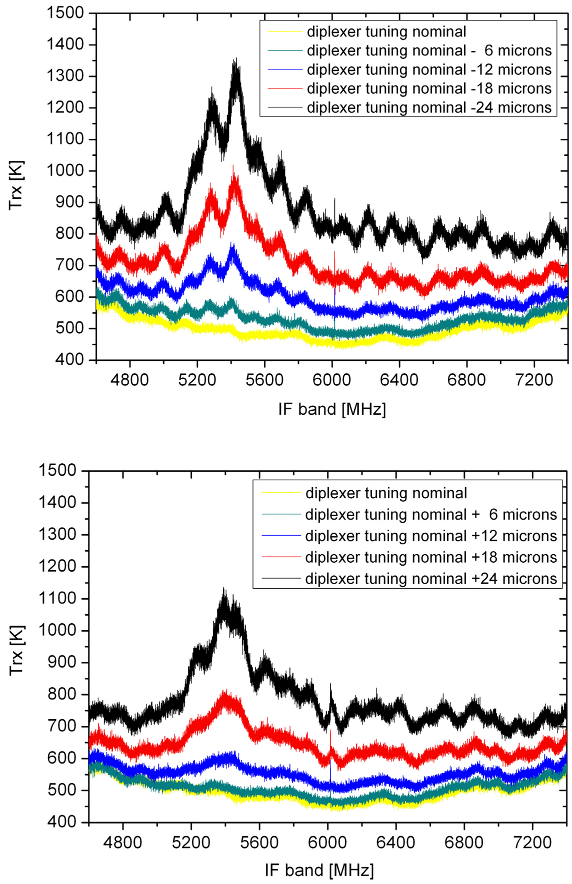


Fig. 12: Trx for various diplexer tunings around the optimum path-length difference. Top and lower figures show the LO noise contribution for negative and positive corner cube mirror movement, respectively. The spike at the band center at the IF center (6GHz) due to the overlay of adjacent backends will be blanked in the calibration pipeline.

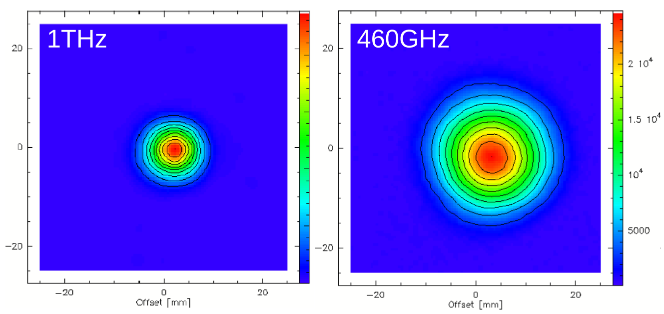
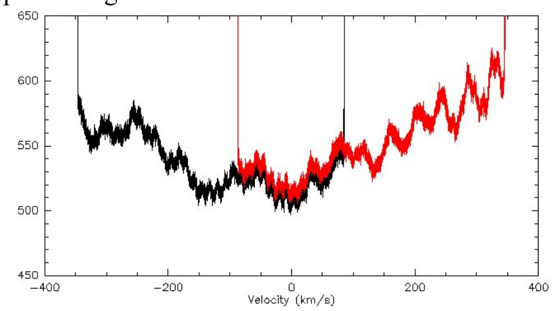


Fig. 13: Beam patterns measured in the laboratory. After de-convolution with the absorber-moon diameter, the waist sizes agree with the telescope nasmyth waist.

IV. RECEIVER AT APEX

The system was installed at the APEX telescope (Fig. 2, Fig. 16) Principle Investigator position #2 of the Nasmyth A flange in mid 2009 for the MPIfR observation periods in August and November.

After first integration tests and fine tunings on the look-up tables, we have been able to reproduce good receiver noise temperatures over the IF range as measured in the laboratory setup. Fig. 14 gives the receiver noise for a remotely invoked tuning by the APEX control system at the CO(9-8) rest frequency. The data was measured by using the telescope's internal calibration load inside the A cabin and the APEX signal processing chain.



V.

Fig. 14: Receiver noise temperature at the CO(9-8) line USB tuning, LO at 1030.91GHz

By pointing scans on planets we determined the beam size on sky for the 460GHz to be 12.7 arcsec and for the THz channel to be 6 arcsec. At that time Mars was rather small in diameter, 5.4 arcsec only, Jupiter 47.3 arcsec, respectively. These results match pretty well to the telescope's diffraction limited beams.

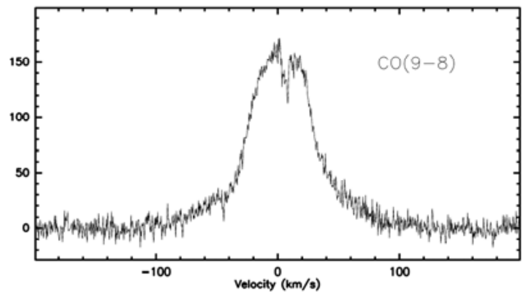


Fig. 15: A CO(9-8) spectrum towards Orion-KL, with PWV ≥0.4mm, main beam brightness of ~170K

Despite of rather bad atmospheric conditions throughout the full observation period, we could make use of nights with PWV values of 0.4mm, just at the edge where useful THz observations are possible. Fig. 15 shows a spectrum towards the star forming region of Orion-KL, centered on the frequency of the CO(9-8) transition. The main beam brightness temperature of ~170K is comparable with those measured with CHAMP+ for the CO(7-6) transition.

VI. CONCLUSIONS

We have presented the system layout and technical details of a dual channel heterodyne instrument, operating in the 300 and 625 micron atmospheric windows at APEX. The 1THz and 460GHz beams are optically co-aligned which allows to guide the 1THz observation with the 460GHz channel (at 1THz there are very few pointing sources available). Unusually bad weather conditions with high PWV during the observation periods in 2009 made challenging observations impossible. After establishing a pointing model, we managed to take a few spectra towards the star forming region of Orion-KL. This, at least, proofed the robustness of our data pipeline and the pointing procedure. The receiver will return to APEX for the 2010 observing season.

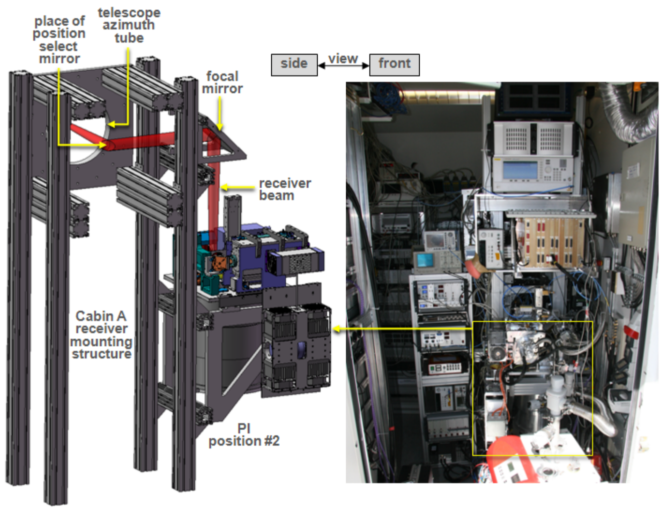


Fig. 16: Receiver installed in A-cabin at APEX, with all the electronics for operation the receiver consumes quite an amount of space

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