First 1.3 THz Observations at the APEX Telescope

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***Abstract*—The Atacama Pathfinder EXperiment (APEX) 12m telescope is operating on the Llano Chajnantor, Chile, since 2003 and a set of state of the art sub-millimeter receivers have been installed for frequencies spanning from 150 GHz to 1500 GHz. In 2008, a balanced 1.3 THz Hot Electron Bolometer (HEB) receiver was installed for the atmospheric window 1250-1380 GHz. This instrument is part of a 4-channel receiver cryostat with the other channels being 211-275 GHz, 275-370 GHz and 380-500 GHz Sideband Separating (SSB) SIS receivers. This paper presents the first observations obtained so far with the 1.3 THz band during its first months of operation. The sky measurements were taken during opportunistic commissioning and science verification phases, when the weather conditions were sufficiently good with a Precipitable Water Vapor (PWV) below 0.25 mm, which was the case only a few nights during these months. We present the first observations of the molecular transition CO J=(11-10) line on different sources such as Orion-FIR4, CW-Leo and SgrB2(M). We describe the many challenges and difficulties encountered for achieving successful THz observations from a large sub-millimeter ground-based telescope.**

***Index Terms*— Balanced receiver, HEB mixer, sub-millimeter waves, THz**

I. INTRODUCTION

THE 12 meter APEX telescope [1] is currently the largest sub-millimeter dish in operation in the southern Hemisphere. It is an early prototype of the Atacama Large Millimeter Array (ALMA) [2] Vertex antenna and its additional Nasmyth cabins (see Fig. 1) together with the Cassegrain cabin, allow the operations of a full suite of instruments. The different receivers installed, both heterodyne and continuum detectors, cover the frequency range from 150 GHz to 1500 GHz [3].

The chosen site at an altitude of 5100 m, is one of the best on Earth for its atmospheric conditions, which opens atmospheric windows up to ~1500 GHz [4]. This 1.3 THz receiver (known as apex-T2), was delivered by the Gard group in Chalmers University with the Onsala space observatory in Sweden, and it covers the atmospheric window from 1250 to 1380 GHz. Figure 2 shows the corresponding calculated atmospheric transmission for Precipitable Water Vapor (PWV) of 0.1, 0.2, and 0.3 mm. Terahertz observations are only worth performing for PWV below ~0.25 mm when the zenith atmospheric transmission gets above 20%. Such good atmospheric conditions are only achieved on average ~20 nights a year or ~5% of the year (statistics from 2003-2008).

Fig. 1. APEX 12 m antenna located on the Llano Chajnantor at 5100 m altitude in Northern Chile. On the picture, a crew of two people is adjusting the 5-screw panels to improve the surface accuracy. This is normally performed once a year after a holography session and is needed to allow efficient THz observations.

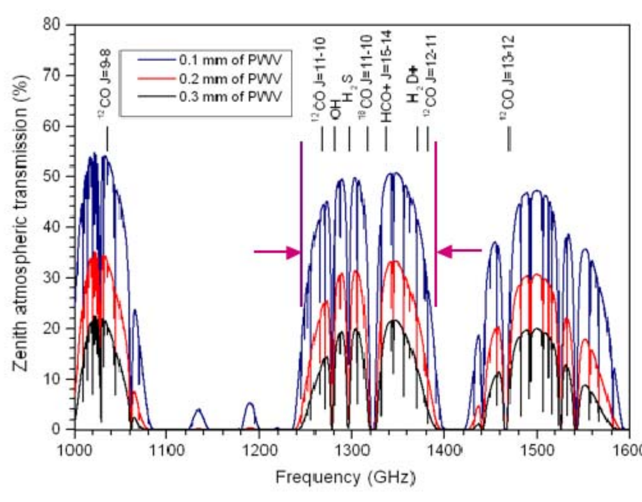

Fig. 2. Atmospheric transmission on the Llano Chajnantor for different weather conditions from 0.1 to 0.3 mm PWV. 0.3 mm is already considered excellent condition for observations until ~900 GHz, but is insufficient for the 1.3 THz window.

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Atmospheric conditions are only one of the many challenges for successful THz observations. At 1.3 THz, the telescope beam is about 4.5”, which becomes comparable with the telescope absolute pointing accuracy (~2-3” rms). As there are basically no pointing sources at those frequencies, the pointing has to rely on relative measurement with the lower frequency bands.

Also, the antenna surface accuracy becomes increasingly critical at those wavelengths and requirements for THz observations are precisions below 18 μm rms.

