A New Facility Receiver on APEX: the Submillimetre APEX Bolometer Camera, SABOCA

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The Submillimetre APEX Bolometer Camera, SABOCA, has been successfully commissioned in March 2009 for operation as facility instrument on the 12-m APEX telescope, located on Llano de Chajnantor at an altitude of 5100 m. This new camera for the 350 µm atmospheric window uses TES superconducting bolometers and was built by the Max-Planck Institute for Radio Astronomy in collaboration with the Institute of Photonic Technology. SABOCA complements the existing suite of submm receivers available on APEX fully exploiting the excellent atmospheric transmission at the site by offering effective mapping of the thermal continuum dust emission at the shorter wavelengths.

SABOCA is a bolometric continuum receiver operating in the 350 µm atmospheric window. Its detector array consists of 39 superconducting transition edge sensor (TES) bolometers with SQUID (Superconducting Quantum Interference Device) amplification and time-domain multiplexing. The receiver has been designed and integrated by the bolometer group at the Max-Planck Institute for Radio Astronomy (MPIfR, Bonn, Germany) in collaboration with the Institute of Photonic Technology (IPHT, Jena, Germany). The MPIfR group has a long track record in the development of bolometers and bolometric cameras for astronomical applications. IPHT is known for building state-of-the-art superconducting devices for over 15 years. The collaboration to build SABOCA merges the technology expertise provided by the two groups.

The active development process took several years as it involved a large number of theoretical studies, cycles of manufacture and tests in the laboratory.

A prototype system was successfully tested on APEX (the Atacama Pathfinder Experiment, Guesten et al. 2006) during May 2008. Some technical problems were identified and fixed. Thus, commissioning began in September with an improved version of the receiver. The final version of SABOCA was installed at the beginning of 2009 and commissioning was completed in March 2009.

Motivation

The high altitude and exceptionally dry atmosphere make Chajnantor a unique site for submm astronomy. With it's suite of high-frequency heterodyne instruments (SHFI, CHAMP+ and FLASH, see Guesten et al. 2008), APEX already provides routine observations in atmospheric windows which were so far only seldom accessible from other sites. Continuum observations are also possible with LABOCA (Siringo et al.2007, 2009) which is currently the world largest 870 µm bolometer array. The new 350 µm camera, SABOCA, complements that opening up a shorter wavelength atmospheric window, offering for the first time to the ESO community continuum mapping capability well within the submm range. With it's 1'.5 field of view (see Figure 3), SABOCA provides a large-scale sensitivity similar to that of the only other 350 µm bolometer array currently in operation, SHARC-II at the Caltech Submm Observatory (2'.6x1'; Dowell et al. 2003). Observations at 350 µm probe warmer dust emission or can constrain dust temperatures and emissivity index, when combined with measurements at other wavelengths (e.g. LABOCA 870 µm). For objects at high redshift, SABOCA observes near the peak of the dust emission and can provide important constraints on the total far-infrared luminosity (see article by Swinbank in this same Messenger issue). Finally, the 7".8 SABOCA beam size provides 2.5x better spatial resolution compared to LABOCA, and 3x better compared to Herschel/SPIRE (Griffin et al. 2006) at the similar wavelengths. The better resolution translates into more accurate size estimates and positions of submm sources, allowing identification of counterparts at other wavelengths.

The addition of SABOCA to the range of existing receivers at APEX further demonstrates the commitment of APEX to serve as a “pathfinder” for ALMA. With SABOCA, it gives new access to the highest frequency band (10) of ALMA, in the same way that LABOCA has done in bands 7 and 8.

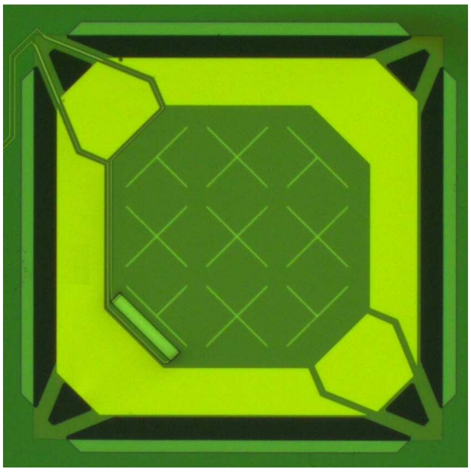

Figure 1. Picture of a bolometer used in the actual version of SABOCA. The thermal conductivity depends on the thickness and number of *legs* connecting the central part of the membrane with the outside. Other layouts were produced and even tested but not used finally. All bolometers have cross-dipole absorbing elements.

