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ORIGINAL ARTICLE

COCHISE: the first light of the Italian millimetre telescope at Concordia (Dome C, Antarctica)

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Abstract COCHISE (Cosmological Observations at Concordia with High-sensitivity Instrument for Source Extraction) is a 2.6 m telescope located on the high Antarctic Plateau near the Italian–French Concordia Base. The telescope is mainly devoted to Cosmological observations, able to operate between 200 μm and 3 mm of wavelength. In this paper we describe the main characteristics of the instrument. We also report on the first light, obtained during summer 2010–2011: this result marks the beginning of millimetre astrophysical observations at Concordia. Responsivity, noise equivalent temperature and field of view of the instrument are reported. At present COCHISE is the largest telescope located at Concordia. Beside the scientific expectations, the use of this kind of instrument in the Antarctic environment poses technological aspects of relevant interest: thus COCHISE can be considered as a pathfinder for future Antarctic telescopes.

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1 Scientific context

Millimetre and submillimetre observations are of great importance in many different Astrophysical fields, since they allow the exploration of a spectral range that provides a wealth of information on various aspects: first at all, the Cosmological studies, since the Cosmic Microwave Background (CMB) has its peak of emission exactly in this range.

There are also other interesting aspects, such as the formation of structures at high redshift, Galaxy formation, local observations related to the presence of cold dust in the Interstellar Medium and in some peculiar sources.

The realization of mm and sub-mm observations is a continuous challenge for two main reasons: the first is the technological problem of operating the detectors (often bolometers, cooled down to 300 mK), the second is posed by the atmosphere: the water vapour, in particular, that represents the main obstacle for ground observations. Indeed the atmospheric water vapour greatly affects the observations by absorbing the millimetre radiation strongly attenuating the signals.

For this reason, high altitude and very dry sites must be chosen in order to carry out millimetre observations. One possible choice is Antarctica. Besides the technical and logistic difficulties, in the last few years an increasing interest has been shown in the White Continent, because it has the right characteristics for the installation of great Astronomical Observatories.

2 Preliminary results

Since 1986 the Italian group carried out a series of experiments in order to check the quality of the site [1–3, 10, 11]. In 1989 the 2.6-meter millimetre telescope OASI (Infrared and Sub-mm Antarctic Observatory) was permanently installed at the Mario Zucchelli Station in Antarctica [12]. OASI provided to the Italian group with a deep experience on the numerous aspects related to the difficulties of the Antarctic environment. The OASI telescope is located at sea level and it is available only in summer season.

Despite its position, OASI supplied, during these years, interesting and original scientific results, including for example millimetre observations of cold dust contained in the Large Magellanic Cloud [1–3, 13] and in galactic HII regions [19, 20]. Unfortunately, these earlier results were overlooked in the review of the status of Antarctic astronomy by Burton [4].

Between 1994 and 1998, the OASI group carried out a series of preliminary experiments on the high Antarctic Plateau in order to check the quality of the site and the feasibility of measurements; these experiments included evaluation of mid-IR sky-noise [32], precipitable water vapour measurements [31], frequency and angular scale dependencies of noise [16], millimetre observations of the galactic emission [14], CMB anisotropy measurements (APACHE96, [33]) In the same period the summer base at Dome C became operative: the challenge was very interesting, and Dome C shown exceptional observational conditions. The atmospheric noise at Dome C is ten times lower than that measured on the coast [9].

All these reasons encouraged the OASI group to install a new telescope. The construction of COCHISE begun in 2005 and during Italian Antarctic Expedition 2007/2008 its installation was completed. In the first phases COCHISE will complete the millimetre site testing program which includes the determination of atmospheric transmission and its daily and seasonal fluctuations. This work has already been started by means of a spectral hygrometer with a systematic monitoring of short-time variations in the PWV (Precipitable Water Vapor) (Sabbatini el al., in preparation).

3 The site

Dome C (Lat 75°06′S, Long 123°21′E) is located at 3200 m above sea level on the East Antarctic plateau, approximately 1200 km from the coast; typical temperatures vary during the year from −35°C to −80°C.