II. Receiver Design

The apex-T2 receiver is a balanced HEB receiver operating from 1250 to 1380 GHz. A full description of the receiver is published in [5]. The balanced scheme is shown in Fig. 3. The RF and LO signals are combined through a 3 dB-90 ° waveguide hybrid built with a combination of photolithography of a thick photoresist and fine copper electroplating, which allow reaching unprecedented accuracy of far less than 2 μm and with better than 100 nm surface roughness for the waveguides [6]. The waveguide outputs are then connected to two block pieces incorporating the HEB mixer chips (Fig. 4). The chips are done in quartz substrate of 17 μm thickness.

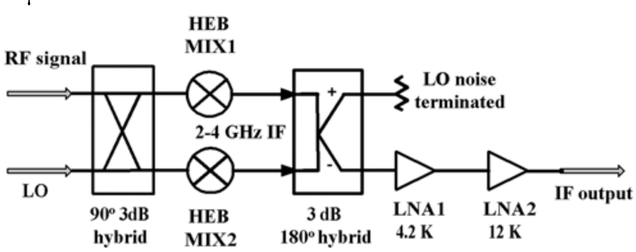

Fig. 3. Mixer layout. The balanced scheme is achieved by using 2 very similar mixers using as inputs the combination of the RF and LO signals through a 3 db-90 ° hybrid.

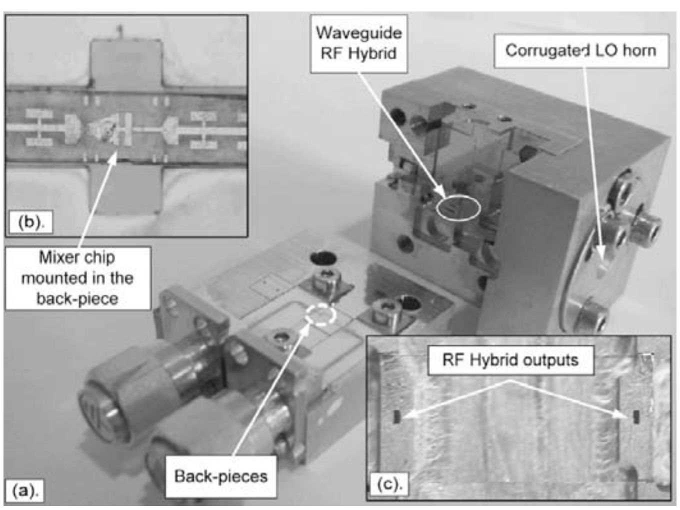

Fig. 4. Picture of the mixer block.

The IF signal outputs from the HEB mixers are then fed into a commercial 3 dB-180 ° hybrid from 2-4 GHz. One of its output is terminated with a 50 Ohm load, corresponding to the LO noise, and the other output is the signal of interest, and is amplified by state of the art cryogenic low noise amplifiers for 2-4 GHz [7].

This balanced scheme has many advantages. There is no need of a beamsplitter or diplexer to inject the LO, and all of the LO power is used advantageously. Furthermore, the LO amplitude modulated noise is terminated onto the load. Also, any unwanted spurious responses are well rejected. These help considerably for example for stability considerations.

The drawback is the need of using similar junctions, which proved to be very difficult for those components, frequency ranges and mounting considerations. Figure 5 shows the measured IV curves unpumped and pumped for the selected HEB mixers.

The receiver is mounted on the 4 K cold plate of a cryostat containing 3 other channels for frequencies 211-275 GHz, 275-380 GHz and 380-500 GHz. This receiver is the Swedish Facility (SHFI) described in [8]. The cooling machine is a closed cycle 3-stage cooler, providing a 4 K cold stage temperature. A temperature-stabilization is implemented in the coldest stage to stabilize the 4 K temperature of the different bands at levels ±2 mK. Having the ability to reach exactly the same physical temperatures allows efficiently using lookup tables.

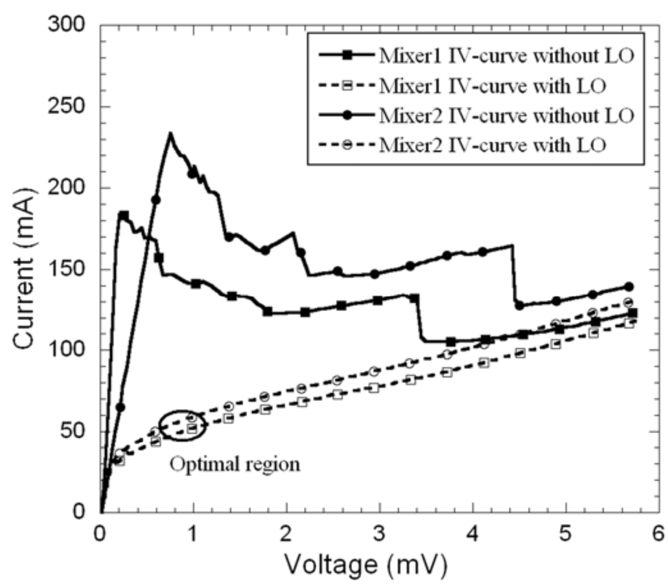

Fig. 5. IV curves for unpumped and optimally pumped conditions for the selected HEB junctions.