Instrument Description

The bolometers of SABOCA are composite bolometers with superconducting TES thermistors on structured membranes. The thermistors are bilayers of molybdenum and a gold-palladium alloy deposited on silicon-nitride membranes together with the niobium wiring and the radiation absorbing layer. As part of the manufacture process, the membranes were structured at IPHT in order to control the thermal conductivity. Several layouts have been studied, with different design of membrane structures, thermistors and absorbing elements.

The bolometers selected for SABOCA (see Figure 1) have moderately structured membranes and show a radiative NEP of $1.6\text{x}10^{-16}$ W/Hz$^{1/2}$ (with 300 K background) during lab tests at MPIfR at a transition temperature of 0.45 K.

The array of SABOCA consists of 39 TES composite bolometers. Of these, 37 are arranged in a hexagonal grid consisting of a central channel and 3 concentric hexagons. Two additional bolometers, identical to the inner 37 but not optically coupled to horns (i.e. *blind* bolometers) were added to the layout, at two diametrically opposing positions, and are used for monitoring purposes. The grid constant of the array is 2.0 mm (see Figure 2).

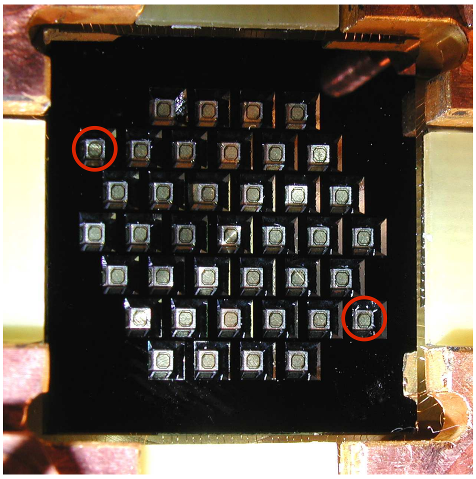

Figure 2. A picture of the bolometer array at the focal plane of SABOCA. One bolometer cell is about 1 mm large and the full size of the array is about 15 mm. The two red circles show the position of the two blind bolometers.

A monolithic array of conical horn antennas, placed in front of the bolometer wafer, concentrates the radiation onto the bolometers. 37 conical horns have been machined into a single aluminum block in the machine shop at MPIfR. In combination with the tertiary optics, the horn antennas are optimized for coupling to the telescope's main beam at a wavelength of 350 µm.

The detectors of SABOCA are designed to work at a temperature of about 300 mK. This temperature is provided by a cryogenic system made of a cryostat using liquid nitrogen and liquid helium, in combination with a closed-cycle helium-3 sorption cooler. After achieving high-vacuum insulation, the cryostat is filled with the liquid cryogens. A dry (scroll) pump, installed in the C-cabin, is used to reduce the vapor pressure on the liquid helium bath in order to lower the boiling point, reaching a temperature of about 1.6 K. This operation requires about 1 hour. A single stage helium-3 sorption cooler (of the type described by Chanin and Torre 1984) is then operated to cool the focal plane to about 300 mK. The cryostat needs to be refilled, pumped and recycled every 48 hours. The helium pumping system and the operation of the sorption cooler have been automated and remotely controlled allowing operation of the telescope during most part of the cool down process (about 2 hour).

The spectral response of SABOCA (Figure 3) is defined by a set of cold filters, installed inside the cryostat, mounted on the liquid nitrogen and liquid helium shields. The passing band is centred at 852 GHz (352 µm), about 120 GHz wide, and is formed by an interference filter made of inductive and capacitive meshes embedded in polypropylene. The low frequency edge of the band is defined by the cutoff of a cylindrical waveguide. A freestanding inductive mesh provides shielding against radio frequency interference.