Dome C is probably the best site in the world for millimetre and sub-millimetre observations [23, 30].

The atmospheric transparency [5–7] is a crucial parameter in the sub-mm and mm range and it is dominated by water vapour absorption. The measured average PWV content at Dome C agrees with the PWV calculated by a combination of atmospheric models and meteorological radio-soundings. It is estimated to be 0.72 ± 0.20 mm during the summer season, dropping to 0.26 ± 0.10 mm during winter ([24, 25, 31, 33]).

Available data show that the PWV content is much lower at Dome C than in Chile and at the South Pole: due to the lower average water vapour, atmospheric models indicate that a higher transparency could be found at Dome C most of the time [22, 27].

Atmospheric stability is another equally crucial parameter: the main results, extracted from Antarctic Automatic Weather Station (AAWS) data, have shown that the wind speed is very low, almost absent in the winter. The turbulence at Dome C is confined in few hundreds of meters above the ground and is nearly absent during the winter [17, 18, 26].

Despite these results, it will be mandatory to obtain more data on the mm and sub-mm site conditions at Dome C in the next future: and this represents one of the preliminary goals of COCHISE.

The telescope is located in the Astrophysical area of Dome C about 400 m from Concordia Station. It was installed on the top of an ice platform, about 4 m above surface level, in order to prevent the accumulation of snow driven by the wind. The platform is intended to host other Astronomical experiments

Fig. 1 The COCHISE telescope at Dome C

in the future, that will share a common laboratory located on a nearby lower platform; at present, the common laboratory is simply a heated tent. The Observatory hosts the necessary tools for the maintenance of the telescope and the detectors, the electronics, the tracking and data acquisition system, both connected to Concordia Base by means of fiber optics. Figure 1 shows the telescope during winter 2008.

A new shelter is being built on the astrophysical platform, in order to replace the tent and to improve the available facilities. Its design and realization, started during summer 2010–2011, are being made by IPEV and PNRA, the French and Italian polar agencies, complying with suggestions and requirements from the astrophysical community. The new shelter will have a better thermal insulation and a wider working space (more than 100 m^2). It will include a workshop, laboratory, control room, storage and technical room.

4 The telescope

The installation of COCHISE was accomplished during two summer campaigns, the XXII (2006–2007) and XXIII (2007–2008) Italian Antarctic Expeditions. In this Section a description of the telescope and the instrumentation is exposed. The main optical characteristics of the telescope are reported in Table 1. A schematic design of the COCHISE telescope is shown in Fig. 2.

4.1 Optics

From the optical point of view, COCHISE is very similar to OASI. It is a Cassegrain telescope: the primary mirror has a diameter of 2.6 m and is made of a monolithic Aluminium alloy. It weighs 124 Kg. Its surface r.m.s. roughness is less than 0.5 μm, making the telescope suitable to operate down to a wavelength of 200 μm (a conservative limit for the mirror efficiency); this condition makes also easier the alignment procedures with visible light. As a

Table 1 Optical characteristics of COCHISE

COCHISE optical characteristics	
Primary mirror diameter	D = 2600 mm
Focal length	f = 1300 mm
Focal ratio	f/D = 0.5
Secondary mirror diameter	d = 410 mm
Equivalent focal length	F = 10400 mm
Equivalent focal ratio	F/D = 4
Cassegrain Magnification	8
Surface r.m.s. roughness	$< 0.5\ \mu m$
Pointing accuracy	10 arcsec
First Airy disc ($\lambda = 1.25$ mm)	9.7 mm
First Airy disc ($\lambda = 2.00$ mm)	19.5 mm
Angular resolution ($\lambda = 1.25$ mm)	$3.2'$
Angular resolution ($\lambda = 2.00$ mm)	$6.4'$
Pointing accuracy	10 arcsec

matter of fact we only use an effective primary diameter of 2000 mm, leaving a large guard ring at the edge. The all optics is mounted on a rotating system to perform derotation of the sky and to keep the parallax angle fixed during the observations.