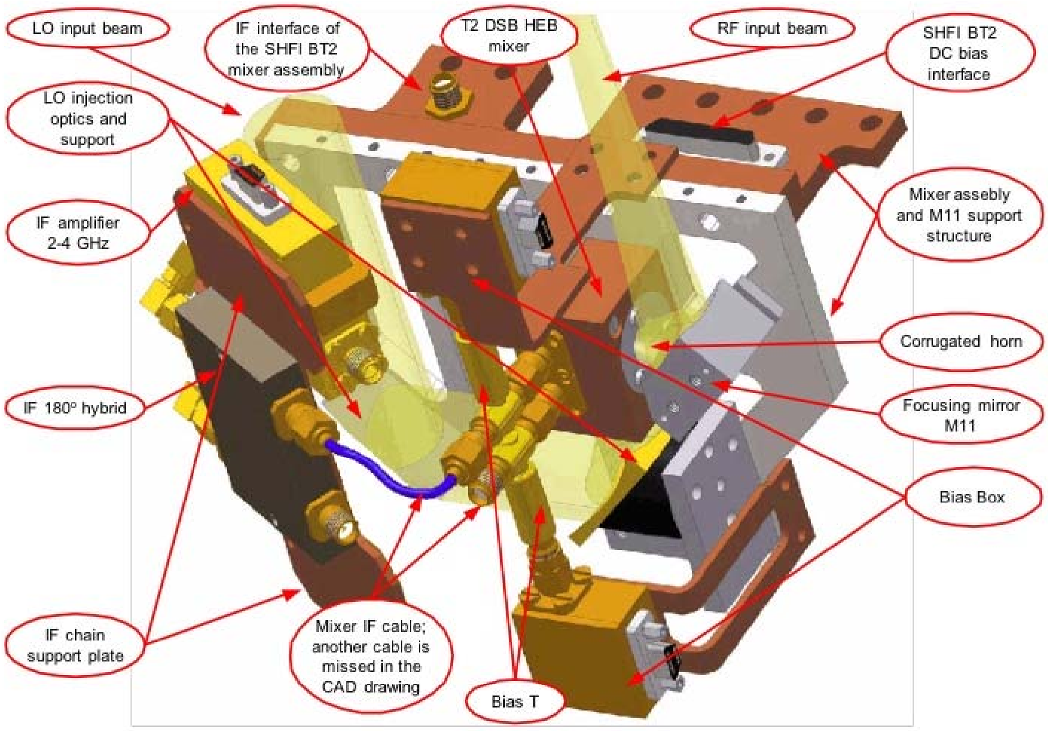

Fig. 6. The whole mixer assembly is mounted on a hexagonal plate which is thermally connected to the cryostat 4K cold stage through flexible copper wires.

III. Receiver Characterization

A. Receiver noise temperature

The receiver noise temperature were first measured on-site with external hot and cold blackbody loads of ~300 K and 77 K, put directly in front of the cryostat window. The Nasmyth A cabin incorporates a calibration unit module, providing hot and cold loads for the routine observations calibrations. At 1.3 THz, the loads coupling coefficients are far from unity, and they were adjusted to fit the external loads measurements.

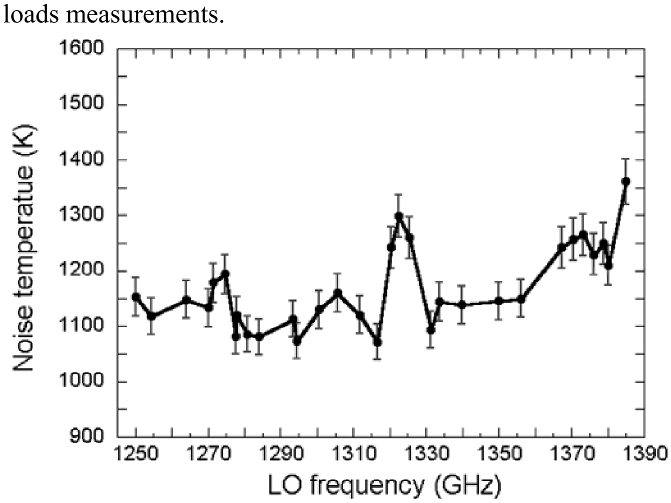

Fig. 7. Receiver noise temperatures as measured in the laboratories. On-site measurements are comparable.