The TES bolometers are read out in a time domain multiplexing scheme via four independent chains of SQUID amplifiers and multiplexers, providing 10 channels each for a total of 40 possible elements. The multiplexers and associated electronics have been designed and manufactured by IPHT. The four SQUIDs amplifiers are attached to the liquid helium cold plate and operated at the temperature of the pumped liquid helium (~1.6 K). The 40 multiplexing SQUIDs are located in four groups of ten at the four sides of the bolometer array. They are operated at the same temperature of the bolometers (~300 mK).

SQUIDs are extremely sensitive to magnetic fields. Thus, the level of static (trapped flux) and variable (therefore interfering) magnetic fields in the Cassegrain cabin of APEX are a concern. Several measures were taken to ensure that these fields do not compromise the performance of SABOCA: a) An external shield, made of high magnetic permeability metal (called mu-metal) is wrapped around the lower part of the cryostat. b) The multiplexing SQUIDs have input coils differentially coupled, therefore only sensitive to gradients of the magnetic field. c) Array and multiplexers are enclosed in a capsule, on the helium-3 stage, made of an aluminum alloy with a critical temperature of 1.2 K, which goes superconducting during operation. The horn array, made of the same material, is part of the capsule. d) The readout SQUIDs are protected by shields made of Cryoperm (a type of mu-metal for low temperature applications). e) Only selected non-magnetic materials are employed in the surroundings of the array.

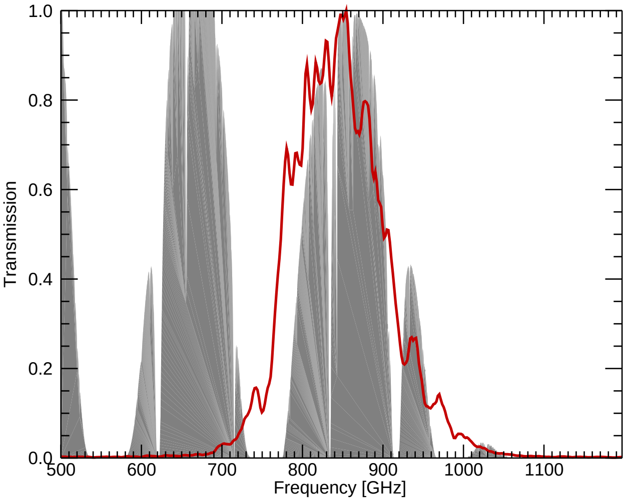

Figure 3. Spectral response of SABOCA (red) compared to the atmospheric transmission (gray). Both curves are normalized to unity.

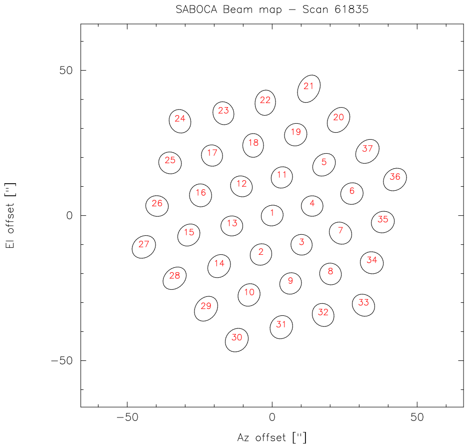

Figure 4. On-sky footprint of SABOCA, derived from one single beam map on Mars. The beam distortions are partially due to atmospheric refraction and fitting accuracy.

The operation of SABOCA at APEX confirmed the reproducibility of the SQUIDs operation point and therefore the effectiveness of the shielding. The multiplexing frequency is fixed to 2 kHz, which gives 200 samples per second per bolometer.

In order to be fully integrated in the APEX environment, SABOCA is provided with a hardware/software infrastructure similar to that one of LABOCA. A frontend software (running on the same frontend computer used by LABOCA) is used to control and monitor the hardware of the system (temperature monitoring, SQUIDs tuning, helium pumping, recycling and more). The backend software (running on the same backend computer used by LABOCA) is used to collect the bolometer signals from the de-multiplexing electronics and to provide a networked data stream required by the APEX control software. With the use of the same bridge computer of LABOCA, real time digital signal processing (anti-alias filtering and down-sampling) of the raw data is possible, although not strictly required. All the software modules of SABOCA provide SCPI interfaces (Standard Commands for Programmable Instrumentation) allowing full remote operation of the instrument.