The secondary mirror (41 cm in diameter) is also made of an Aluminum alloy and weighs about 1.4 Kg. The secondary mirror is mounted on a spider made of 4 aluminium thin legs. The distance between the primary and

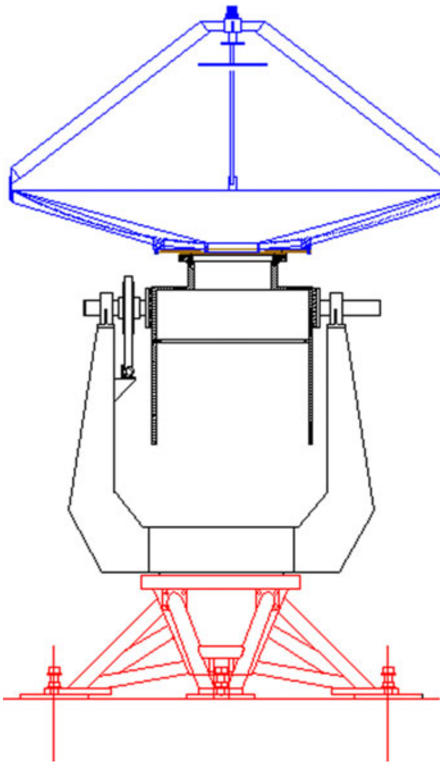

Fig. 2 Mechanical drawing of the telescope

secondary mirror can be set with a fine adjustment. A further alignment of the mirrors planes can be achieved by means of a three screws system. In order to perform the beam-switching on the sky, the secondary mirror is mounted on a modulating system, that uses a wobbling mass in counterphase at the resonance frequency, which is about 5 Hz. The equivalent beam-switching amplitude of the combined optics can be selected up to $\pm 0.5°$ and its stability is better than 1%.

COCHISE is equipped with two optical finders: one of 5 cm of diameter, one of 20 cm of diameter.

The rough optical alignment of primary and secondary mirrors has been obtained by using a laser beam. Then by pointing the Sun a better alignment was obtained.

The final step was done by placing an IMPATT diode microwave source on a remote site. The whole system fine alignment was furthermore checked by centering Planets (Venus, Jupiter) by means of the 20 cm optical finder and looking for the maximum amplitude of the millimetre signal.

4.2 Mechanics

The telescope was built by OFFICINE OTTICO-MECCANICHE MARCON (www.marcontelescopes.com) San Donà di Piave (VE), the same Industry that had made also the OASI one, acquiring a great experience in this kind of manufactures. The mounting is alto-azimuthal. The overall height of the telescope is about 4 m, with the altitude axis at a height of 2 m. The fork dimensions are 1 m diameter and 1.2 m height.

The motion is provided by hybrid stepping motors able to operate at very low temperature.

Mechanical coupling between the azimuthal worm and worm wheel ensures an accuracy better than 10 arcsec. An elastic coupling between the two is used to avoid blocking due to thermal contraction. Friction is reduced by using Molykote® extreme low temperature grease suitable to use at $-70°$C.

A wooden base has been realized to sustain the mounting and preventing it from the sinking into the ice, providing the thermal decoupling between the compacted ice of the platform and the metallic feet of the mounting. This structure consists of three wood boxes of about 60 cm each side, filled with compressed ice and sunk into the snow of the platform. Periodically, the levelling of the telescope is controlled by using a high accuracy level with a resolution of 20 arcsecs.

One of the main advantages of the site is the lack of natural and artificial obstacles on the horizon, thus the sky is almost completely free; to maintain this condition COCHISE has not been equipped with a dome. For installation and maintenance operations, that could require long periods of outdoor work, a fabric cover can be set around the structure in order to protect from wind.

The observations are not feasible only below 5° in elevation in West direction due to the presence of the shelter.