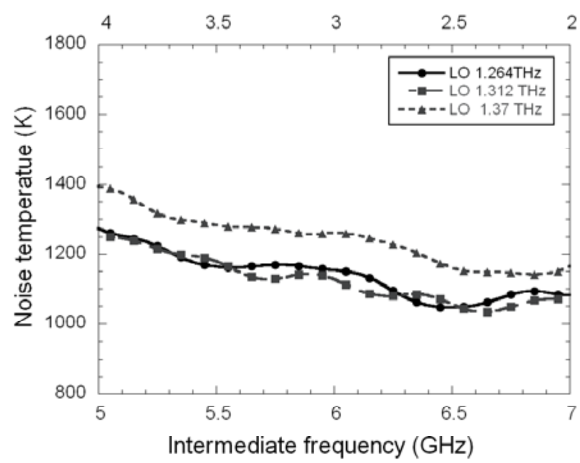

Fig. 8. Noise temperature across the IF band The 2-4 GHz IF output is unconverted to 7-5 GHz. Note that though there is no isolator between the HEB mixer and low noise amplifier, there are no IF standing waves.

Figure 7 shows the receiver noise temperature measured in the laboratory across its whole RF range. The noise temperature function of the IF frequency is shown in Fig. 8. Characteristics on site are very similar.

Although there are no isolators between the mixers IF outputs and the low noise amplifiers, the IF band-pass is very smooth and there are no visible IF ripples, quite strong for example in HIFI HEB bands [9, 18], where the HEB IF outputs are directly connected to the LNA inputs.

B. Receiver stability

The receiver stability was measured on site looking at a hot blackbody load of about 300 K. The backend is a Fast

Fourier Transform Spectrometer FFTS [10], which recorded during several hours the IF signals with a resolution bandwidth of 1 MHz. A standard way of characterizing the receiver stability is the Allan Variance [11-12].

Total power stabilities of ~50 seconds are achieved and spectroscopic stabilities are higher than 100 seconds. These numbers are comparable to SIS receivers and unusually good compared to other HEB receivers [13]. Results are even more impressive given that the HEB receiver is mounted on a closed-cycle cooling machine, which generates relatively strong 1 Hz vibrations.

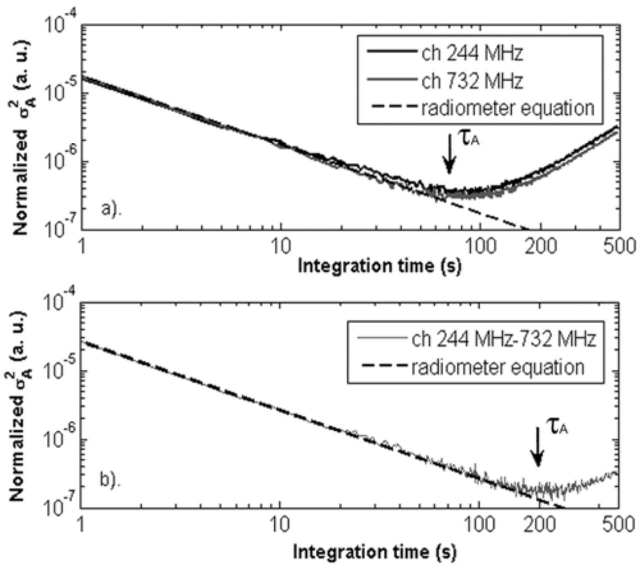

Fig. 9. Total power and spectroscopic Allan Variances measured at the 1316 GHz LO frequency. The backend bandwidth was of 1 GHz and channels corresponding to 244 and 732 MHz at IF were selected randomly to calculate the spectroscopic Allan Variance.

IV. Telescope

A. Pointing

During the first years of operations, it was noticed that the telescope tilt (defined as the telescope azimuth rotation axis) was drifting and could change in very short timescales. Figures 10 and 11 show the tilt direction and angle in a 1-year timescale. The reason for this is unknown, but causes significant problems at high frequencies, where the tilt changes can be comparable or larger than the beam sizes. The long-term variations are most likely due to seasonal and geographic variations (also seen with ALMA antennas) but the very rapid and short-term variations are not understood yet.

To minimize this effect, a standard calibration routine is performed daily at APEX, consisting in measuring the telescope tilt with a set of tiltmeters and correcting the pointing model for the change in tilt. With this correcting scheme, the absolute pointing accuracy can still be of about 2-3" rms as it can be seen with the low frequency receivers.