Performance on Sky

Characterization on sky of the final version of SABOCA was completed in February 2009. The array parameters are estimated averaging the results of fully sampled maps (called beam maps) of planets with useful flux and angular size (namely Mars, Uranus and Neptune, see Figure 4). The main beam, determined combining several beam maps, is circular and has a deconvolved FWHM of 7”.8, close to the expected value of 7”.5. The beam starts to deviate from a Gaussian at a relative intensity of ~6% (-12 dB) where the error pattern of the telescope becomes visible.

The 37 on-sky bolometers of SABOCA all perform better, in terms of detector noise distribution, than the bolometers with semiconducting thermistors (used in LABOCA) and do not show 1/f noise down to below 30 mHz. The clean quality of the signals is mainly due to the use of the new superconducting TES bolometers, which are practically insensitive to microphonics therefore particularly suitable for a noisy environment like the C-cabin of APEX.

Following the successful example of LABOCA, SABOCA has also been designed to be operated in “fast scanning” mode (Reichertz et al. 2001) without chopping the secondary mirror. The observing modes, therefore, are the same as for LABOCA but scaled to the different sizes of the beam and of the array: spiral patterns and raster of spirals for compact sources and rectangular on-the-fly for large maps of extended sources (for more details see Siringo et al. 2009 or on-line at www.apex-telescope.org/bolometer/laboca/observing/)

The sensitivity of SABOCA was derived from blank-sky observations after correlated noise removal. The mean receiver sensitivity was found to be 200 mJy·s$^{1/2}$. For average observing condition (PVW~0.5 mm and 60 degrees source elevation) the former value translates into an on-sky sensitivity of 750 mJy·s$^{1/2}$. In terms of mapping speed, that value corresponds to an uniform coverage of a 10'x10' sky area down to a residual rms noise of ~300 mJy/beam in one hour (two including overheads) of observing time (see Figure 5). The effective sensitivity, however, strongly depends on the content of PWV along the line of sight. An observing time calculator is available on-line at www.apex-telescope.org/bolometer/saboca/obscalc/

Science with SABOCA

SABOCA is a versatile instrument that can observe a range of objects of great interest in the different fields of today's astrophysics: from our own Solar System to the debris discs around nearby young stars, from molecular clouds and star forming regions in our Milky Way to cold dust in galaxies at various redshift and evolutionary stages, all the way to the early epochs of our Universe, constraining the star formation rates in high-redshift starburst galaxies.
Within the first year of operations, a number of relevant scientific results have been already obtained with SABOCA. One of the most frequent application of this new bolometer camera has been in follow-up observations of targets already observed with LABOCA. The 2.5x higher angular resolution of SABOCA can reveal new details in the morphology of sources with compact extended emission. In parallel, its spectral passband centred at 350 µm complements determine the characteristic temperatures of the source.

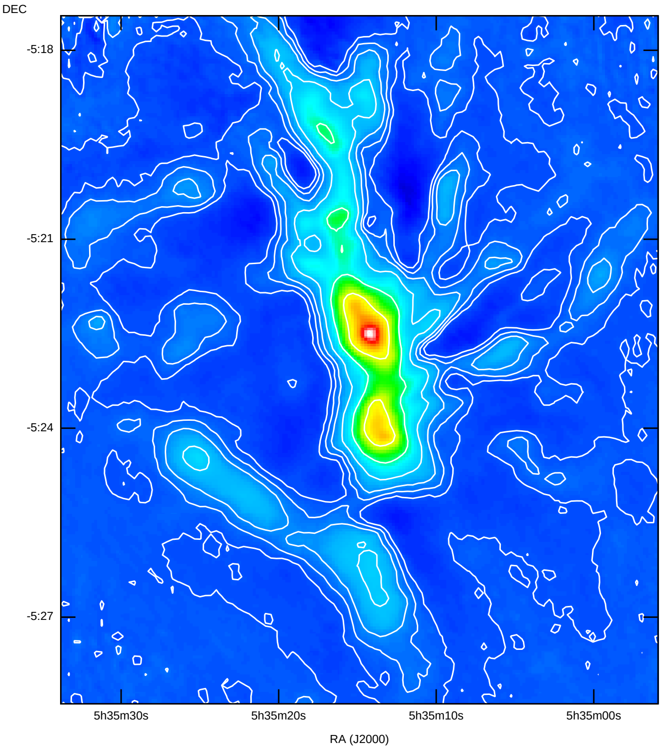

Figure 5. The Orion Molecular Cloud 1 (OMC-1) as seen by SABOCA at 350 µm. Contours show the flux at 0.3%, 1.0%, 3.0%, 10%, 30% of the 720 Jy/beam peak at the center of the map.