4.3 Pointing and tracking system

The tracking system was developed by ATEC-ROBOTICS Company (Advanced Technologies for Research and Industry, www.atec-robotics.com). It makes use of the Magellano version ST7 software for an alt-azimuthal telescope modified according to COCHISE specific requests. It is composed by two packages: Magellano ST7 CTRL, dedicated to the direct telescope control, and Magellano ST7 GUI for the remote control by means of network connection. Besides the typical procedures common to all the telescopes, other special commands have been implemented in the Magellano software, including the procedure for In–Out, rast scan and skydip observations. The system is provided with a GPS for coordinates and time control; a handset is available for manual pointing. The pointing and tracking can be controlled by means of absolute encoders mounted on the main axes. At present, Heidenhain ROD 280 encoders are available for COCHISE, with an accuracy of 10 arcsec. They can operate in a temperature range between −20°C and +70°C: they need to be heated and thermally insulated in order to work at Dome C temperatures. Their readout and thermal control is integrated in the Magellano software.

To avoid the breaking of the cables due to the low temperatures, the pointing and tracking system has been upgraded by means of wireless technology. A new version was made and tested during the Summer Campaign 2009–2010. In this configuration, three wireless units are located next to each motor of the telescope (ALT, AZ, ROT); the three units are controlled by a PC located inside the laboratory. This system requires the use of only one power supply cable. The three external units are thermally insulated and controlled through heaters, fans and thermometers. A wireless handset is also available.

4.4 Acquisition system

COCHISE has been equipped with a National Instruments Compact-RIO system, that is an advanced reconfigurable embedded control and acquisition system designed to work in the harshest environments, having an operating temperature guaranteed between −40°C and 70°C. All the electronic parts have been prepared, installed and tested on site at different temperatures, including the cables, the acquisition system, the modulation system of the secondary mirror, the lock-in amplifiers. The lock-in amplifiers and the acquisition module are located outdoor, at the feet of the telescope, in a thermally insulated case that communicate with the indoor computers by means of teflon net cable.

4.5 Defrosting system

Since COCHISE is at the moment the largest telescope installed at Concordia, it has been used not only for Astronomy but also for technological experiments. All the telescopes that operate on the high Antarctic plateau suffer for the formation of frost on the surfaces. For this reason, the primary

Fig. 3 A view of the primary mirror

mirror has been provided with an experimental defrosting system, realized within an international collaboration lead by the CEA Saclay Group, under the coordination of Dr. G. Durand.

The defrosting system has been realized by using three methods, based on conduction (heating), convection (blowing) and radiation (infrared); the three subsystems can be used independently or in combination. The first one makes use of an heating cable located on the rear of the primary mirror and properly covered by an insulation material in order to avoid heat losses on the back side; the second one blows dry air on the mirror surface by means of a ventilator and ventilation tubes; in the last method infrared lamps located on the edge of the mirror radiate tangentially to the beam. All the system is remotely controlled from the Station. The primary mirror is also observed by a webcam.

The defrosting system has been properly working during all the 2008 winter. It gave interesting results, useful for the telescope itself and in the perspective of future applications. A short description can be found in Sabbatini et al. [21]. Figure 3 shows the defrosting system on the primary mirror.

4.6 Power consumption

The overall power consumption of the telescope during observations is 1 kW; it includes the power supply for pointing system and acquisition system. The defrosting power consumption depends on the chosen combination: it can span between 300 W (when using blowing alone) and 2 kW (when the three subsystems are working simultaneously at maximum power). Anyway the defrosting is usually switched off during astronomical observations and is considered as an experiment independent from COCHISE telescope.

5 First light observations

The first light of COCHISE has been achieved in December 2010, during the XXVI Italian Antarctic Expedition. This important result marks the beginning of millimetre astrophysical observations at Concordia. In the following we give the details of the instrument and a description of the observations.

5.1 Cryogenics

For the first light, COCHISE has been equipped with a two-channel millimetre photometer, whose wavelengths have been selected in order to perform the Sunyaev–Zeldovich effect. The detectors of bolometric type are cooled at pumped ^{3}He temperature.

