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

Giorgio Siringo[1]
Ernst Kreysa[2]
Carlos De Breuck[1]
Attila Kovacs[3]
Andreas Lundgren[1]
Frederic Schuller[2]
Thomas Stanke[1]
Axel Weiss[2]
Rolf Guesten[2]
Nikhil Jethava[4]
Torsten May[5]
Karl M. Menten[3]
Hans-Georg Meyer[5]
Michael Starkloff[5]
Viatcheslav Zakosarenko[5]

[1] ESO
[2] Max-Planck Institute for Radio Astronomy, Bonn, Germany
[3] Department of Astronomy, University of Minnesota, Minneapolis, USA
[4] NASA Goddard Space Flight Center, Greenbelt, USA
[5] Institute of Photonic Technology, Jena, Germany

The Submillimetre APEX Bolometer Camera, SABOCA, was successfully commissioned in March 2009 for operation as a facility instrument on the 12-metre APEX telescope, located on Llano de Chajnantor at an altitude of 5100 m. This new camera for the 350-μm atmospheric window uses 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 sub-mm receivers available on APEX, fully exploiting the excellent atmospheric transmission at the site by offering effective mapping of the thermal continuum dust emission at 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) in collaboration with the Institute of Photonic Technology (IPHT). 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 instrument 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 2008 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 sub-mm astronomy. With its suite of high frequency heterodyne instruments — the Swedish Heterodyne Facility Instrument (SHFI), the Carbon Heterodyne Array of the MPIfR (CHAMP+) and the First Light APEX Sub-millimetre Heterodyne instrument (FLASH), see Guesten et al. (2008) for details — APEX already provides routine observations in atmospheric windows that have so far only seldom been accessible from other sites. Continuum observations are also possible with LABOCA (Siringo et al., 2007; 2009) which is currently the world's largest 870-μm bolometer array. The new 350-μm camera, SABOCA, complements LABOCA and opens up a shorter wavelength atmospheric window, offering, for the first time to the ESO community, a continuum mapping capability well within the sub-mm range.

With its 1.5-arcminute 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 Sub-mm Observatory (with a

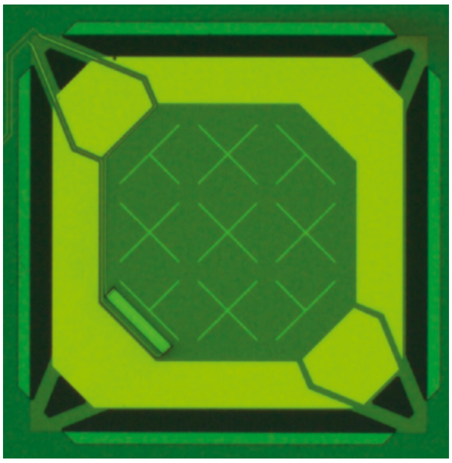

Figure 1. Picture of a single bolometer used in the actual version of SABOCA. The thermal conductivity depends on the thickness and number of "legs" connecting the central part of the membrane with the outside. Other layouts were produced and even tested but not used finally. All bolometers have cross-dipole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

field of 2.6 × 1 arcminutes; Dowell et al., 2003). Observations at 350-μm probe warmer dust emission or can constrain dust temperatures and the 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 for example the article by Swinbank et al., p. 42 in this issue). Finally, the 7.8-arcsecond SABOCA beam size provides 2.5 times better spatial resolution compared to LABOCA, and three times better compared to Herschel/SPIRE (Griffin et al., 2006) at similar wavelengths. The better resolution translates into more accurate size estimates and positions of sub-mm sources, aiding 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.

Instrument description

The bolometers of SABOCA are composite bolometers with superconducting

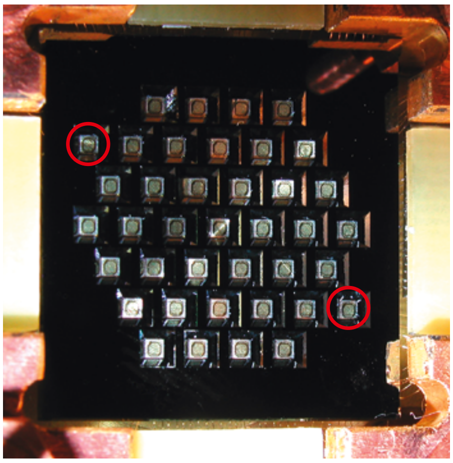

Figure 2. A picture of the bolometer array at the focal plane of SABOCA. One bolometer cell is about 1 mm in size and the full size of the array is about 15 mm. The two red circles show the position of the two blind bolometers.