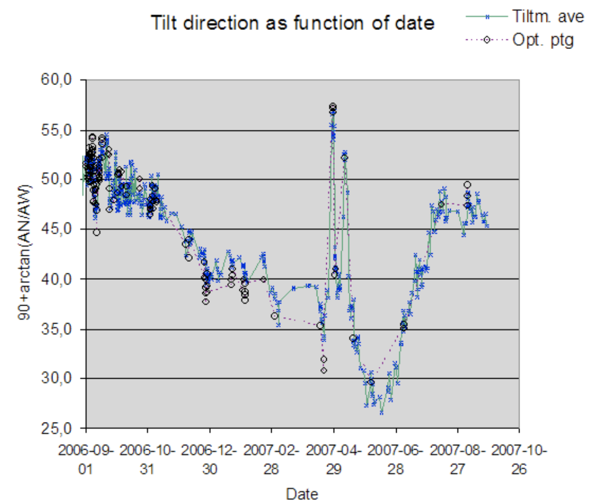

Fig.10. Tilt direction change during a 1 year period. Very sudden changes were seen on few occasions in April 2009.

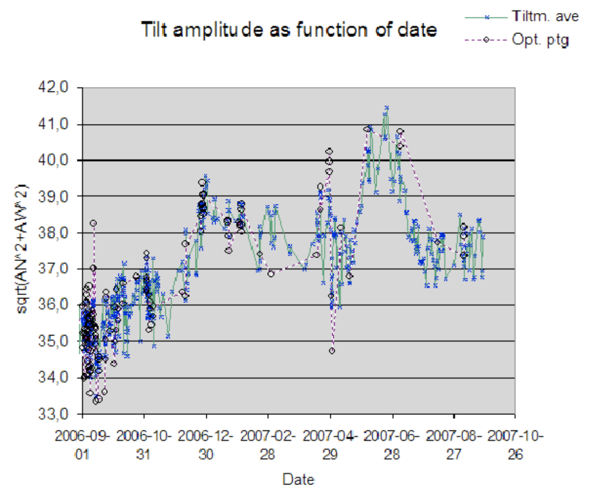

Fig. 11. Tilt amplitude change during a 1 year period.

When performing apex-T2 observations, as there are basically no pointing sources strong enough at those wavelengths, the idea is to use one of the low frequency bands within SHFI, either the 230 GHz or the 345 GHz and use them for pointing towards a source nearby the selected target. The relative pointing offsets and focus offsets are not expected to change and once derived, the switching between the different bands takes less than 5 minutes, all included. The difficulty lies in deriving the initial relative offsets between the bands, but once this is done, this would ensure efficient observing.

B. Telescope Surface accuracy

The ALMA 12 m antennas have a specification for their surface accuracy of 18 µm rms. This is sufficient for observations up to ~1 THz but for higher frequencies, requirements are greater. Holography sessions are typically ran once a year to check the surface accuracy and if needed adjust the panels to improve it. The 12 m telescope is made of 264 small aluminum panels in 8 rings on a Carbon Fiber

Reinforced Plastic (CFRP) backup structure, which ensures thermal stability.

Figure 12 shows the surface accuracy after the panels had been adjusted. This is about the best settings that can be achieved. However, this is measured at an elevation of ~13 degrees (the holography transmitter is located on a neighboring mountain), so a correction for the expected gravity deformation is done to optimize the surface for 50 degrees elevation.

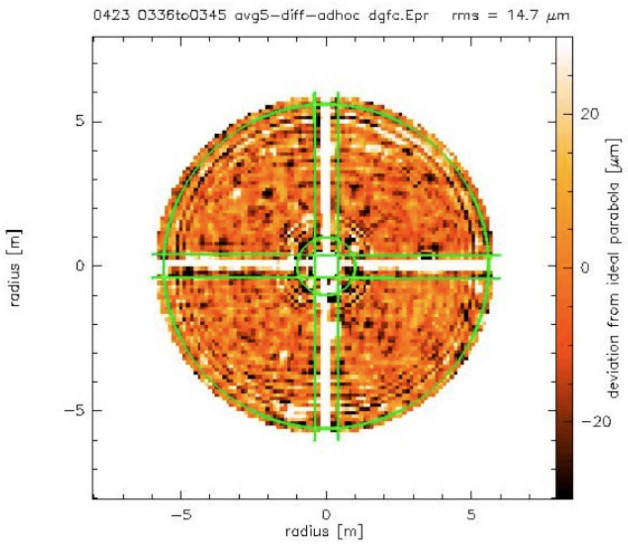

Fig. 12. Surface accuracy of the APEX dish after a successful holography run and subsequent panel adjustment in 2007. The achieved rms was of 14.7 µm.