The cryogenic photometer uses only liquid ^{4}He. ^{4}He vapours are used to keep a pure aluminium shield at a temperature of about 90 K. In addition, sixty layers of superinsulation ensure an adequate thermal insulation.

This configuration allows the use of the photometer at extreme locations, such as Concordia, where the supplying of two cryogenic liquids can be unaffordable. Moreover the photometer is much lighter than the configuration with liquid nitrogen, with an overall weight of only about 12 Kg, making easier the installation at the telescope.

A ^{3}He refrigerator (described in Dall'Oglio et al. [15]), mounted on the liquid ^{4}He flange, operates at 312 mK, with a stability in temperature better than 1 mK. The operating temperature is maintained for 48 hours: the same duration of the liquid ^{4}He in the main tank. The recycling phase takes 4 hours (including the liquid ^{4}He refilling, pumping on the ^{4}He bath, heating the cryopump and the cooling time). The duty cycle is thus 90%. The evaporator temperature is measured by a calibrated LakeShore four-wire Germanium thermometer.

5.2 Cold optics

The detectors are Si-composite bolometers (Infrared Laboratories) coupled to band-pass meshes which are anchored to the 4.2 K shield. A 4.2 K dichroic mirror, a low-pass edge filter with cut-off at 6 cm^{-1} (beam-splitter), splits the incoming radiation between two f/4 Winston cones, cooled at 0.3 K, located orthogonal to each other. The wavelength ranges are defined by two band-pass interference filters, cooled at 4.2K, centered at 5 and 8 cm^{-1} ($\lambda = 2.0$ and 1.25 mm) with bandwidths 1.3 and 2.3 cm^{-1} (540 and 360 μm) respectively. Their rejection factor has been estimated to be better than 10^{-6}. At the Winston cone entrance a further Yoshinaga type filter is installed with a cut-off at 55 cm^{-1}. A low-pass filter with a cut-off at 14 cm^{-1} is mounted on the 90 K shield. A schematic drawing of the cold optics configuration is shown in Fig. 4.

5.3 Observations

The modulation of the secondary mirror is sinusoidal with a frequency ν_{mod} ~5.33 Hz. This modulation frequency is chosen in a range where the bolometers have an optimal frequency response and are not affected by the 1/f noise; the modulation is always parallel to the horizon, with the source in

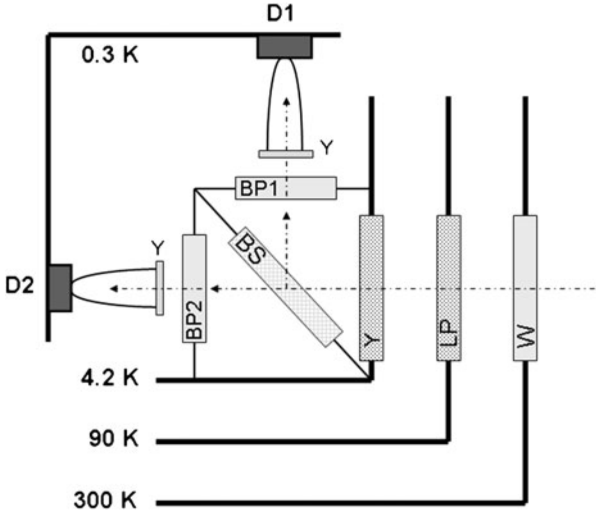

Fig. 4 Scheme of the cold optics showing the two detectors (*D*1, *D*2), the band pass meshes (*BP1*, *BP2*), the beam splitter (*BS*), the Yoshinaga filters (*Y*), the low-pass (*LP*) and the rigidex window (*W*)

the central field. The signal due to the central field, at frequency twice the $\nu_{\rm mod}$, is demodulated by a lock-in amplifier, which is also used to integrate the detector signal for 3 sec in order to remove high frequency fluctuations. The beam-throw amplitude is estimated to be 15.5 arcmin based on mechanical considerations; measurements of this parameter are reported in the next Section.

