CHAMP$^+$: A powerful submm Heterodyne Array

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***Abstract*— To make best use of the exceptional good weather conditions at Chajnantor we developed CHAMP$^+$, a two time seven pixel dual-color heterodyne array for operation in the 350 and 450 µm atmospheric windows.**
CHAMP$^+$ uses state-of-the-art SIS-mixers provided by our collaborators at SRON. To maximize its performance, optical single sideband filter are implemented for each of the two sub-arrays, and most of the optics is operated cold (20K) to minimize noise contributions. The instrument can be operated remotely, under full computer control of all components.
The autocorrelator backend, currently in operation with 2 x 1GHz of bandwidth for each of the 14 heterodyne channels, will be upgraded by a new technologies FFT spectrometer array in mid 2008.
CHAMP$^+$ has been commissioned successfully in late 2007. We will review the performance of the instrument "in the field", and present its characteristics as measured on-sky.

I. Introduction

Based upon the experience gained with the successful precursor array receiver CHAMP (Carbon Heterodyne Array of the Max-Planck-Institute [1]), we developed CHAMP$^+$, an even more sophisticated heterodyne array. The precursor instrument CHAMP was build for the 460GHz atmospheric window and showed the high scientific potential of hetero-dyne array receivers during its almost four years of operation at the CSO. Its unmatched performance especially in large scale mapping projects like in the horsehead nebula as shown in figure 1 was proven during that time.

In 2003 the receiver was returned to MPIfR and was heavily re-worked for operation at APEX: CHAMP$^+$, as it is now called, operates in the 660GHz and the 850GHz atmospheric windows having two individual sub-arrays. Both sub-arrays are operated in orthogonal polarizations to make parallel use possible. Each consists of 7 pixels in a hexagonal arrange-ment including a center pixel. Cold optics, single side-band filters and powerful spectrometers guarantee for optimum performance. The development was done in collaboration with SRON, providing the SIS-mixer devices for both colors.

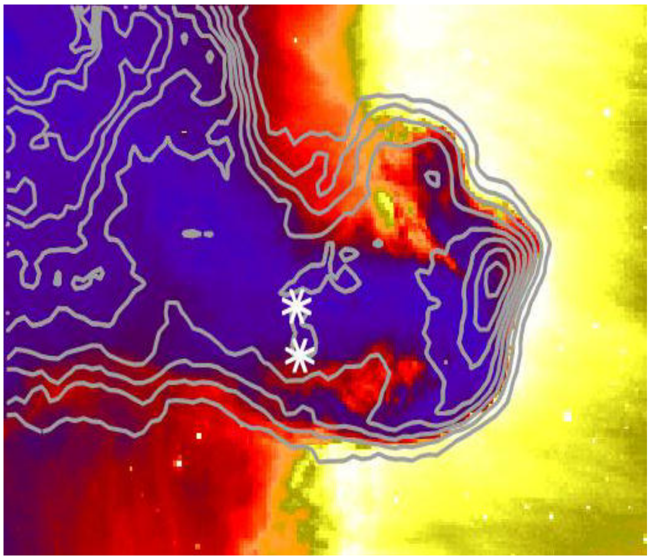

Fig.1: Contours show the distribution of warm carbon monoxide CO(4-3) as measured toward the Horsehead nebulae with CHAMP, the precursor instrument to CHAMP$^+$ [3].

CHAMP$^+$ was installed at the APEX telescope – the Ata-cama Pathfinder EXperiment[1] [2] – in early 2007. With the unique observing conditions of the telescope, CHAMP$^+$ now offers unmatched mapping capabilities in the high sub-milli-meter regime. This article describes the instrument and pre-sents some of the first data taken during the commissioning and first observing runs in 2007. The receiver is operated as Principal Investigator (PI) instrument and will be available to the APEX community on a collaborative basis with MPIfR.

[1]APEX is a collaboration between the Max-Planck-Institut für Radioastrono-mie, the European Southern Observatory, and the Onsala Space Observatory

