

# Beginning of operation on APEX of the polarimeter for the Large APEX Bolometer Camera (LABOCA)

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## ABSTRACT

An enhanced version of the "Polarimeter für bolometer Kameras" (PolKa) has been installed on the APEX telescope (Atacama Pathfinder EXperiment) in October 2009, to work in combination with LABOCA (the Large APEX Bolometer Camera). This polarimeter was included in the design of LABOCA's optics from the beginning and it is now going through a commissioning phase. Preliminary tests on sky have confirmed that the combination of PolKa, LABOCA and APEX provides unprecedented capabilities in mapping the polarization of the continuum emission at submillimeter wavelengths.

**Keywords:** submillimeter, polarization, bolometer, array, APEX, LABOCA

## 1. INTRODUCTION

Submillimeter continuum radiation can be partially linearly polarized. The processes that produce measurable levels of linear polarization can have different nature and depend on the type of astrophysical source that is considered.

Optically thin synchrotron emission from extragalactic objects, like radio galaxies and active galactic nuclei, is intrinsically linearly polarized. The degree of polarization depends on the strength of the magnetic field but also on the morphology of the source and on its orientation along the line of sight (see Cawthorne et al. 1993<sup>[1]</sup>).

Interstellar molecular clouds, in our Galaxy or in other galaxies, can be source of linearly polarized continuum emission. In this case the polarization is produced by partial magnetic alignment of elongated dust grains (Hildebrand 1988<sup>[2]</sup>).

In both cases, the morphology of the magnetic field can be deduced from the direction of the polarization vectors, and polarimetry at millimeter and submillimeter wavelengths can trace the magnetic field in a more direct way than in the optical and radio regimes, where scattering and Faraday rotation can dominate the polarized signals. In the latter case, the emission is almost always optically thin, thus bolometers are the ideal detectors because the bolometric signal is proportional to the dust column density. Practically speaking, this makes dense cloud portions, in particular those associated with star-forming regions and protostellar envelopes, promising targets for polarimetry using bolometers.

The last decades saw an increasing effort in the development of receivers for continuum emission at millimeter and submillimeter wavelengths. The biggest step forward has been the introduction of bolometer arrays, devices made of several bolometers joint together in a larger structure (the array) where they perform simultaneous multi-beam observations.

The Large APEX Bolometer Camera (LABOCA, Siringo et al. 2009<sup>[3]</sup>) with its field of view of more than 100 squared arc-minutes is the largest submillimeter bolometer camera available today. LABOCA is a bolometer

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camera specifically designed for fast mapping of large sky areas at relatively high resolution and sensitivity. It was developed by the bolometer group of the Millimeter and Submillimeter Astronomy Group at the Max-Planck-Institut für Radioastronomie of Bonn (MPIfR) and commissioned in May 2007 as facility instrument on the Atacama Pathfinder Experiment telescope (APEX, Güsten et al. 2006<sup>[4]</sup>), a collaborative effort between MPIfR, the European Southern Observatory (ESO) and the Onsala Space Observatory (OSO).

APEX, as the name implies, serves as a pathfinder for the exploration of the submillimeter sky, in particular by performing large angular scale observations for later Atacama Large Millimeter Array (ALMA) follow-up studies on selected regions at much smaller angular scale.

The bolometer group in Bonn has developed the polarimeter working in combination with LABOCA at APEX. We present here a description of this instrument and of the installation on the APEX telescope.

## 2. INSTRUMENT OVERVIEW

The polarimeter for LABOCA is a new, enhanced version of the polarimeter for bolometer cameras that was developed at MPIfR between 2000 and 2004. The design of this instrument (named *PolKa* after the German *Polarimeter für Bolometer Kameras*) was aimed to provide a versatile instrument, capable of giving good results with any of the MPIfR bolometer arrays, at different wavelength and on different telescopes. A complete description and some results are presented in G. Siringo 2003<sup>[5]</sup> and Siringo et al. 2004<sup>[6]</sup>. We give here only a short overview.