In order to evaluate the detectors responsivity, strong point-like sources like the planets are the best choice as millimetre calibrators. During the period of observations, Jupiter and Venus were in excellent observing conditions with respect to altitude and solar elongation. They have been observed regularly during the whole period; both drift scan and In–Out techniques have been applied. Every drift scan session consists of various transits at different declination positions, in order to find the maximum of the signal and thus check (and eventually reset) the pointing system. The observations have been conducted close to the transit of the planets.

6 System parameters

For each drift scan, the time-ordered data are fitted with a function that describes the response of the field of view convolved with the three fields sinusoidal modulation. The free parameters are the beam size, the beam-throw and the signal amplitude. For each day, the best drift scan has been chosen. The Figs. 5 and 6 show the Jupiter transit.

6.1 Beam shape

Based on geometrical considerations, the angular response AR(θ, φ) of the instrument can be considered circularly symmetric (i.e., function of θ alone).

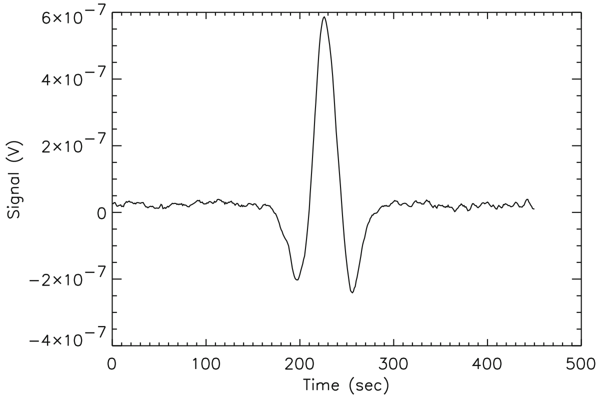

Fig. 5 Transit of Jupiter at 1.25 mm

The beam shape has been proven to be symmetric by means of scans of an artificial source (IMPATT diode) and of point-like bright sources (planets). The scans of the IMPATT source have been performed both in horizontal and in vertical directions. For symmetrical motivations, the field of view has the same width along the various directions.

6.2 Beam-throw

The beam-throw is given by the distance between the two minima, $d_m(s)$, converted by taking into account the speed of the source in the sky ($15''\cos\delta$) and the projection of the minima position due to the parallactic angle between source passage and constant elevation modulation ($1/\cos p$):

$$beam - throw(') = d_m(s)\frac{15''\cos\delta}{60}\frac{1}{\cos\ p}$$

where $p = \tan^{-1}\left(\frac{\sin H}{\cos\delta\tan\varphi - \sin\delta\cos H}\right)$, δ is the source declination, φ is the geographic latitude of the observatory and H is the hour angle. Planets have been

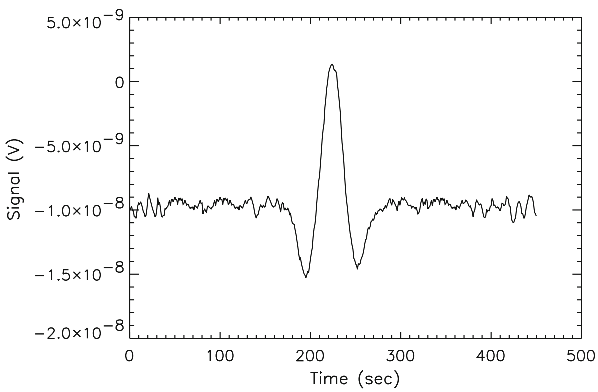

Fig. 6 Transit of Jupiter at 2.0 mm

observed close to their transit, so that the parallactic angle p is small, hence the correction $1/\cos p$ is negligible. By averaging all the beam-throw values obtained in every single fit, we found a mean value of 15.6 ± 0.3 arcmin, in agreement with the mechanical estimate.

6.3 Beam size

At the beginning of the observations, the focus has been adjusted on Jupiter.

