Atmospheric monitoring in the millimetre and submillimetre bands for cosmological observations: CASPER2

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ABSTRACT

Cosmological observations from ground at millimetre and submillimetre wavelengths are affected by atmospheric absorption and consequent emission. The low- and high-frequency (sky-noise) fluctuations of atmospheric performance necessitate careful observational strategies and/or instrumental technical solutions. Measurements of atmospheric emission spectra are necessary for accurate calibration procedures as well as for site-testing statistics. CASPER2, an instrument designed to explore the 90–450 GHz (3–15 cm−1) spectral region, was developed and had its operation verified in the Alps. A Martin–Puplett interferometer (MPI) operates by comparing sky radiation, coming from a field of view (FOV) of 28 arcmin (full width at half-maximum) and collected by a 62-cm-diameter Pressman–Camichel telescope, with a reference source. The signals at the two output ports of the interferometer are detected by two bolometers cooled to 300 mK inside a wet cryostat. Three different but complementary interferometric techniques can be performed with CASPER2: amplitude modulation (AM), fast-scan (FS) and phase modulation (PM). An altazimuthal mount allows sky pointing, possibly co-aligned with the optical axis of the 2.6-m-diameter telescope of MITO (Millimetre and Infrared Testagrigia Observatory, Italy). The optimal time-scale to average acquired spectra is inferred by Allan variance analysis at five fiducial frequencies. We present the motivation for and design of the atmospheric spectrometer CASPER2. The procedure adopted to calibrate the instrument and the preliminary performance of it are described. Instrument capabilities were checked during the summer observational campaign at MITO in 2010 July by measuring atmospheric emission spectra with the three procedures.

Key words: instrumentation: interferometers – site testing – cosmology: observations.

1 INTRODUCTION

Ground-based cosmological observations can be carried out in the millimetre and submillimetre bands (hereafter mm and submm), but a continuous monitoring of the atmospheric contribution is required. Accuracy in the calibration procedure towards known photometric sources results from a good knowledge of transmission and emission along this optical path. Sky brightness can be suitably monitored in this frequency range by spectrometers designed specifically for this purpose (for example the Fourier Transform Spectroscopy [FTS] interferometers employed in Matsuo, Sakamoto & Matsushita 1998; Matsushita et al. 1999; Paine et al. 2000) or, more generally, by spectral observations of sky objects when optically matched to existing telescopes [see the description of the instrument installed at the Caltech Submillimeter Observatory (CSO) focal plane in Serabyn & Weisstein 1996]. We have developed an instrument, CASPER2, to record atmospheric emission spectra in the millimetre band to assist with cosmological observations with the 2.6-m-diameter Cassegrain telescope at MITO (Testa Grigia, Italy, 3480 m a.s.l.) (De Petris et al. 2007). It is conceptually similar to CASPER, the experiment proposed for the Italian–French Antarctic base, Dome C (De Petris et al. 2005), but with a more limited spectral band (Decina et al. 2010). Such an instrument makes it possible to avoid specific telescope procedures, with consequent loss of observational time, such as skydips, and to infer atmospheric opacity in a wide spectral range.

After a brief description of the importance of an instrument such as CASPER2 in Section 2, the instrumental concept and its major characteristics are described in Section 3. In Section 4 a discussion about the Martin–Puplett interferometer (MPI) and the options adopted for signal sampling are presented. Section 5 reports

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preliminary atmospheric spectra as recorded at MITO in 2010 July. Final remarks are made in the Conclusions.

2 COSMOLOGICAL OBSERVATION REQUIREMENTS

Ground-based observations focused on cosmological targets in the mm/submm bands (sub-THz frequencies) are greatly affected by the presence of the atmosphere. The performance in this spectral region is dominated mainly by water vapour content, which is modelled by a continuum-like term and a series of absorption lines peaked at 183, 325, 380, 448 and 557 GHz. Oxygen is also present as an absorber at 118, 368 and 425 GHz but, in contrast to $\text{H}_2\text{O}$ fluctuations, it is well-mixed in the atmosphere and so contributes mainly only as a constant radiation background, still dependent on the elevation, with consequent photon noise in the detectors. Atmospheric synthetic spectra, derived from models, are a valuable support for predicting atmospheric brightness starting from thermodynamic parameter values; see, for example, the $\text{ATM}$ code (Pardo, Cernicharo & Serabyn 2001). However, a validation of the model for a specific site is mandatory and this is possible only when on-site recorded spectra are available. This is the case at MITO with CASPER2.