### 2.1 Principle of operation

In order to extract the polarized component from the unpolarized signal and foregrounds it is common to use a polarization modulator to modulate the polarized component of the incoming radiation at a precise frequency. If the modulation acts only on the  $Q$  and  $U$  Stokes parameters of the radiation, the total intensity  $I$  will be unchanged, at least in the ideal case. Since MPIfR bolometers are only sensitive to the total intensity  $I$  of the wave, a linear polarizer must be inserted along the optical path to transduce the modulation of Stokes  $Q$  and  $U$  into a modulation of  $I$ . PolKa uses a rotating half-wave plate (HWP) as polarization modulator and free-standing wire-grids as linear polarizers.

### 2.2 Continuous spinning technique and Stokes parameters

Placing a rotating HWP in the beam path will produce a modulation of the Stokes parameters, but the total intensity will remain unchanged. To quantify this assertion, let us consider the Müller matrix for an HWP rotating at angular velocity  $\omega$ <sup>[7]</sup>.

$$\mathbf{H}(\omega t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\omega t & \sin 4\omega t & 0 \\ 0 & \sin 4\omega t & -\cos 4\omega t & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (1)$$

If we compare this matrix to a rotation matrix, we see that it produces a rotation of the polarization vector in the direction opposite to the mechanical rotation of the device. More importantly, we see that the rotation frequency of the polarization vector is doubled: this is the biggest benefit that we gain by using an HWP instead of a rotating linear polarizer. Most of the spurious effects, in fact, will have a frequency equal to the mechanical one,  $\omega$ , while the polarization signal will be modulated at  $4\omega$  resulting in an improved extraction of the signal from foreground and systematic effects. The Stokes vector modulated by the HWP is

$$\mathbf{H}(\omega t) \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I \\ Q \cos 4\omega t + U \sin 4\omega t \\ Q \sin 4\omega t - U \cos 4\omega t \\ -V \end{pmatrix} \quad (2)$$

and we see that, in the ideal case, the total intensity  $I$  of the incoming radiation is not modified because the polarization vector is rotated without any change in its magnitude.

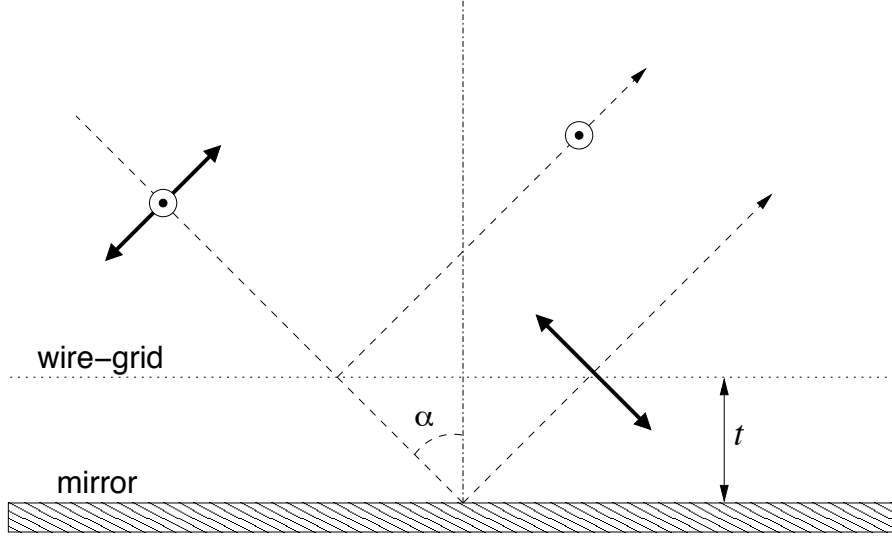


Figure 1. Scheme of a reflection-type half-wave plate. The incident radiation is divided into two beams with orthogonal polarization states. The two emerging rays will have a relative phase shift proportional to  $t$ .