The fit allows the estimation of the FWHM beam-width of the system. The fluctuations of the results are due to statistical errors of the signal and to a small change in the position of the detector on the optical axis, due to the removal and reinstallation of the photometer for the cryogenic cycles. The average value over the whole period is estimated to be 5.2 ± 0.1 arcmin.

6.4 Flux density calibration

A 77 K blackbody has been used to calibrate the detectors in laboratory. The most reliable sky calibration is performed with the signal from Jupiter. However, consistent values (within the errors) for the responsivities are found with data from the other planets observed.

Taking the planet brightness temperatures from Werner and Neugebauer [34], Ulich [28] and Ulich et al. [29] we find for the responsivities 15.7 and 0.25 μV/K at 1.25 and 2.0 mm respectively.

These values show that the efficiency at 2.0 mm is lower than the DC responsivity obtained from laboratory calibration. Probably, during the observations, a fault in the thermal contact between the components of the bolometer has led to a reduction in the detector's frequency response and hence a reduced sensitivity. Indeed a visual check at the end of the observations has revealed a weak thermal contact between the absorber and the thermometer of the bolometer, but its substitution during the observations has been prevented by the lack of enough liquid helium at Dome C.

7 Sky noise

Measurements of sky noise have been performed on blank sky and the N.E.T. (Noise Equivalent Temperature) values are 1.4 and 2.5 mK$\sqrt{\ }$sec at 1.25 and 2 mm respectively. The signal-to-noise ratio observed on planets is exceptionally good. These measurements confirm the previous results obtained by the Group with preliminary experiments on site testing.

8 Future developments

In the future, the use of a pulse tube cryocooler will substitute for Liquid Helium to cool down the detectors, in order to avoid the problems of transporting

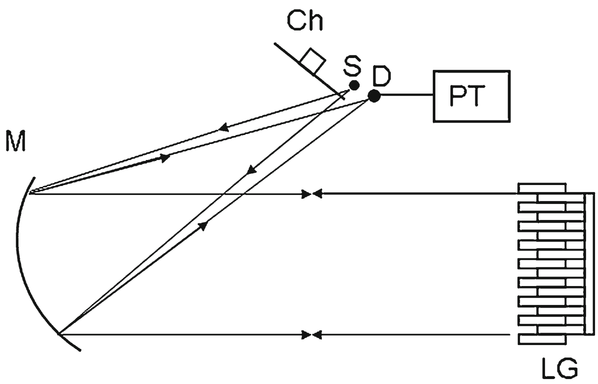

Fig. 7 Optical system of the Fourier-transform Lamellar-Grating. *M* off-axis parabolic mirror; *LG* Lamellar Grating; *S* source; *Ch* chopper; *D* SHAB detector; *PT* pulse-tube cryocooler

and handling Liquid Helium at Concordia. The cryocooler must be specifically adapted for operating at the temperature of Dome C; this work is in progress.

Furthermore, a multi-channel photometer equipped with SHAB (Superconducting Hotspot Air-bridge Bolometer) is under test in laboratory. These detectors are composed by a superconducting stripe (Niobium in our case) coupled to a logarithmic spiral antenna, kept at $T<T_C$. The bias voltage V_{bias} forms in the middle of the Niobium bridge a resistive volume (the so-called "hotspot") whose dimension is modulated by the incoming radiation. A measure of the current circulating in the SHAB allows the measure of the radiation. A detailed description of these devices, first developed for THz medical and security applications, can be found in Cibella et al. [8]. Optimization for use at millimetre wavelengths requires a new drawing of the antenna and light collimator. This process is ongoing and preliminary measurements with SHAB detectors have been already performed using the OASI telescope at MZS.

Due to their nature, SHABs work at $T<T_C$, where in our case T_C is 8.2 K. This means that liquid ^{4}He temperature is adequate to cool down the detectors. In this case the new photometer will not require the use of ^{3}He refrigerator; the coupling of SHAB to a pulse tube cryocooler has been already tested and does not pose major problems.