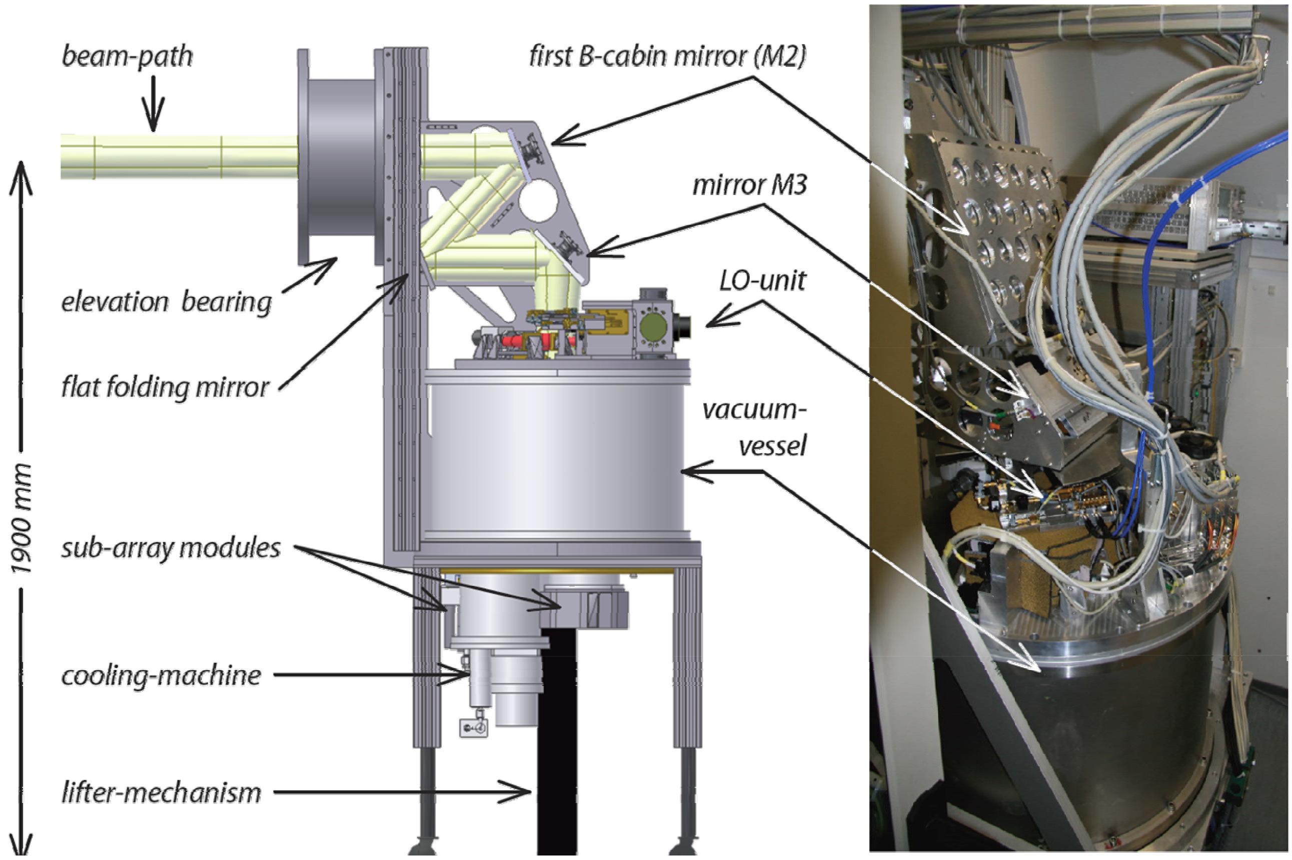

Fig. 2: System overview (CAD 3D model – left hand side) and photograph of CHAMP^{++} as mounted in the Nasmyth B-cabin of the telescope.

II. SYSTEM DESCRIPTION

CHAMP^{+} consists of two 7-pixel sub-arrays: the low-frequency array (LFA) has a RF-tuning range from 620 to 720 GHz, and the high-frequency array (HFA) from 780 to 950 GHz. Both sub-arrays are operating on orthogonal polarizations, hence can be operated simultaneously.

As mixer devices fixed tuned DSB (double sideband) SIS (superconductor isolator superconductor) mixers, developed at SRON with the TU Delft, are used. They offer a usable IF-band range from 4 to 8 GHz; but due to the limited bandwidth of the spectrometer and losses in the quasi-optics we currently only use the inner 2.8 GHz. Operating temperatures for the mixer devices are provided by a commercial Sumitomo 3-stage closed-cycle refrigerator. The mixers are attached to the 4K-stage, while the first IF-amplifiers and the main optics are connected to the 15K-stage. The 77K-stage is used only as an outer radiation shield to reduce the heat-load of the inner two stages.

The main optics provides optical SSB (single sideband) filters, a Martin-Puplett interferometer as LO-diplexer, and re-imaging optics for both sub-arrays. The local-oscillator (LO) system is a spin-off development from our Herschel/HIFI developments [4]. The LO-power distribution is done by collimating phase-gratings (CFG) [5]. The whole dewar can be rotated for image de-rotation.

A. *Mixer devices*

The SIS-mixers are provided by our collaborative partners from SRON. The devices are spin-off designs from the ALMA band 9 and the Herschel/HIFI development programs (see also [6], [7]). For the 660 GHz band a Nb-junction could be used while for the 850 GHz band a Nb-NbTiN-junction has been developed to overcome the Nb-gab frequency limitations starting below 700GHz.

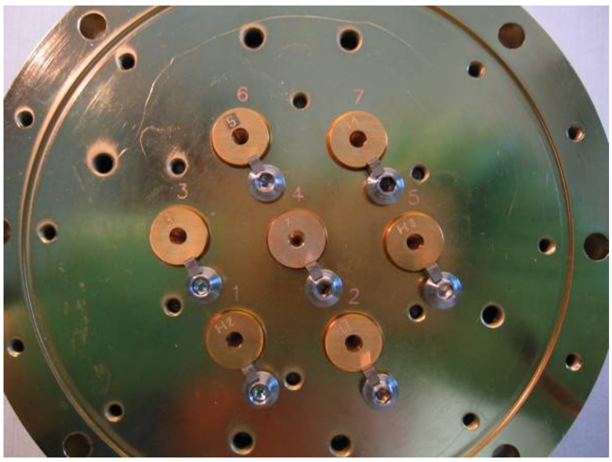

Fig. 3: Photograph of the LFA mixer-assembly showing the seven horn antennas in their hexagonal arrangement.