At this point we introduce a fixed linear polarizer along the beam to produce an intensity modulation detectable by the bolometers. The bolometer output is

$$V_H = \frac{1}{2} (I + Q \cos 4\omega t + U \sin 4\omega t) \quad (3)$$

$$V_V = \frac{1}{2} (I - Q \cos 4\omega t - U \sin 4\omega t), \quad (4)$$

in the cases of a horizontal and a vertical linear polarizer respectively. The Stokes parameters of the linear polarization can be then extracted by those signals using synchronous demodulation methods.

### 2.3 The Reflective Half-Wave Plate (RHWP)

The polarization modulator used in PolKa is a rotating reflection-type half-wave plate (hereafter RHWP). The RHWP mainly consists of two parts: a wire-grid linear polarizer and a plane mirror, kept parallel to each other. By tuning the distance  $t$  between the two parts (see Fig. 1), it is possible to produce a phase shift between the two components of polarization, because one is reflected by the wires and the other one by the mirror, causing a difference in path length. The phase shift is given by the simple relation

$$\varphi(\lambda) = 2\pi \frac{t}{\lambda \cos \alpha} \quad (5)$$

where  $t$  is the distance between the polarizer and the mirror,  $\alpha$  is the angle of incidence of the incoming radiation and  $\lambda$  is the operating wavelength. To have an HWP we assign  $\varphi = \pi$  and the value of  $t$  for a central operating wavelength  $\lambda_0$  is given by

$$t = \frac{1}{2} \lambda_0 \cos \alpha \quad (6)$$

The RHWP works with reflections: even small oscillations of the rotation axis could produce large oscillation of the beam, increasing the noise of the measurements. On the other hand, the RHWP has the advantage that radiation does not pass through it and it can therefore be supported from the back. For these reasons we decided to mount it on a motorized air bearing. This device, which has an embedded on-axis electric motor, maintains the rotation plane within less than  $1 \mu\text{m}$ . To minimize the errors in positioning the wire-grid parallel to the mirror, we reduced the number of surfaces to be machined with high accuracy to only two: the mirror plate and the upper side of the polarizer frame. The mirror plate is mounted on the air bearing and the distance of the wire-grid can be tuned to the operating wavelength (see Eq. (6)) by means of three micrometer heads.

Large wire-grid polarizers were produced at MPIfR purposely for the RHWP. These grids have a clear aperture of 246 mm with 20  $\mu\text{m}$  tungsten wires and 63  $\mu\text{m}$  grid step. The measured mean error in the wire spacing is 18  $\mu\text{m}$  rms. Before the beginning of the observations the RHWP must be accurately tuned to maximize the polarization modulation efficiency.

It is worth noting that the RHWP is actually a tunable retarder that can be tuned to produce any phase shift: tuned to produce a  $90^\circ$  phase shift it can be used to modulate circular polarization.

### 3. PREVIOUS INSTALLATIONS

The PolKa polarimeter has been already installed in two other radio telescopes, before the actual installation at APEX.

#### 3.1 At the Heinrich-Hertz Telescope (HHT) - 2001/2002

PolKa was tested at the Heinrich Hertz Telescope (hereafter HHT, also known as SMT<sup>[8]</sup>), a 10 meter submillimeter telescope (at 3200 m on Mt. Graham, AZ, USA) that was equipped with a 19-channel MPIfR bolometer array operating at 870  $\mu\text{m}$ , today decommissioned. In May 2001 we made a first test with a prototype with an undersized RHWP. Unfortunately the weather didn't allow us to get any astronomical data, nevertheless the telescope run was useful to identify problems and to perform some calibrations. A second, more fruitful run with a full size RHWP was made in January 2002<sup>[5,6]</sup>.

The receiver and its electronics, already existing at the telescope, were optimized to work at the frequency of the telescope's chopping secondary mirror (hereafter called wobbler), in most cases 2 Hz. For this reason, the amplifiers had high-pass filters cutting off signals below 1 Hz to suppress  $1/f$  noise and very slow fluctuations of the signals. If we apply such a filter to Eqs. (3) and (4) we see that the information about the total intensity of the signal is lost because it is not modulated.