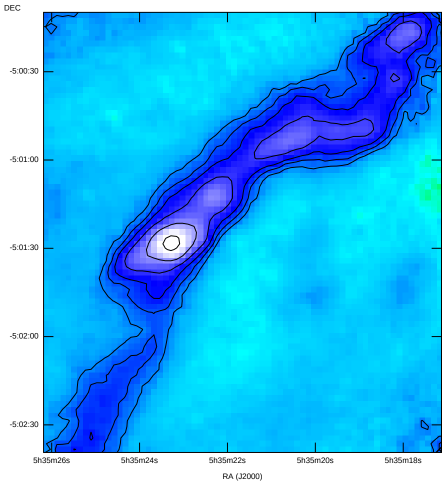

Figure 6. SABOCA map of the OMC-3 at 350 µm. Contours show the flux at 1%, 5%, 10%, 20%, 40% of the brightest peak in the map, 60 Jy/beam.

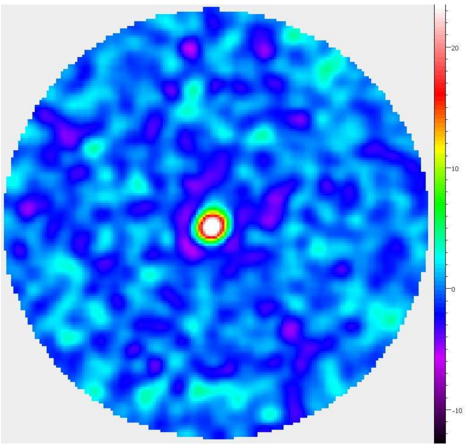

Figure 7. SABOCA map of the “eyelash”, the brightest submm galaxy known to date, at z=2.326. The observed 350 µm flux is 530+/-60 mJy (colour bar in S/N units). This map has a diameter of 180 arcseconds.

To show the mapping capabilities of SABOCA, in Figure 5 we show a large map of the 350 µm emission from the Orion Molecular Cloud-1 (OMC-1) that, at a distance of 500 parsec, is the closest known star-forming region undergoing massive star formation. The map covers a sky area of more than 10x10 arcminutes with an angular resolution of ~8” and an uniform residual noise of ~100 mJy/beam. It required 1.5 h of on-source integration time under very good sky conditions (PWV~0.1 mm).

Figure 6 shows the Orion Molecular Cloud-3 (OMC-3, located about 20 arcminutes North of OMC-1) belonging to the same dense filament of which OMC-1 is the brightest part. It features a chain of very young, deeply embedded low- to intermediate-mass protostars (Chini et al. 1997).

Figure 7 shows SABOCA observation of SMM J2135-0102, also known as "the eyelash". This object, at z=2.326, is the brightest submm galaxy known to date (see article by Swinbank et al. in this same issue of the Messenger). The source shows a 350 µm peak flux of 530 mJy and was detected at a 20-sigma level in a total observing time of 2.7 hours (including all overheads). The map was obtained with a sequence of scans in raster-spirals observing mode, providing a fully sampled image.

New possibilities for APEX

The successful commissioning of SABOCA on APEX has further significance: it demonstrates that the new superconducting technology (TES bolometers and SQUID amplification and multiplexing) can be viable outside of the protected environment of the laboratory. With proper shielding, the devices can be used even in an electromagnetically polluted environment, such as the Cassegrain cabin of APEX. Moreover, our tests at the MPIfR lab have also shown that the superconducting technology is compatible with the use of a pulse tube cooler (a type of closed-cycle cooling machine) thus allowing to operate instruments without the need for regular replenishment of liquid cryogens. An immediate advantage of a bolometer camera based on superconducting technology and operated on closed-cycle cryogenics is the possibility to keep the receiver cold most of the time with minimum maintenance. This would greatly enhance the operability of the system, allowing a more flexible observing schedule and reducing the work load for the ordinary maintenance of the receiver at the telescope.

Acknowledgments

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