Short-term variation of the atmospheric emission on different spatial scales contributes as sky noise, while slow fluctuations of the attenuation can affect the quality of sky calibrations. Regarding observations only in the mm/submm bands, two kinds of approaches for atmospheric monitoring are widely applied. The atmosphere is usually dealt with through an isothermal slab model, in which opacity follows a zenithal secant law. Under this assumption large telescopes are periodically employed to perform altitude scans in the sky (i.e. skydips) to derive the zenith optical depth, integrated in the operating photometric band. Owing to the fact that this procedure takes time away from the astronomical observations, the opacity is alternatively derived by employing ancillary instruments such as tippers, GPS or water vapour radiometers (see for instance Radford & Holdaway 1998; Coster et al. 1996; Wiedner et al. 2001). All these instruments feature wide fields of view and limited spectral capabilities different to working telescopes. This makes the assessment of the effective site quality (i.e. in-band transparency and fluctuations at the angular scales of interest) a non-trivial task. A spectrometer is the natural solution for continuous sky monitoring over a wide spectral band, and an MPI is an efficient solution for reaching this goal. Furthermore, if the spectrometer is optically matched to its own medium-size telescope it is possible to observe the sky in a specific direction and at an angular scale closer to that of the main telescope. In any case, a model for extrapolating the atmospheric opacity at different frequencies is mandatory.

A semi-empirical procedure was proposed by De Gregori et al. (2012) to perform an analysis of atmospheric transmission employing radio-sounding data to feed the $\text{ATM}$ code for generating synthetic spectra in the wide spectral range from 100 GHz to 2 THz.

3 INSTRUMENT

CASPER2 is composed of a two-mirror telescope, an interferometer, a wet cryostat and an altazimuthal mount. The atmospheric emission spectra are acquired using an MPI that can be easily converted into a spectropolarimeter with many consequent scientific applications. The MPI is fully described here, while in Section 4 the basics of the interferometer and the calibration procedures are detailed. The detectors, two Ge-bolometers with a Noise Equivalent Power (NEP) $\sim 10^{-15}$ W Hz$^{1/2}$, are cooled down to 290 mK by a wet cryostat, using liquid nitrogen and helium combined with a He$^3$ fridge. The cryostat (Infrared Labs, HDL-8) is identical to the one described in Catalano et al. (2004). In Fig. 1 a schematic Computer Aided Design (CAD) drawing of CASPER2 is shown, while Fig. 2 illustrates the instrument in operation at the Testa Grigia station (Alps, 3480 m a.s.l.).

The optical design satisfies the expected measurement requirements: a low-resolution spectrometer in the range of 90–450 GHz ($R \sim 50$) and a small field of view (FoV; less than 1'). To achieve...
these goals we matched a two-mirror telescope with an MPI. The optical layout, with the main components labelled as described in the text, is shown in Fig. 3.

A f/3.5 Pressman–Camichel telescope collects sky radiation and feeds one of the two input ports of the MPI. With this optical solution the wavefront aberrations introduced by the 62-cm concave spherical primary mirror (M1) are compensated by a 12-cm convex ellipsoidal subreflector (M2). The primary mirror is under-illuminated by the secondary mirror, which operates as an aperture stop of the telescope alone, resulting in an entrance pupil 46 cm in diameter. Both the mirrors were manufactured in an aluminum alloy, ensuring a fast and homogeneous thermalization of the surfaces. The mirrors were carefully polished to reflect visible light: the final rms surface roughness is lower than 0.1 μm. The primary mirror was manufactured by the Officine Ottico Meccaniche Marcon di San Donà di Piave (Italy), and the ellipsoidal subreflector at the INFN machine workshop at the Department of Physics in Rome. The secondary mirror is maintained in the right position along the telescope axis by a 2-cm-thick polystyrene foam plate (ST) (BASF, Styrodur 3035N), allowing a null obscuration owing to the subreflector support and avoiding any possible consequent diffracted radiation. Laboratory measurements show high transmission values (>97 per cent) and low polarization (<1 per cent) of this material across the whole band. The telescope is shielded from off-axis unwanted radiation (i.e. from the Sun during daytime measurements) by eight panels with inner reflective surfaces, 0.5-mm-thick Peraluman sheets, shaped as vanes to operate like roof mirrors (Gervasi et al. 1998).