Observations were therefore done alternating between two modes: first a photometric observation was done to detect the total flux of the source, using the wobbler to modulate Stokes  $I$ ; then a polarization observation, done without using the wobbler but modulating Stokes  $Q$  and  $U$  with the polarimeter. To reduce the systematic effects and for a better removal of the spurious polarization, each polarization scan was made twice, once using an horizontal analyzer and once using a vertical one. We were forced to use two data acquisition systems, one for total intensity and one for polarization observations, and then merge the data offline. Moreover, given the temporary nature of the installation, no effort was devoted to make the system remotely controllable and the switch-over between polarization and photometry required manual intervention to exchange the analyzers and to switch on and off the modulator.

#### 3.2 At the IRAM 30 m Millimeter Radio Telescope (MRT) - 2004

PolKa was shortly tested at the IRAM MRT<sup>[9]</sup> (Pico Veleta, Spain) in June 2004, working at the central wavelength of 1.2 mm in combination with the MAMBO-1 bolometer camera<sup>[10]</sup>.

The weather didn't permit science observations, however we could perform some technical tasks as calibrations or spurious polarization measurements. The polarimeter showed again high polarization efficiency and low systematics, proving the effective versatility of a polarimeter based on a tunable HWP. Moreover, this time we used a motorized filter exchanger, remotely controlled through the local network.

### 4. AT APEX

An enhanced version of the PolKa polarimeter was shipped from Bonn to APEX in 2008. Unfortunately the air bearing was damaged during the transport and it was sent back to Europe for repair. In the meanwhile, the installation of the other components was done in successive steps. The full system was ready at the end of October 2009. This installation, in contrast to the previous ones at the HHT and at the MRT, is permanent. The instrument is going to be used with LABOCA and with its successor, LABOCA-2, as long as these receivers will be in operation.

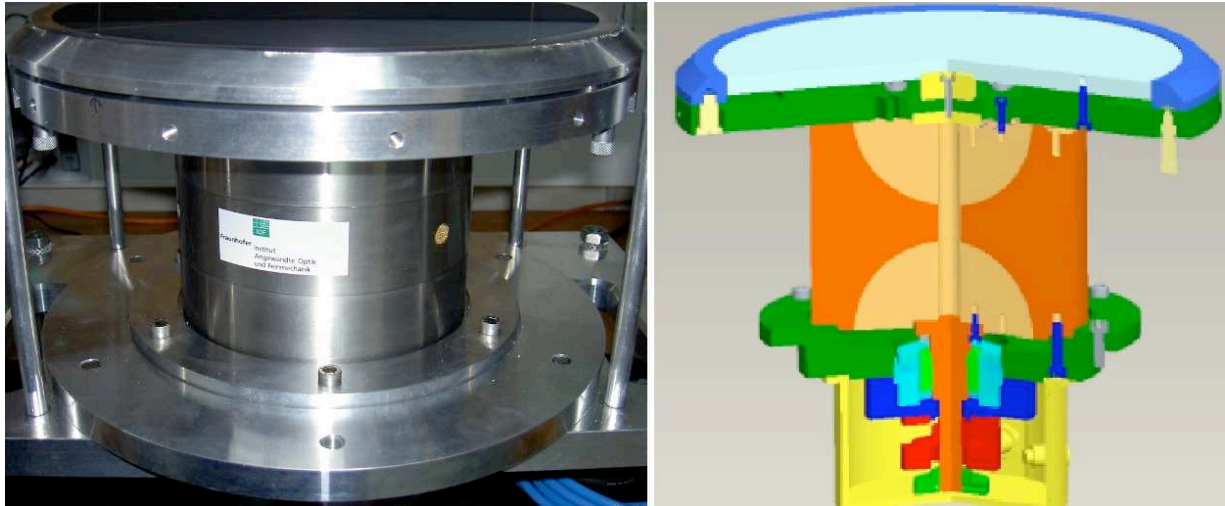


Figure 2. Left: a picture of the new RWHP module in a lab at APEX, before being installed in the receiver cabin. Right: a schematic drawing showing a section of the modulator. The two hemispheres represent the air bearing.