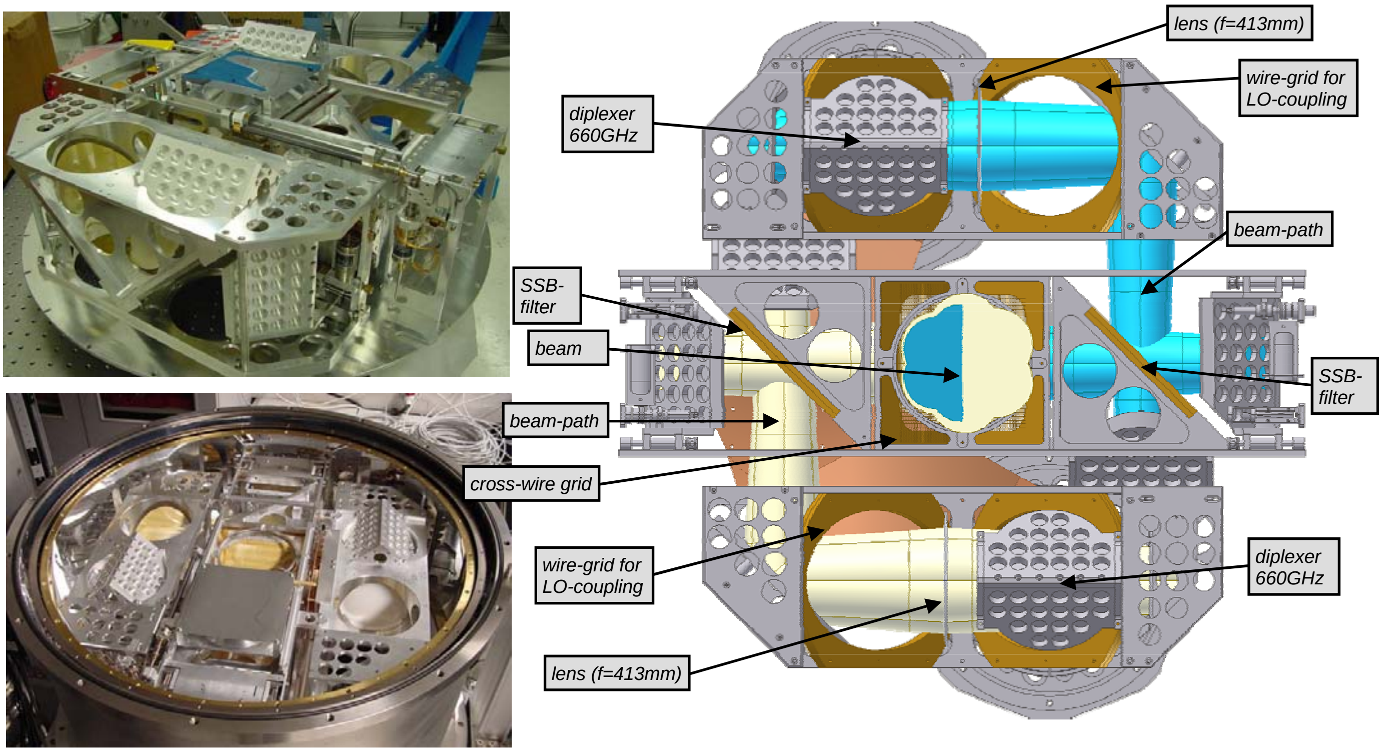

Fig. 4: Cold-optics assembly, including the filter elements (SSB-filter and LO-diplexer), wire-grids and lenses.

All mixers are fixed tuned DSB waveguide devices with a commercial corrugated feed horn. A magnet coil, to suppress the Josephson current, is attached to each of the mixers. All mixers of a given sub-array are connected to a common electronics board providing the BIAS- Tees and the BIAS-network of the junctions.

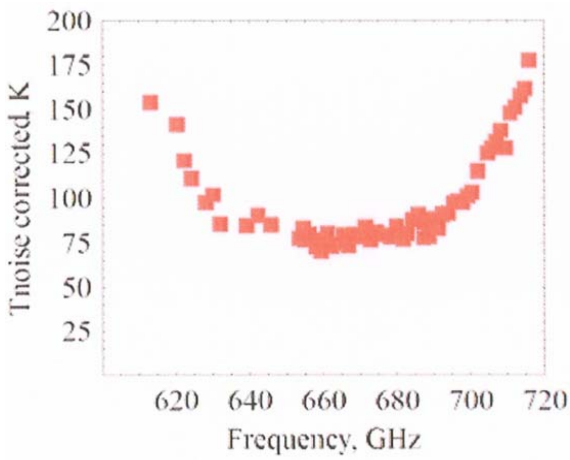

FIG. 5: TYPICAL NOISE-PERFORMANCE OF ONE OF THE 660GHZ MIXER DEVICES VERSUS RF-TUNING RANGE

B. Optics

The imaging optics of CHAMP+ consists of two Gaussian telescope set-ups (e.g., [8]). The first one is required to pass the elevation bearing of the telescope. For a compact arrangement of the diplexer and the single sideband filter a small beam diameter is required. The second Gaussian telescope provides the smaller beam diameter and gains extra path-length for the cooled optical elements. At the focal plane of the second Gaussian telescope a so-called flies-eye-lens, a hexagonal arrangement of 7 lenses with parabolic shape, is located. This lens adapts the individual beam of the mixer-horn antennas to the common optics and ensures the proper illumination of the telescope for each of the sub-array pixels. The magnifications of the Gaussian telescopes are 3138 / 662 ~ 4.75 and 413 / 826 = 0.5.