3.1 Optics

A 45°-tilted wire-grid (WG1) linearly polarizes the transmitted sky radiation focused by the telescope (sky) (see Fig. 3). The radiation emitted by a reference source at ambient temperature (ref), realized by a disc of Eccosorb AN72, enters the second input port of the MPI and is reflected by WG1 with a perpendicular polarization. An alternative colder reference source, closer to atmospheric emission, is under consideration. The two inputs are combined in planar waves at the entrance of the MPI by a HDPE (High-Density PolyEthylene) plano-convex lens (L1). A second wire-grid (WG2), still tilted at 45° inside the MPI, is rotated around the optical axis by 35.26° to correctly split the two polarization axes. It acts as beam-splitter separating the linearly polarized incoming radiation into two orthogonal components. Two 90° roof-mirrors (RM1 and RM2), made from diamond-turned stainless steel, can move along the two split optical beams changing the optical path difference (OPD). RM1 is mounted on a linear stage (AICOM SPA, Model SMP-123) to create a ±15-mm mechanical path difference, corresponding to a 5-GHz spectral resolution, while RM2 is sinusoidally wobbled by a shaker (Lynge Dynamic System, Model 409) on a linear stage with an amplitude of ~1 mm (see Section 4.5.3).

The radiation undergoes a polarization rotation of 90° when reflected back onto the roof mirrors. A second HDPE plano-convex lens (L2) focuses the beam in front of the cryostat window. The last HDPE plano-convex lens (L3) is mounted inside the cryostat, on the radiation shield of the helium liquid tank, cooled down to 1.6 K. This lens refocuses the radiation towards two detectors, namely the two output ports, after the splitting of the two polarization states by the third wire-grid (WG3), cooled down to 300 mK. The port corresponding to the transmitted radiation is named Channel 1, and the other port is named Channel 2. All the wire-grid polarizers have 10-μm-diameter tungsten wires spaced by 25 μm and show an efficiency in the reflected and transmitted polarizations better than 10^{-3} in our spectral range.

The first two lenses, L1 and L2, were carefully shaped to image the subreflector on L3, at least for the zero path difference (ZPD) RM1 position, meaning that it acts as the cold-aperture stop of the full optical system, that is, the Lyot stop. We have the possibility of selecting the last optical element as the aperture stop only because a single pixel is present in the focal plane. Incidentally, L3 is also the exit pupil. The optical design was developed with ZEMAX, ensuring diffraction-limited performance in the whole 90–450 GHz spectral range. The two bolometers are illuminated by f/3.5 Winston cones with a 10.5-mm-diameter aperture entailing a throughput, A2, equal to 0.05 cm^2 sr.

The optical axis, from the MPI exit to the cryostat entrance window, overlaps the elevation axis, ensuring a vertical position for the cryostat for all the telescope pointing positions. The optical consequences of this choice, as derived from the variable orientation between the wire- grids with elevation angle, are discussed in Section 4.

After fixing the telescope configuration and assuming a FoV equal to 28 arcmin (full width at half-maximum; FWHM) we limited the lower value for the focal length of the lens L1, f_{L1}, to satisfy the Jacquinot condition. The minimum spectral resolution can be related to telescope–MPI optical matching in the following way:

\[ \delta \nu \geq \frac{v_{\text{max}}}{8} \left( \frac{d_{\text{tel}}}{f_{\text{tel}}} \right)^2 = \frac{v_{\text{max}}}{8} \left( \frac{\text{FoV} f_{\text{tel}}}{f_{\text{L1}}} \right)^2, \]

where \( v_{\text{max}} \) is the maximum frequency (450 GHz), \( d_{\text{tel}} \) is the telescope field stop diameter (13.2 mm) and \( f_{\text{tel}} \) is the telescope effective focal length (1621 mm). In our case, \( f_{\text{L1}} \) was chosen equal to 145 mm, satisfying the Jacquinot condition up to \( R \sim 4000 \) at \( v_{\text{max}} \).