#### 4.1 New polarization modulator

The polarimeter for LABOCA has a new modulator assembled by the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) of Jena, Germany (see Fig. 2).

The modulator is assembled on a motorized, double-sphere, rotary air bearing (DLL200, Mikromechnik GmbH). A metal mirror of optical quality (manufactured at IOF) is attached to the upper part of the rotor. The RWHP is composed with the same wire-grid polarizer used in the previous versions of PolKa, described in Sect. 2.3. Precision positioning of the polarizer in front of the mirror is ensured by three micrometer heads. At the lower shaft of the rotor is connected one incremental encoder (Heidenhain ERO 1285 with IBV606 interpolator) that produces two trains of 2048 pulses in quadrature, per rotation. The position angle of the RHWP can thus be measured with an angular accuracy of  $\sim 10'$ . The air bearing requires a pressure of 5 bar, provided by a dedicated compressor. The unit is operated via a controller connected to the serial server of LABOCA and can be completely controlled in remote from the local network.

#### 4.2 Filter wheel

As described in Sect. 2, between the modulator and the bolometers we need to insert a linear polarizer to transduce Stokes  $Q$  and  $U$  modulation into a measurable  $I$  modulation. From our experience at the HHT, we know that combining data acquired with orthogonal analyzers (horizontal and vertical in our description) can reduce the contribution of systematic effects on the final results of the data reduction. For this purpose we designed a filter wheel unit that holds two free-standing wire-grid polarizers (see Fig. 3). The wheel can be rotated to exchange the analyzer from orthogonal to vertical and vice-versa. Additionally, the unit can be rotated between other two positions: an empty slot, for photometry, and a hot load, used for flux calibration (skydip).

The two polarizers are two identical wire-grids, produced at MPIfR, of 146 mm clear aperture, made of gold-coated tungsten wires with a diameter of  $25 \mu\text{m}$  at a grid step of  $100 \mu\text{m}$ . The wheel is moved by a step motor and can be remotely controlled.

#### 4.3 Incorporation in the LABOCA optics

LABOCA is located in the Cassegrain cabin of the APEX telescope and the optical coupling to the telescope is provided by a series of 5 metal mirrors and a lens (see Siringo et al. 2009<sup>[3]</sup> for the description of the optics.) The polarimeter was included in the design of the optics from the beginning, The polarization modulator, therefore, was incorporated simply by replacing one plane mirror (M6, see Fig.4) with the RHWP. The paddle used for the hot calibration was replaced by the filter wheel. No other modifications were required.

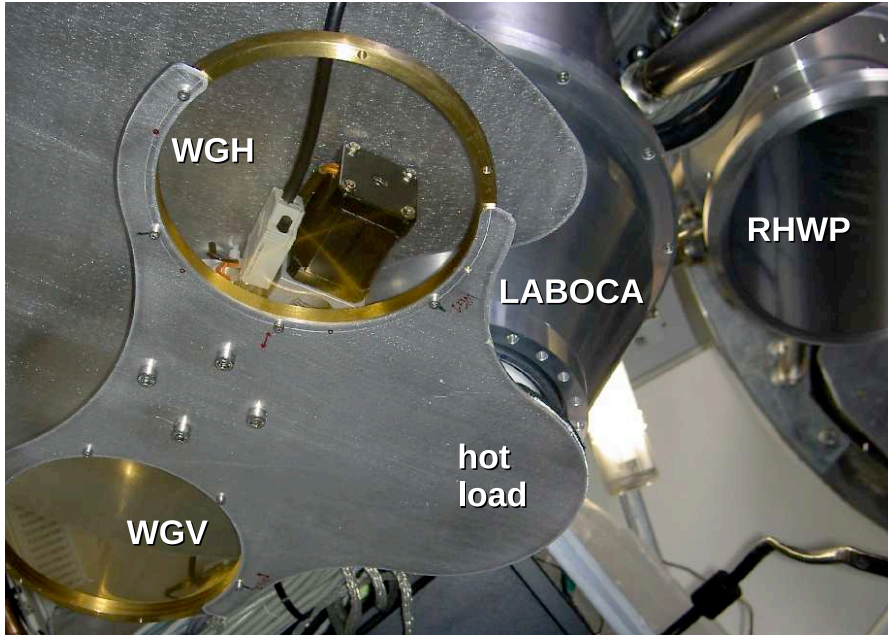


Figure 3. The picture shows the filter wheel attached at the lower part of LABOCA. The wheel is in the position for calibration on the hot load. The step motor used to move the wheel is visible through the WGH polarizer. The polarization modulator (RHWP) is also visible in the background.