The arrangement of the warm optics is visualized in figure 2, while figure 4 shows the cold optics layout. The beam spacing on the sky is – at the center of the tuning bands – approx. 2.1 × FWHM for both sub-arrays, which is the optimum between signal losses due to small individual apertures and the filling factor of the focal-plane. Since the beam size is frequency dependent, the field-of-view is different for both sub-arrays. For on-the-fly mapping an array angle of 19.1° against the scanning direction is used. Full sampling can then be achieved with two OTF scans.

The arrangement of the filter elements (two Martin-Puplett interferometers per sub-array, acting as LO-diplexer and as single sideband filter) together with the wire-grids for polarization splitting and LO-injection is shown in figure 4.

All lenses, the IR-filter and the dewar window in the signal path have anti-reflection grooves, which were laser-machined into the elements´ surface. Since the LO-system is producing more than enough LO-power, the LO-windows are un-coated.

C. LO-Diplexer

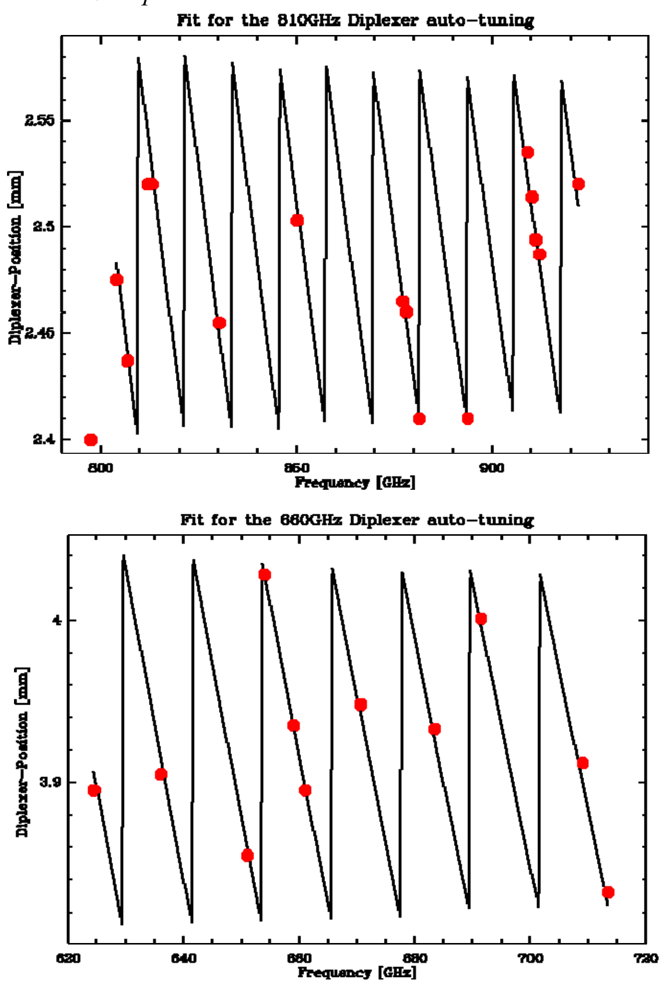

Fig. 6: Diplexer-behaviour of both sub-arrays; measured optimum tuning points (dots) and best fit theoretical behaviour (black line).

To characterize the diplexers and to establish an automatic tuning algorithm for the LO sub-system we measured the diplexer behavior over the whole tuning range of a given sub-array (figure 6). Tuning points were determined by searching for the best average noise-temperatures (averaged over the IF-band and all 7 pixels). A fit to the theoretical model of the Martin-Puplett interferometer with only two free parameters (linearity and zero position of the roof-top position-encoder) can well explain all measured points. An auto-tuning algorithm using this model has been established and is working well for routine observations.

Single-sideband filters

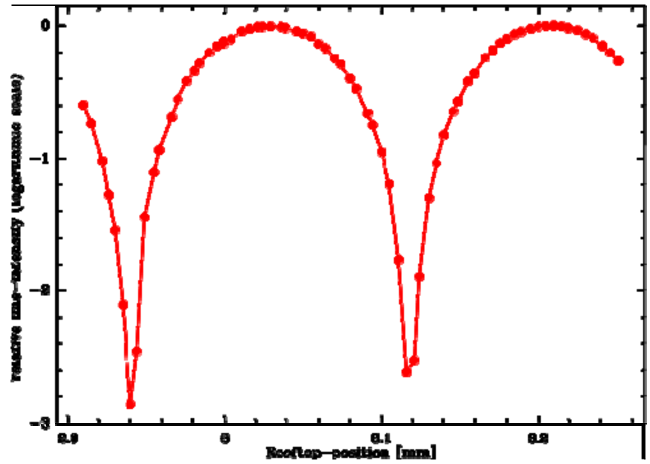

Fig. 7: Relative line intensity of a harmonic mixer RF-signal, injected into the receiver signal path, versus SSB roof-top position.