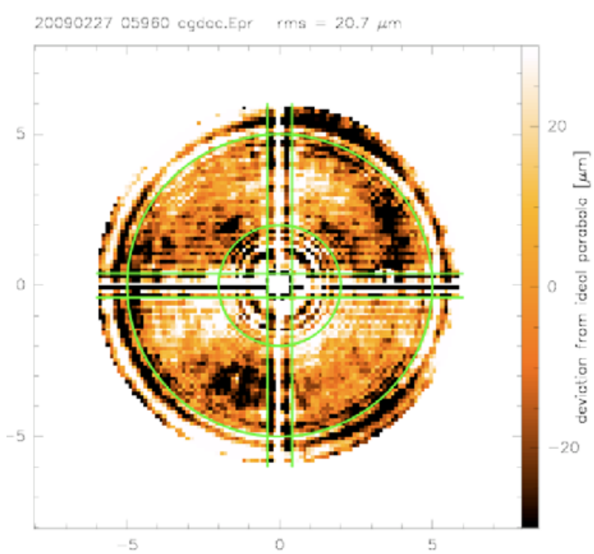

Fig. 13. Surface accuracy of the APEX dish after a holography run in 2008. The measured average rms is of 20.7 µm.

After several months, the surface might degrade and Fig. 13 shows the accuracy when measured in 2008. The antenna surface is very sensitive to temperature changes and the temperature control in the Cassegrain helps maintaining stable temperature. The latest measurements in 2008 show a worsening, and the surface accuracy during the THz observations presented in this paper were more likely to be between 20-25 µm, which is consistent with the derived beam efficiencies.

Figure 14 shows the aperture efficiency dependency on the surface accuracy of the antenna. It can be seen for example that from 15 to 20 µm surface accuracy rms, the aperture efficiency drops a factor of 2 at 1.3 THz.

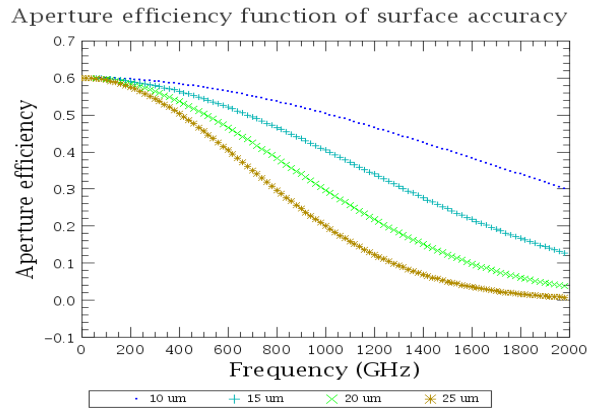

Fig. 14. Aperture efficiency dependency on surface accuracy. Best achievable results seem to be about 15 µm rms after a panel adjustment session but 20 µm rms is more likely to be the average value after few months.

V. First Observations

A. Astronomical lines of interests

The installation of this 1.3 THz receiver was motivated by the relative good atmospheric transmission achievable from this site. Also several important molecular transitions are observable within this window. Table 1 summarizes the most important lines.

TABLE 1 Molecular lines in the 1.3 THz window

Molecular transition	Frequency (GHz)
CO(11-10)	1267.014486 GHz LSB
HNC(14-13)	1268.200385 GHz LSB
CS(26-25)	1270.952878 GHz USB
H2CO(422-303)	1274.49247 GHz USB)
C18O(12-11)	1316.244114 GHz USB
HCN(15-14)	1328.302232 GHz LSB
LiH(3-2)	1329.41543 GHz LSB
HCO+(15-14)	1336.71492 GHz LSB
C17O(12-11)	1347.115 GHz LSB
HDO(303-202)	1353.77657 GHz USB
HNC(15-14)	1358.612610 GHz USB
CS(28-27)	1368.234047 GHz USB
H2D+(101-000)	1370.146 GHz USB
CO(12-11)	1381.995105 GHz USB

Among the most important lines in this band are the high-J transitions of CO, the J=11-10 and J=12-11. These lines can be emitted only from hot (T>100 K) and dense (n□$10^{5.5}$ cm^{-3} or higher) molecular gas.
One of the most interesting lines in this frequency range is the ground-state para-H_2D^+ transition at 1370 GHz. This molecule is an appropriate tracer for the deeply embedded parts of dark cloud cores where other molecules freeze out onto the grains surface. The ground-state ortho-H_2D^+ transition at 372 GHz was already detected in several sources, however, the p-H_2D^+ has never been detected so far, and therefore its first detection is one of the receiver priorities.
It is worth noticing that the HIFI instrument does not cover this frequency range, and therefore both instruments could benefit from each other. The HIFI band 5 currently reaches 1271 GHz, therefore at least the CO(11-10) and CS(26-25) are observable with both receivers, which is very important for cross calibration purposes.