At the position of M6, where the RWHP is today, the angle of incidence is only  $\alpha = 16^\circ 23'$  (see Fig. 1 and Eqs. 5 and 6.), at the HHT and MRT it was  $45^\circ$ .

#### 4.4 Observations

The polarimeter was operated at the beginning of November 2009, during MPIfR observing time. Technical observations were carried out during the night of November 5th, for about 12 hours. Weather conditions were not good, with a content of precipitable water vapor (PWV) of 2.5 mm that, at the wavelength of LABOCA ( $870 \mu\text{m}$ ) corresponds to a zenithal opacity of 0.7. Before the beginning of the observations the RHWP was accurately tuned to maximize the polarization modulation efficiency. For that, a reference polarized target was placed at the focal plane of the telescope and the distance between the grid and the mirror was adjusted maximizing the modulated signals. Observations were done using a compact raster of spirals pattern, similar to the mapping mode typically used for photometry with LABOCA.

We used the same hardware and a slightly modified data acquisition chain to operate LABOCA but new software was installed to operate the polarimeter and to acquire the position reference from the encoder. The final raw data were stored in the usual MBFITS format (Multi-Beam FITS) by the data writer embedded in the APEX Control Software<sup>[11]</sup>.

The bolometers of LABOCA are DC-coupled and the total intensity is preserved in the acquired signals, well described by Eqs. (3) and (4) respectively for observations done with horizontal and vertical analyzer. There is an advantage here in comparison to the previous installations of PolKa: in fact, we get simultaneously Stokes  $I, Q, U$  and there is no need to repeat the observation in photometry mode, as it was required at the HHT and at the MRT (see Sect. 3.1).

#### 4.5 Data reduction

The reduction of the data was done using the program CRUSH (Comprehensive Reduction Utility for SHARC-II, A. Kovács 2008<sup>[12]</sup>) that since version 1.99a has been updated to handle our polarization data. The program reduced the data and produced four FITS tables per observation, respectively containing Stokes  $I, Q, U$  and the total polarization  $P = \sqrt{Q^2 + U^2}$ .