Important for operation of a SSB-system is how well the image sideband can be suppressed. Therefore we injected as “sky signal” the output of a harmonic mixer. Recording the signal strength versus filter position calibrated the SSB filter for each of the pixels in both sub-arrays (see also figure 7).

From these data we derived the maximum signal strength for each pixel. The sideband suppression for all pixels is then calculated from their maximum signal strength and the signal strength measured at the optimum tuning point for that frequency. The ratio should be above 10dB for all pixels to ensure proper astronomical calibration across the (used) IF-band of the receiver. We derive typical values of more than 15dB as shown for a few typical set-ups in table 1. The best tunings for the whole sub-array were determined to be always very close (within 2-3µm) to the optimum point of the center pixel. Therefore we could take the optimum point for the center pixel to establish the SSB-filter behavior versus RF-frequency. As for the LO-diplexer, we derived the optimum points for several frequencies distributed across the RF-tuning range. Since both filters are build as Martin-Puplett type interferometers we could use the same fitting and auto-tuning scheme as described for the LO-diplexers. Also this auto-tuning works well during routine observations.

Frequency [GHz]	Side-band	Filter-position [mm]	Pixel 1 [dB]	Pixel 2 [dB]	Pixel 3 [dB]	Pixel 4 [dB]	Pixel 5 [dB]	Pixel 6 [dB]	Pixel 7 [dB]
630	LSB	3.240	-17,7	-24,4	-16,6	-21,0	-27,1	-34,7	-23,3
650	USB	3.274	-16,1	-25,4	-14,6	-23,5	-24,4	-28,3	-25,4
691.47	LSB	3.118	-16,6	-24,6	-15,3	-27,6	-21,6	-25,5	-28,3
806.65	USB	3.118	-16,9	-22,1	-16,3	-21,7	-29,6	-23,6	-26,6
850	LSB	3.150	-15,1	-20,9	-16,3	-26,7	-22,8	-25,4	-27,3
921.8	LSB	3.153	-15,4	-21,5	-19,8	-25,8	-23,3	-19,0	-19,4

Table 1: Sideband gain ratios for all pixels at selected frequencies.