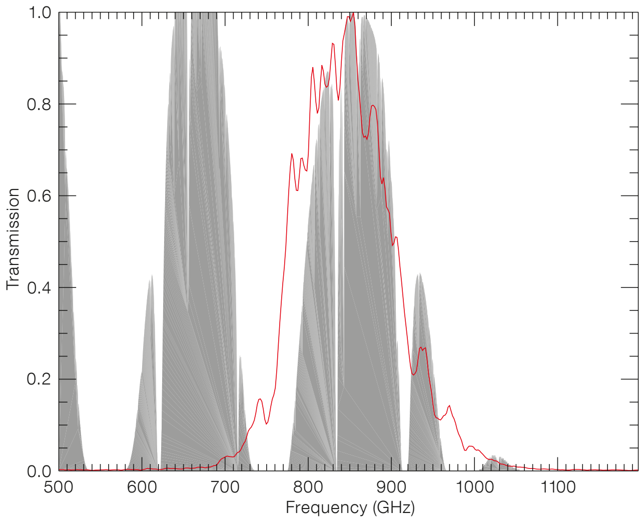

Figure 3. Spectral response of SABOCA (red) compared to the atmospheric transmission (gray). Both curves are normalised to unity.

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 designs of membrane structures, thermistors and absorbing elements. The bolometers selected for SABOCA (see Figure 1) have moderately structured membranes and showed a radiative noise equivalent power (NEP) of 1.6×10^{-16} W/Hz$^{1/2}$ (with 300 K background) during laboratory 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 three 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 opposite positions, and are used for monitoring purposes. The grid constant of the array is 2.0 mm (see Figure 2).

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

SABOCA's detectors 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 APEX Cassegrain cabin, is used to reduce the vapour 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 one 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 part of the cool-down process (about 2 hours).

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 passband 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 ten channels each for a total of 40 possible elements. The multiplexers and associated electronics have been designed and manufactured by IPHT. The four SQUID 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 as 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) the

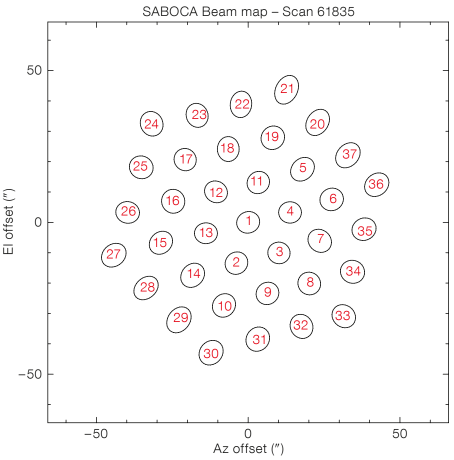

Figure 4. On-sky footprint of SABOCA, derived from one single beam map of Mars. The beam distortions are partially due to atmospheric refraction and fitting accuracy.

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 becomes superconducting during operation. The horn array, also 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. 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.

So as to be fully integrated into the APEX environment, SABOCA is provided with a hardware/software infrastructure similar to that of LABOCA. Front-end software (running on the same front-end computer used by LABOCA) is used to control and monitor the hardware of the system (temperature monitoring, SQUID tuning, helium pumping and recycling, and more). The back-end software (running on the same back-end 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 as 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

Characterisation 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 full width at half maximum (FWHM) of 7.8 arcseconds, close to the expected value of 7.5 arcseconds. 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, and therefore particularly suitable for a noisy environment like the Cassegrain 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 size of the beam and of the array: spiral patterns, a 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 online[1]).

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 conditions (i.e. precipitable water vapour [PVW] ~ 0.5 mm and 60-degree source elevation), the receiver sensitivity translates into an on-sky sensitivity of 750 mJy $s^{1/2}$. In terms of mapping speed, that value corresponds to a uniform coverage of a 10 × 10 arcminute sky area down to a residual root mean square (rms) noise of ~ 300 mJy/beam in one hour of observing time (two hours including overheads). The image in Figure 5 for example was made in 1.5 hours of on-source integration. The effective sensitivity, however, strongly depends on the amount of PWV along the line of sight. An observing time calculator is available online[2].

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 redshifts and evolutionary stages; all the way to the early epochs of the Universe, constraining the star formation rates in high-redshift starburst galaxies.

Within the first year of operations, a number of important scientific results have already been obtained with SABOCA. One of the most frequent applications of this new bolometer camera has been in follow-up observations of targets already observed with LABOCA. The 2.5 times 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 the determination of the characteristic temperatures of sources.