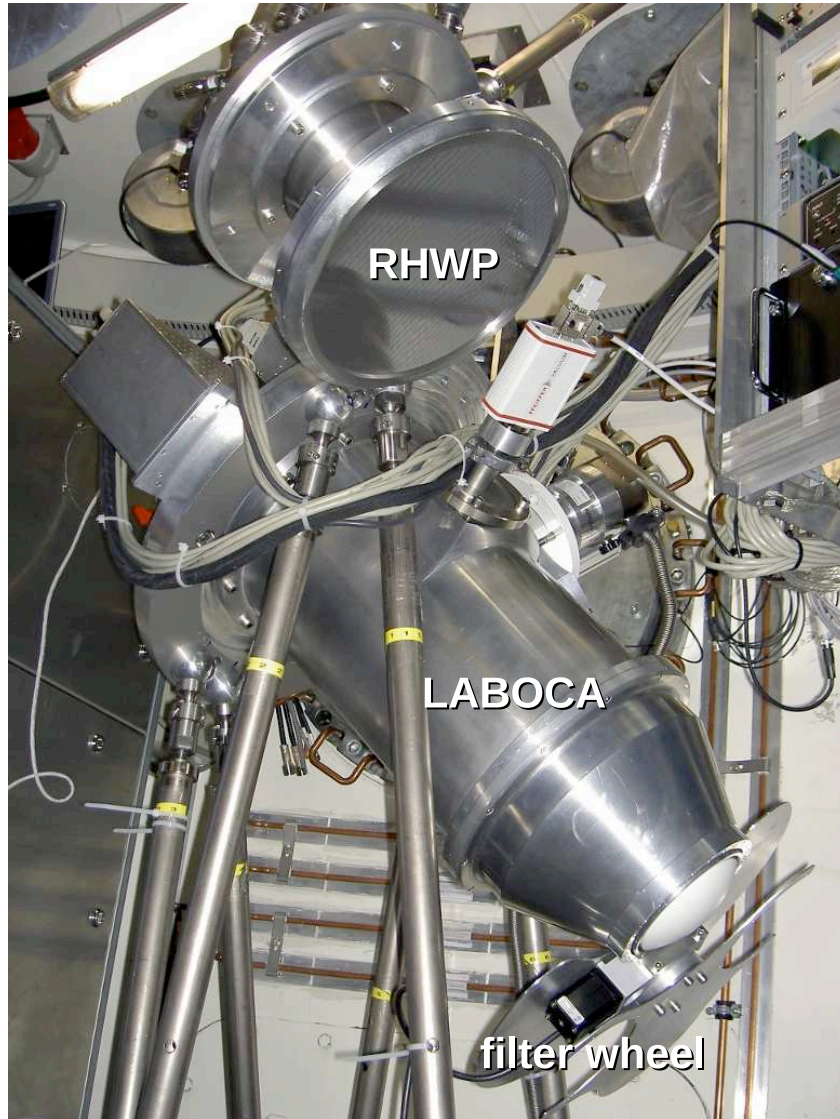


Figure 4. A picture of the polarimeter installed in the Cassegrain receiver cabin of APEX. The polarization modulator is the round object visible in the upper part of the picture. In the center, the cryostat of LABOCA with the filter wheel mounted at the lowest extremity. See also Figg. 3 and 4 in Siringo et al. 2009<sup>[3]</sup>.

## 5. RESULTS

Although the weather conditions, in terms of atmospheric transmission and stability, were not ideal (PWV $\sim$  2.5 mm), we could observe the Orion Molecular Cloud 1 (OMC-1). The result is shown in Figure 5. For comparison, in the same figure we show the polarization map of OMC-1 produced by PolKa at the HHT.

In order to compare the NEFD (Noise Equivalent Flux Density) of the polarimeter at APEX to the NEFD measured when it was installed at the HHT, we need to consider some differences between the two installations. First of all, at the HHT the bolometer array was made of only 19 elements, while LABOCA, during our tests at APEX, had more than 250 working elements. The APEX telescope, with 12 m diameter, is larger than the 10 m HHT, therefore the beam in the two cases was slightly different, with 19'' at APEX and 22'' at the HHT. Finally, the atmospheric conditions were quite different, at the HHT we had 0.5 mm of PWV, corresponding to a zenithal opacity of 0.25, while at APEX we had 2.5 mm of PWV, corresponding to a zenithal opacity of 0.7, almost three times higher. In terms of transmission, considering an average elevation of 60°, during our tests at