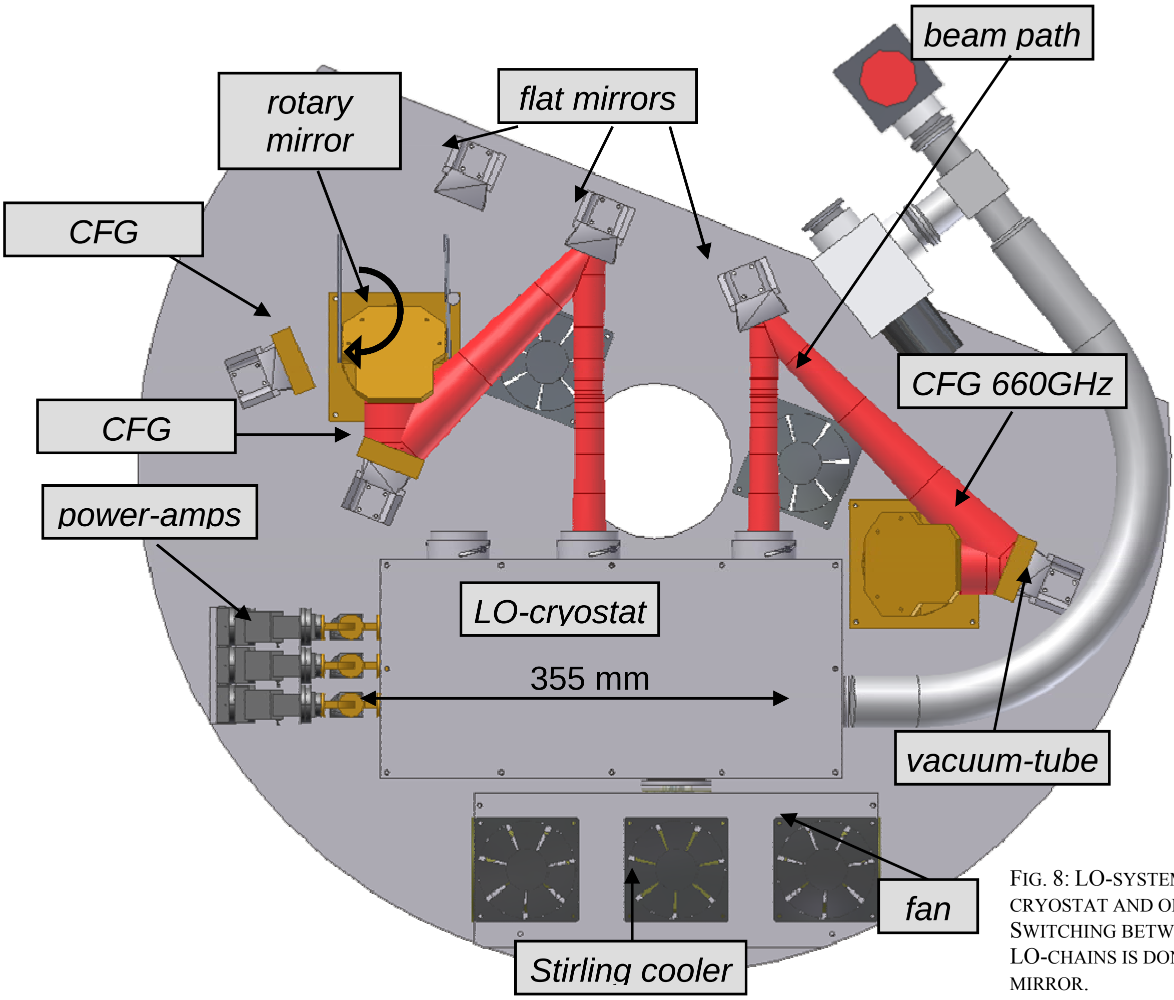

FIG. 8: LO-SYSTEM WITH LO-CRYOSTAT AND OPTICS PATH (RED). SWITCHING BETWEEN THE TWO HFA LO-CHAINS IS DONE BY A ROTARY MIRROR.

D. LO-system

The Local Oscillator chains are spin-off from our Herschel /HIFI developments. A commercial synthesizer is driving a multiplier chain with additional amplifier stages. The LO-chain input frequency is in the range from 10-20 GHz, depending on the RF-frequency and the overall multiplication factor of the individual chain. Two different LO chains were necessary to cover the wide RF tuning-range of the HFA band: one chain covering 780 – 840 GHz and the second 840 – 950 GHz. We select between the two chains optically, via a rotating mirror with two positions. To improve life-time and performance we operate the last tree multiplier stages of all three chains at ~130K, using a compact Stirling cooler.

To distribute the LO-power equally between the individual mixers in each of the sub-arrays we use collimating Fourier gratings (e.g. [5], [9], [10]). These are phase gratings superimposed to a parabolic mirror. The phase grating is calculated to produce the required hexagonal interference pattern, while the parabola matches the beams to the optics of the signal-path. This makes the optical layout very simple (see also figure 8).

III. SYSTEM DEFINITION

During the commissioning period and two observing runs in 2007 we gained experience with the overall system.

A. Noise performance

We tuned the receiver and hence measured its noise performance for those frequencies that were requested in our observing programs. In the LFA, we established an auto-tuning that covered the whole LO tuning range. Since the tuning of the higher frequency LO-chains is more difficult, only in segments around the most important astronomical lines tuning parameters were tabulated. For the actual observations, the frequency is then tuned automatically via the receiver control computer.

In figure 9 we display the noise temperatures as measured across the central 1GHz wide IF-band (limited by the total-power detector in the IF-processor).

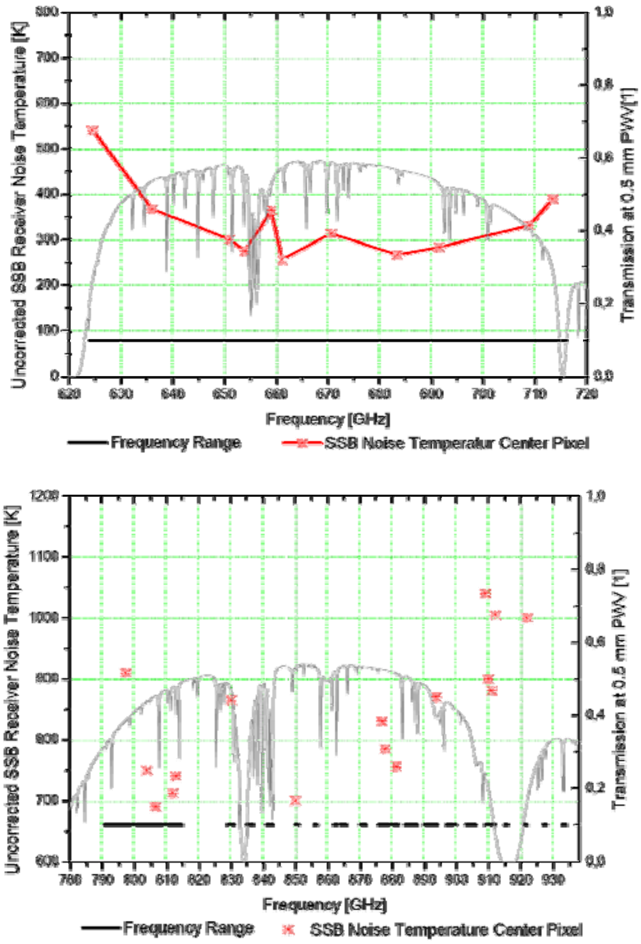

Fig. 9: Instrument noise performance, as measured across the central (1GHz) IF-bandwidth (top: LFA; bottom: HFA). The thick black line indicates the tuning range of the LO-system, for which remote tuning has been established. In thin lines the atmospheric transmission for 0.5mm PWV is superimposed.