\(^{1}\) ZEMAX Development Corporation; www.zemax.com
Table 1. CASPER2 instrumental main features.

| Telescope                  | f/3.5 Pressman–Camichel |
|----------------------------|-------------------------|
| Telescope effective focal length | 1621 mm                |
| Primary mirror diameter    | 620 mm                  |
| Primary mirror conic constant | 0                     |
| Primary mirror curvature radius | 978.4 mm               |
| Secondary mirror diameter  | 120 m                   |
| Secondary mirror conic constant | 8.86                   |
| Secondary mirror curvature radius | 354.9 mm              |
| Entrance pupil diameter    | 460 mm                  |
| Field of view (FWHM)       | 26 arcmin               |
| AG                         | 0.05 cm² sr             |
| Interferometer             | Martin–Puplett          |
| Spectral range             | Channel 1: 90–360 GHz   |
|                           | Channel 2: 90–450 GHz   |
| Mechanical path difference | 30 mm                   |
| Spectral resolution        | 5 GHz                   |
| Detectors                  | Two composite NTD       |
|                           | bolometers @ 0.3 K      |
| Calibrator                 | Eccosorb AN72          |
| Mount                      | Altazimuthal            |
| Star tracker field of view | 1 arcmin                |
| CCD field of view          | (14.4 × 13.6) arcmin   |

Table 2. Filter chain characteristics.

| Type                  | Cut (GHz) | Temperature (K) |
|-----------------------|-----------|-----------------|
| Quartz window         | Off (>3000) | 300             |
| ARC quartz + black polyethylene | Off (>1200) | 77              |
| Yoshinaga             | Off (>1650) | 1.6             |
| Mesh                  | Off (>450)  | 1.6             |
| Yoshinaga             | Off (>1500) | 0.3             |
| Mesh channel 1        | Off (>360)  | 0.3             |
| Mesh channel 2        | Off (>450)  | 0.3             |
| Winston cones         | On (<90)    | 0.3             |

3.2 Filter chain

Blocking filters are employed in our system in order to reduce radiative input during the various cryogenic stages in the cryostat (and consequently on the bolometers), while mesh filters are used to select the frequency bandwidth of interest. In Table 2 all the components in the filter chain are listed. We chose to perform measurements inside two similar bandwidths: 90–360 GHz for Channel 1 and 90–450 GHz for Channel 2. Channel 2 was spectrally enlarged to explore high-frequency atmospheric emission more prone, and so more sensitive, to precipitable water vapour (PWV) fluctuations at the expense of a larger background emission with consequent photon noise: 0.5 and 1 nW respectively, under the assumption of PWV = 1 mm.

The vacuum window of the cryostat is a 4-mm-thick quartz window. The 77-K quartz filter is 3.3 mm thick with a diamond powder Anti Reflection Coating (ARC). A black polyethylene filter, 0.1 mm thick, is employed to reduce the visible and near-infrared (near-IR) background. At 1.6 K a Yoshinaga filter blocks IR radiation, while an interference mesh filter limits the high frequencies at 450 GHz. On the entrance apertures of the two Winston cones at 300 mK, two Yoshinaga filters work as last IR blockers. Two final mesh filters perform the effective band selection. All the filters were supplied by QMC Instruments, Ltd. The lower-limit band in frequency is dictated by the output aperture of the Winston cones operating as high-pass filters.

3.3 Electronics and data acquisition

The first stage for the readout of the bolometer signals are Junction gate Field-Effect Transistors (JFETs) (model IFN146) in a common-drain configuration. Those unitary gain amplifiers are mounted on the He cooler tank inside an aluminium-shielded box, close to the detectors, but at a temperature of 120 K by self-heating. The measured noise is ~3 nV Hz^{-1/2}. The expected total incident power on the detectors is 0.5 and 1 nW respectively, implying a sensor thermal conductivity of the order of 10^4 W K^{-1} (Haller–Beeman). The low-impedance signals from the JFETs feed an ambient temperature differential preamplifier with a gain equal to 250 for both the channels and an output noise of ~10 nV Hz^{-1/2} for frequencies higher than 20 Hz. Rechargeable batteries inside the preamplifier box supply the bias voltage, as well as all the readout electronics boards and cryogenics maintenance. All the electrical connections are ensured by twisted pairs of NbTi wires (0.1 mm diameter) shielded within CuNi (0.03 mm thick). Depending on the signal modulation (see Section 4.5) the data acquisition is carried out by a low-frequency (<1 Hz) data sampling of two synchronous demodulation amplifiers (Stanford Research Instruments, SR850) or a high-frequency (5 kHz) data sampling by an ADC (National Instruments PCI-6031).