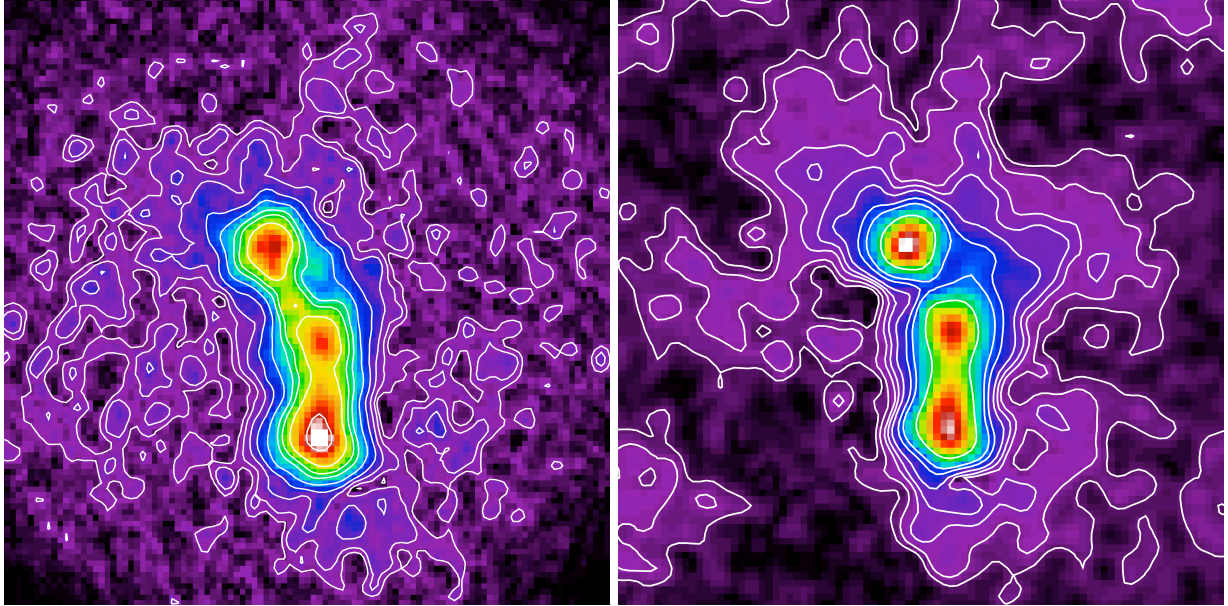


Figure 5. Maps of the polarized flux from the Orion Molecular Cloud-1, centered on the BN/KL object, observed with PolKa at the HHT (left, 6 hours integration, 0.5 mm PWV,  $6' \times 6'$ , 75 mJy/beam residual rms) and at APEX with LABOCA (right, 1 hour integration, 2.5 mm PWV,  $14' \times 18'$ , 50 mJy/beam residual rms). The two maps have been scaled to show the same portion of sky.

APEX the atmospheric transmission along the line of sight was 75% at the HHT and only 44% at APEX.

Figure 5 shows two polarization maps of the same area of OMC-1, centered on the BN/KL object, as observed with PolKa at the HHT and at APEX with LABOCA. The two maps have different size, the one at the HHT is  $\approx 6' \times 6'$  while the one at APEX is  $\approx 14' \times 18'$ , thus covering an area 6 times larger. The residual rms noise ( $1 \sigma$  level) in the two maps is respectively 75 mJy/beam for the HHT and 50 mJy/beam for the APEX one, reached in 6 and 1 hour integrations respectively.

Assuming same beam size and same spectral response for the two receivers, we can summarize this comparison saying that the polarimeter working in combination with LABOCA at APEX has been about 50 times faster than PolKa at the HHT in mapping the same area of sky. Additionally, the area observed with LABOCA is 6 times larger.

## 6. CONCLUSIONS

The installation of PolKa at the HHT in 2002 (Sect. 3.1) demonstrated that our concept of a polarimeter with a RHWP is successful. The instrument showed good polarization mapping capability, giving results of the same quality of comparable instruments (e.g. HERTZ<sup>[13]</sup>, SCUPol<sup>[14]</sup>, SHARP<sup>[15]</sup>).

The installation of PolKa at APEX to work in combination with LABOCA has shown to be more than 50 times faster than its predecessor. Moreover, it produces simultaneous maps of the first three Stokes parameters  $I, Q, U$ .

We are planning to complete the commissioning of PolKa at APEX as MPIfR PI instrument in 2010, and some more work still needs to be done before the instrument can start science observations. Apart from minor technical work on the hardware, we need to improve the calibrations, measure the actual NEFD corresponding to  $I$  and  $P$  mapping and provide an online data reduction pipeline.

After that, it could be possible to call for proposals for science verification projects to be observed during MPIfR telescope time.



## ACKNOWLEDGMENTS

The authors would like to thank the staff at the APEX telescope for their support during the installation and on-sky testing of the instrument. Special thanks to Stefan Risse and his precision systems group at IOF, Jena.

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