B. Initial pointing, focus on Jupiter

Only the Moon and the brightest planets, e.g. Jupiter are possibly detectable with total power continuum observations. Jupiter was only detected at high elevations and with PWV less than 0.25 mm, when the T_{SYS} is below 15000 K. To take advantage of the maximum atmospheric transparency, the receiver is tuned to 1353 GHz USB, where although the T_{REC} is slightly worse than at lower frequencies, the overall T_{SYS} is better. Unfortunately, only 1 GHz of the 2 GHz IF range is currently handled at APEX (backend limitations), so a factor of 1.4 in sensitivity is directly lost.

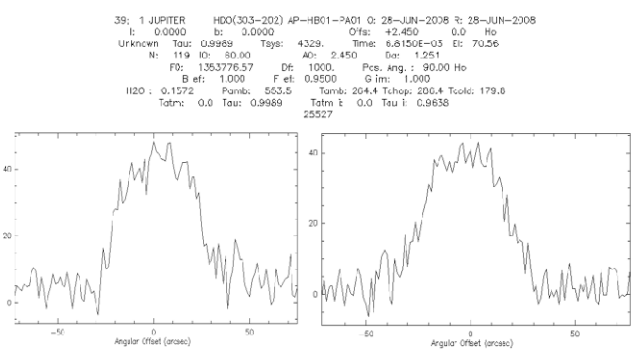

Fig. 15. Jupiter pointing in elevation (left) and azimuth (right).

Figure 15 show the pointing on Jupiter under very good weather conditions, and high source elevation. After the telescope pointing corrections were taken into account, the focus is normally found by moving the sub-reflector in every direction and finding the maximum of flux, which corresponds to a focused telescope. However for Jupiter, which is extended (~30”) for the T2 beam, this procedure doesn’t work well as a defocused beam still ends up on Jupiter.

A smaller sized planet such as Mars would work better, but it was not visible at the time and was also too weak for this purpose (too far from the Earth at the time).

Therefore, until now, few pointing measurements were performed and only initial relative offsets were found between the different bands within SHFI. More measurements are needed to fully cover this part and the focus relative positions should be performed whenever possible when Mars will be strong enough.

Calculations and models from [1], show that we expect a first error beam of ~80”.

C. Observations of Orion-FIR4

The very first spectroscopic observations were done on the 14th of March 2008, looking at the very strong line of CO(11-10) in Orion-FIR4 [17]. The telescope was not pointed (nor focused) properly, explaining the narrower line width and lesser intensity than expected (Fig. 16). This region is very extended; therefore the line was easily detected.

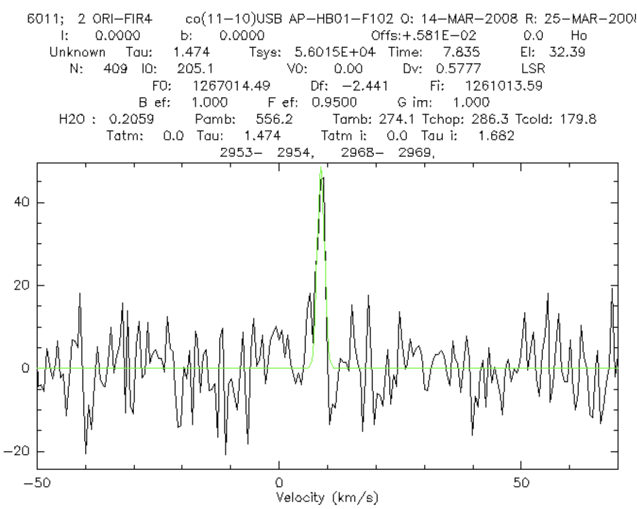

Fig. 16. First light on Ori-FIR4. Telescope was not pointed, nor focused, explaining the lower T_{MB} than expected (~ 200K).

D. Observations of CW-Leo (IRC-10216)

During the Science verification of the SHFI receiver, the evolved Carbon star CW-Leo (also know as IRC-10216) was observed at CO(11-10) (Fig. 17) and the line was clearly detected with a T_{mb} of ~ 41 K. This source is routinely used as pointing source for low frequency receivers and will be intensively observed by HIFI.