B. System stability

The overall system stability limits the integration times for a given observation. For efficient spectroscopic on-the-fly mapping a spectroscopic Allan-Variance minimum time of around 100s is required. All CHAMP$^+$ channels comply with this requirement, most channels show AV times around 200s. With the (inherently even more stable) FFT-spectrometers we hope for even better Allan-times

Important for continuum pointing observations are the total-power Allan times. In this mode excellent Allan stability-times of more than 25s for all channels have been demonstrated.

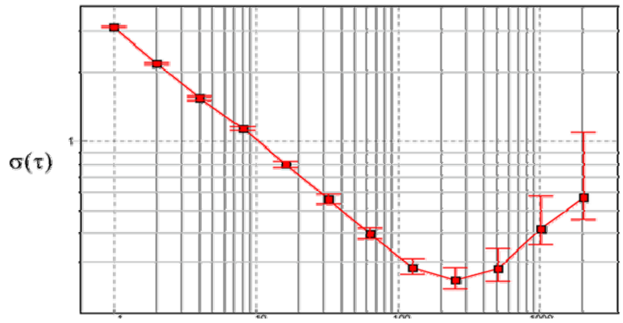

FIG. 10: TYPICAL ALLAN-PLOT HERE FROM ONE OF THE HFA CHANNELS SHOWING APPROX. 200S ALLAN MINIMUM TIME AT A SPECTROSCOPIC RESOLUTION OF 1MHZ.

C. Footprint on the sky

For the astronomical observations good control of the receiver pointing is absolute necessary. For an array receiver this requires knowledge about the relative pixel positions. We confirmed the footprints of the arrays by measurements of the planets. They confirmed the pre-alignment that was done in the laboratories prior to shipment. Mars was chosen because

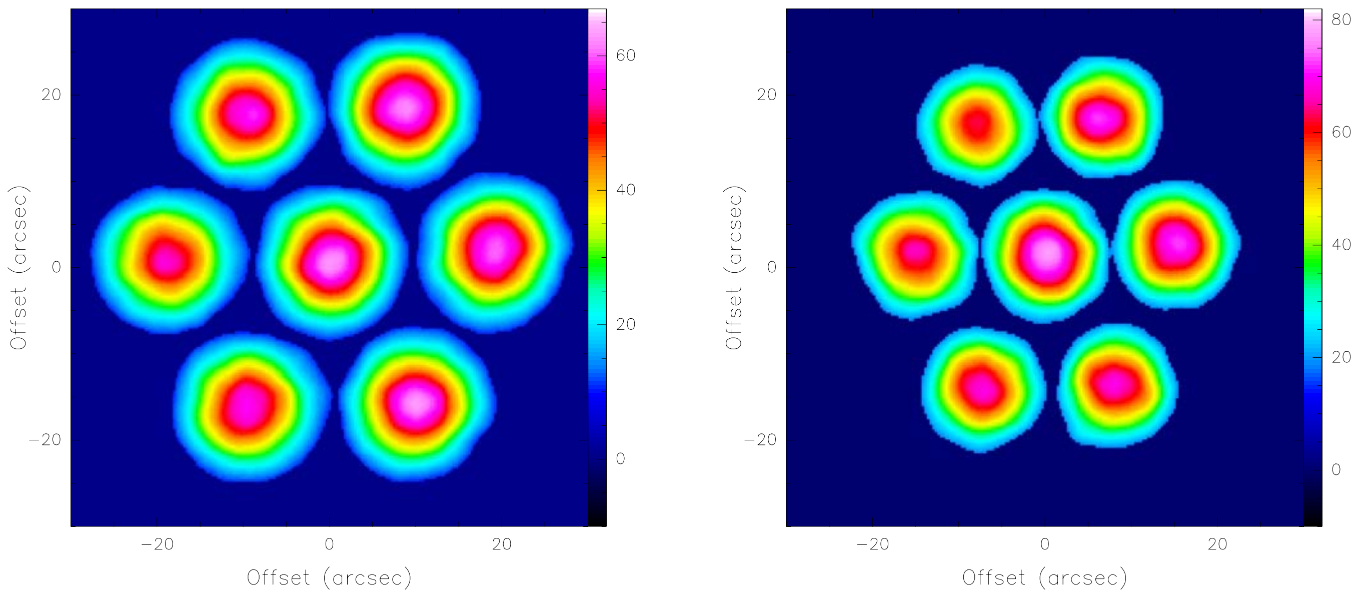

FIG. 11: CHAMP$^+$ BEAM PATTERN AS OBTAINED TOWARDS MARS (IN TOTAL POWER SCANNING MODE). LEFT HAND SIDE: LFA; RIGHT HAND SIDE: HFA. POSITIONS AND SHAPE AGREE WELL WITH DESIGN-VALUES, WHILE THE ARRAY IS NEARLY INVARIANT AGAINST ROTATION OF THE 60° SYMMETRY ANGLE.