To display 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 400 parsec, is the closest known star-forming region undergoing massive star formation. The map covers a sky area of more than 10 × 10 arcminutes with an angular resolution of ~ 8 arcseconds and with a uniform residual noise of ~ 100 mJy/beam. It required

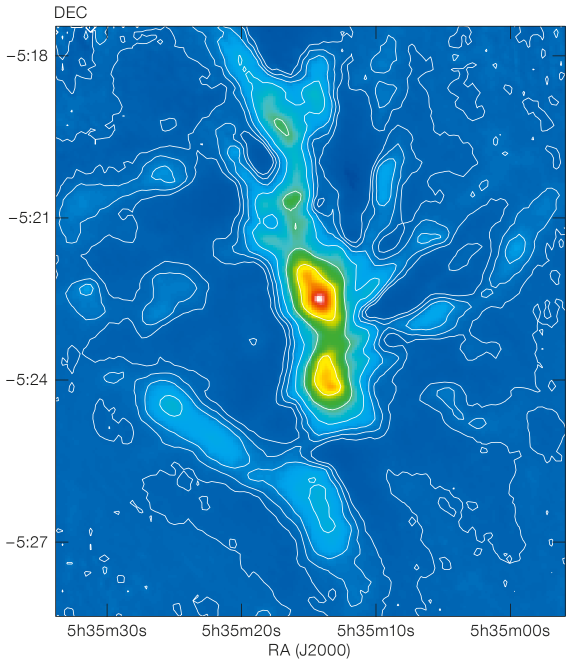

Figure 5. The Orion Molecular Cloud 1 (OMC-1) as seen by SABOCA at 350 μm. Contours show the flux at 0.3 %, 1.0 %, 3.0 %, 10 %, 30 % of the 720 Jy/beam peak at the centre of the map.

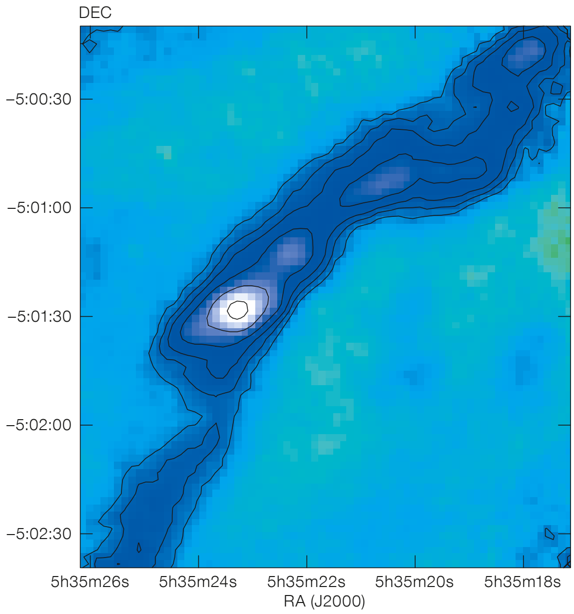

Figure 6. SABOCA map of the OMC-3 molecular cloud at 350 μm. Contours show the flux at 1 %, 5 %, 10 %, 20 %, 40 % of the brightest peak in the map, 60 Jy/beam.

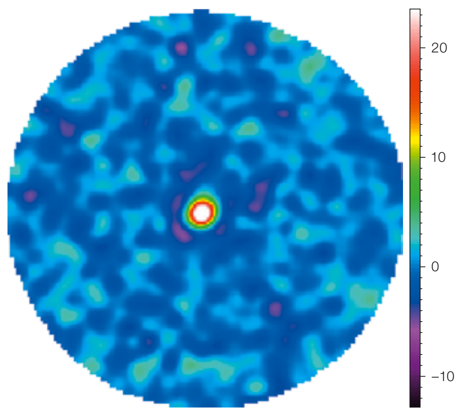

Figure 7. SABOCA map of the "Eyelash", the brightest sub-mm galaxy known to date, at $z = 2.326$. The observed 350-μm flux is 530 ± 60 mJy (colour bar in signal-to-noise units). This map has a diameter of 180 arcseconds.

1.5 hours 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 observations of SMM J2135-0102, also known as the "Eyelash". This object, at $z = 2.326$, is the brightest sub-mm galaxy known to date (see article by Swinbank et al., p. 42). The source shows a 350-μm peak flux of 530 mJy and was detected at a 20 σ 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) is 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 instruments to be operated 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 option of keeping 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.

Acknowledgements

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Links

[1] Observing with LABOCA: http://www.apex-telescope.org/bolometer/laboca/observing/
[2] SABOCA observing time calculator: http://www.apex-telescope.org/bolometer/saboca/obscalc/