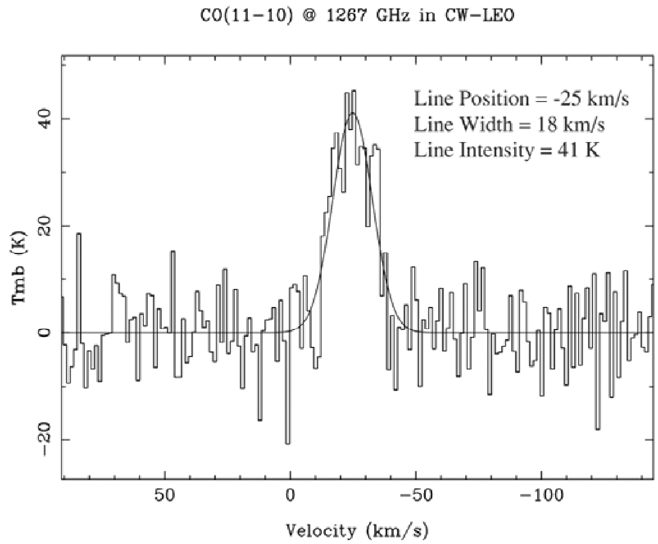

Fig. 17. CO(11-10) observations performed on April 2008.

E. *Observations of Sagittarius B2 (SGR-B2(M))*

The normal operation of the apex-T2 receiver is an opportunistic one. As the observations can only be done during few nights a year, whenever the conditions are good enough, the high frequency receivers have priority and take over the observations.

During one of those opportunities, commissioning observations were done on the Sagittarius B2 region. Several transitions were looked for, namely CO(11-10), CO(12-11), HCN(15-14) and SH. Only the first one was clearly detected and is shown in Fig. 19. The T_{MB} is of ~20K. The line shows a strong dip in the center, pointing to different causes. Either the line is excited enough and shows here self-absorption (which is seen at the lower J transitions) , either the reference OFF position during the observation had emission; therefore the ON-OFF will cause a similar line profile. More observations are needed to disentangle between both scenarios.

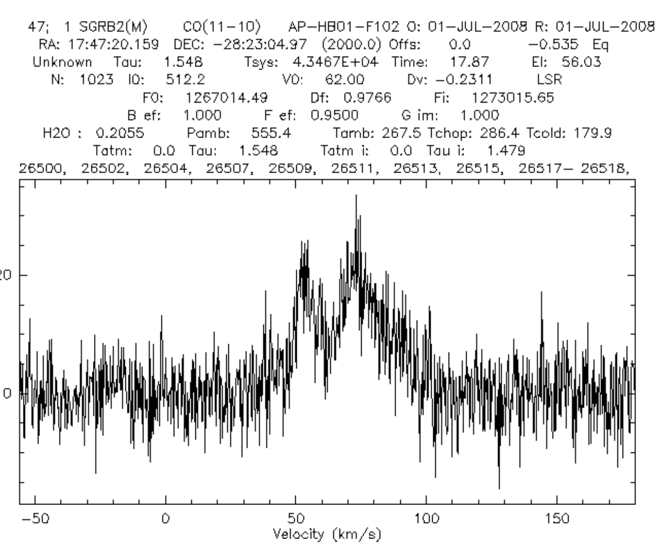

Fig. 18. CO(11-10) in SGR-B2(M) during T2 commissioning opportunistic observations.

VI. Conclusion

A state of the art balanced HEB receiver was installed at the APEX telescope in 2008, achieving excellent sensitivities and stability. Only a few nights of observations on sky were performed so far, but already several detections were readily performed.

The main challenges at those frequencies are:

- Weather conditions should be better than 0.25 mm PWV, which is the case only ~5% of the time.
- The antenna surface accuracy needs to be below 18 μm rms to achieve acceptable aperture efficiencies, however the antenna surface accuracy seems to be degrading with time and was probably above that threshold.
- Pointing is very difficult due to the absence of pointing sources, to variations in the telescope tilt causing change of several arcseconds, which is then comparable to the 1.3 THz beam of 4.5”. Also, pointing to Jupiter can be very difficult due to the previous point, with a poor aperture efficiency.

Therefore, a prerequisite for efficient use of the 1.3 THz receiver is to have the best antenna surface possible, which would in turn allow an easier pointing and focus estimation using planets, and tie those to lower frequency bands. Also, an improvement would be to use the full IF bandwidth to improve the sensitivities.

This would allow very efficient use of the THz receiver as it can be readily used any time and take advantage of opportunistic weather conditions. This receiver covers a frequency band that won’t be observed with the HIFI instrument of Herschel [18]. As such, the apex-T2 receiver, in combination with the 12 m APEX antenna at the Chajnantor site, offers excellent opportunities for THz astronomy, to complement and cross calibrate HIFI. Especially, APEX follow-up studies can be envisioned whenever higher spatial resolution is needed.

Acknowledgment

We would like to thank the APEX staff for their support during the receiver installation and observations.

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