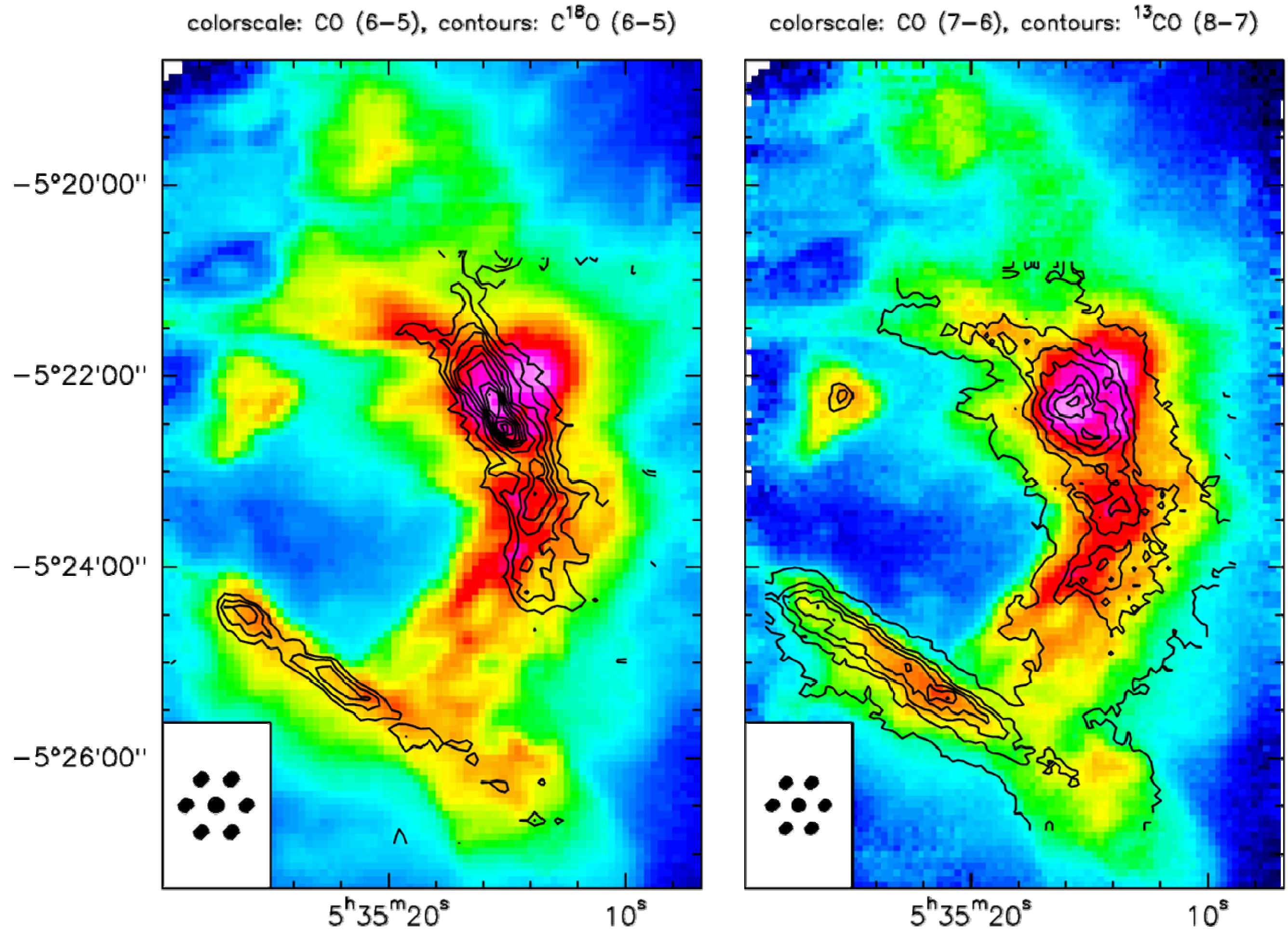

Fig. 12: CHAMP+ on-the-fly map of the Orion A molecular cloud. Peak temperatures of in total four different CO isotopomers are displayed. The observing time was ca. 20 hours, each image composes of approximately 1 million spectra

of its small diameter during the 2007 commissioning, which was comparable to the APEX beam at 850 GHz. Figure 11 displays the pixel matrix, as measured in total power on-the-fly scans across Mars. The array has the designed hexagonal arrangement with clean beams (better than 15 dB) and good 60° rotation symmetry. The offset between the sub-arrays is measured to be better than 1 arcsec..

IV. First Astronomical Results

In figure 12 we present first astronomical results: four CO isotopometers have been measured towards the Orion A molecular cloud. The data-cube consists in total of more than two million individual spectra. Each spectrum was taken with a dump time of 1 second. The overall observing time including overheads was ca. 20 hours. This work shows impressively the potential of the new receiver system for large scale mapping projects.

Conclusions

CHAMP+ at APEX offers unique high-resolution heterodyne mapping capabilities to the sub-millimeter community. The new instrument meets all critical design requirements and offers a good performance over its whole RF-tuning range. With its large IF-bandwidth of now 2.8 GHz (after upgrade of the back-end) and the compact hexagonal array-footprint, CHAMP+ will provide key supplementary supporting observations to near future far-infrared missions like the Herschel/HIFI satellite or the airborne observatory SOFIA. Both missions are scheduled to provide first astronomical observations in 2009.

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