With respect to OASI, a wider space has been left for the focal plane of COCHISE in the perspective of further experiments. Indeed, in the future the focal plane will include a Lamellar Grating (LG) interferometer, useful to perform spectra in the sub-mm range, particularly useful for Cosmological studies.

The Lamellar Grating has already been realized and some preliminary calibrations have been performed in the laboratory. With respect to the Fig. 7,

Table 2 Characteristics of Lamellar-Grating spectrometer

Lamellar Grating characteristics	
Dimensions	15×15 cm^2
Resolution	0.2 cm^{-1}
Spectral range	2–10 cm^{-1}

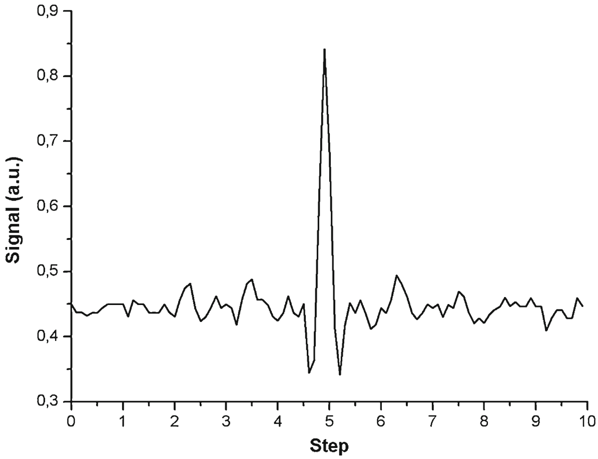

Fig. 8 Interferogram obtained with LG spectrometer

that shows a sketch of the optical system used, the signal from the source S (a halogen lamp), modulated at 15 Hz by the chopper Ch, is collimated by the off-axis parabolic mirror M (diameter 37 cm, focal length 60 cm) toward a Lamellar Grating LG (whose characteristics are shown in Table 2). After the reflection on LG, the beam is refocused by M on the detector D, a SHAB bolometer. The matching between the optics and the detector is provided by a Winston cone and a Yoshinaga edge filter, with cut-off at 55 cm^{-1}. The incoming radiation enters the cryostat through a polyethylene vacuum window and a low-pass edge filter with cut-off at 14 cm^{-1}. The bolometer is cooled down to 2.6 K through a pulse-tube cryocooler PT. Figures 8 and 9 show an example of interferogram and spectrum realized by a FFT software. This LG will be installed to the focal plane of COCHISE probably in the next Antarctic Campaign 2011–2012.

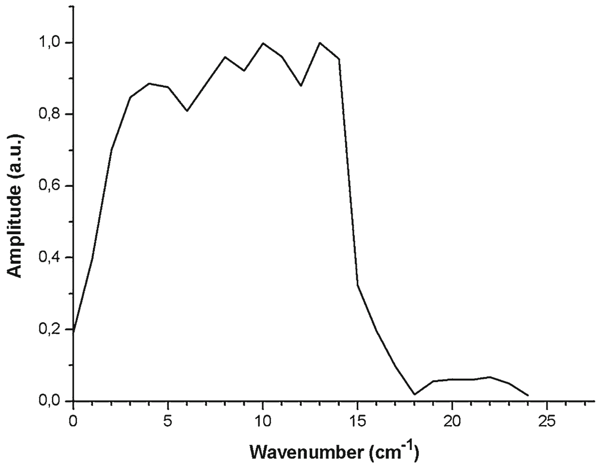

Fig. 9 Spectrum obtained with LG spectrometer

9 Conclusions

In this paper we reported the first light of COCHISE. The telescope is now fully working and ready for astrophysical and cosmological observations. The achievement of this first goal represents an important milestone. A two-channel millimetre photometer, operating with 300 mK bolometers, is already available; the optimization of a new focal plane including the Lamellar Grating coupled with the Pulse Tube cryocooler is in progress.

The first COCHISE observations are extremely promising. These results encourage the OASI Group to pursue the main goal of the Project: to turn COCHISE into a permanent astrophysical Observatory.

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