3.4 Pointing system

The pointing system was developed with two aims. The first is to track in the sky the FoV of the MITO telescope during its observations, exploring in this way an identical optical path through the atmosphere; the second is to be able to point in specific directions to perform skydips for every azimuth angle. The telescope control is realized with Magellano ST77, supplied by ATEC Robotics (Advanced Technologies for Research and Industry). The movement of the two axes is performed by hybrid stepper motors (MAE, HS200), while the position is transduced by two incremental encoders (Baumer Electric, BHK 16OSA400). Both encoders ensure an accuracy of 400 steps/turn and have a zero position to record and to reset the sky coordinates to before every observational run. This reference position also corresponds to the telescope rest position.

The gear ratio for the altitude (and azimuth) axis is equal to 5:1:1, with the two gear wheels having 112 and 22 teeth respectively. In order to have stable and accurate movements, this low value was increased by a right-angle gear (TLS, SF40/PB3) with a 100:1 gear ratio. Finally, the total gear ratio is 510:1. The transmission is ensured by two gear belts (Trasmecam, HTD 1040-8M-20 for the altitude axis and 1200-8M-20 for the azimuth axis).

A CCD camera (SBIG, ST-402ME) is used to check the pointing system, as a star tracker. It is equipped with a 135-mm focal length lens to have a total FoV of 14.4 × 13.6 arcmin², with a FoV per pixel of about 14 arcsec. The magnitude limit is 15.

The co-alignment between the visible and millimetre axes was checked in the laboratory with a fixed artificial source, considering its finite distance, and than verified in situ by pointing at planets. The final error in pointing is less than 1 arcmin, which is more than adequate for atmospheric emission measurements.

The whole instrument is accommodated inside a 1.6 × 2.9 × 1.4 m (W × D × H) deployable dome in PVC Precontraint® 502 (AMA, series 8000).
4 THE MARTIN–PUPLETT INTERFEROMETER

The MPI employs, as polarizers, three wire-grids distributed inside the instrument as described in Section 3.1. First of all we recall the basics of an MPI.

4.1 MPI basics

Stokes and Mueller matrix formalism can be used to describe any state of polarization and superposition of beams when no phase relation has to be taken into account. Alternatively, as for example in the analysis of an interferometer, one needs to perform a Jones matrix calculation, reverting to the Mueller matrix formalism afterwards (Catalano et al. 2004).

We assume unpolarized radiation at the entrance of the two input ports and describe it with the Stokes formalism as

\[ S_{in} = B_{in} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \]

(2)

where \( in \) denotes \( in_1 \) and \( in_2 \), the two input sources.

The two signals pass through WG1 and are linearly polarized in the following way:

\[ S'_{in} = M_{WG1} S_{in} = B_{in} \begin{pmatrix} \cos 2\vartheta_{in} \\ \sin 2\vartheta_{in} \end{pmatrix}, \]

(3)

where \( \vartheta_{in} \) is the projected angle of the WG1 principal axis on the plane orthogonal to the optical axis. The angles for the two inputs are linked as: \( \vartheta_{in_2} = \vartheta_{in_1} + \pi/2 \). \( \vartheta_{in_1} = 0 \) corresponds to the vertical position. The Muller matrix used for a wire grid is

\[ M_{WG} = \begin{pmatrix} 1 & \cos 2\vartheta_{in} & \sin 2\vartheta_{in} & 0 \\ \cos 2\vartheta_{in} & \cos^2 2\vartheta_{in} & \cos 2\vartheta_{in} \sin 2\vartheta_{in} & 0 \\ \sin 2\vartheta_{in} & \cos 2\vartheta_{in} \sin 2\vartheta_{in} & \sin^2 2\vartheta_{in} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \]

(4)

After the MPI, each exiting beam can be described as

\[ S'_{out} = M_{MPI} S'_{in} = B_{in} \begin{pmatrix} \cos 2\vartheta_{in} \cos \delta \\ -\sin 2\vartheta_{in} \sin \delta \end{pmatrix}, \]

(5)

where we used the Muller matrix for an ideal MPI:

\[ M_{MPI} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \delta & 0 & \sin \delta \\ 0 & 0 & -1 & 0 \\ 0 & \sin \delta & 0 & -\cos \delta \end{pmatrix}. \]

(6)

The mechanical path difference between the two split beams is \( \Delta x_{mec} \). The OPD, \( \Delta x_{opt} \), equal to \( 2\Delta x_{mec} \), is related to the phase shift, \( \delta \), for each wavelength, \( \lambda \), through the well-known equation:

\[ \delta = 2\pi \Delta x_{opt}/\lambda. \]

WG3 splits each beam in the output ports in the following way:

\[
S''_{out} = \begin{pmatrix} 
1 + \cos 2\vartheta_{in} \cos 2\varphi_{in} \cos \delta - \sin 2\vartheta_{in} \sin 2\varphi_{in} \\
\cos 2\vartheta_{in} + \cos 2\vartheta_{in} \cos^2 2\varphi_{in} \cos \delta - \sin 2\vartheta_{in} \sin 2\varphi_{in} \cos 2\varphi_{in} \\
\sin 2\vartheta_{in} + \cos 2\vartheta_{in} \sin 2\varphi_{in} \cos 2\varphi_{in} \cos \delta - \sin 2\vartheta_{in} \sin^2 2\varphi_{in} \\
0
\end{pmatrix}
\]

(7)

where \( \varphi \) stands for \( \varphi_1 \) or \( \varphi_2 \), corresponding to the two output ports optically matched to Channel 1 and Channel 2, respectively.

Owing to the fact that our detectors are only sensitive to signal intensity, namely the first element of the Stokes vector, we can express the signals of the two output ports as

\[ I_{out_1} = \Delta^+ + \Delta^- \cos 2\vartheta_{in_1} \cos 2\varphi_{out_1} \cos \delta - \Delta^- \sin 2\vartheta_{in_1} \sin 2\varphi_{out_1}, \]

(8)

\[ I_{out_2} = \Delta^+ - \Delta^- \cos 2\vartheta_{in_1} \cos 2\varphi_{out_1} \cos \delta + \Delta^- \sin 2\vartheta_{in_1} \sin 2\varphi_{out_1}, \]

(9)

where \( \Delta^+ = B_{in_1} + B_{in_2} \) and \( \Delta^- = B_{in_1} - B_{in_2} \) and rewriting \( \varphi_{out_1} = \varphi_{out_1} + \pi/2 \).

Under the assumption that \( \vartheta_{in_1} = \varphi_{out_1} \), namely that the polarization axis of WG1 is aligned with that of WG3, we can rewrite equations (8) and (9) in the following way:

\[ I_{out_1} = \Delta^+ + \Delta^- \cos \delta, \]

(10)

\[ I_{out_2} = \Delta^+ - \Delta^- \cos \delta. \]

(11)

The spectra of the two input sources are linked to equations (8) and (9) in Section 4.6.

4.2 MPI efficiency versus telescope altitude

The cold WG3, inside the cryostat, is at rest during telescope altitude movements. Its wire change orientation by an angle \( \varphi_{out_1} \) with respect to the input polarizer WG1, related to the altitude angle \( \alpha \) as \( \varphi_{out_1} = \vartheta_{in_1} + \alpha - \pi/2 \). For this reason we refer to the function \( f(\alpha) \) as an instrumental efficiency, the signal dependence on altitude. This has to be carefully taken into account to characterize the pointing performance. The two outputs at ZPD, see equations (8) and (9), can be expressed as

\[ I_{out_1,ZPD} = \Delta^+ \pm \Delta^- f(\alpha), \]

(12)

where \( f(\alpha) = \cos 2\alpha \).

When \( \alpha = 45^\circ \) the signals, even modulated by \( \cos \delta \) along the interferogram, are null. To check this expected instrument efficiency we filled the sky input with a blackbody source at ambient temperature (an Eccosorb AN72 sheet in front of the telescope) and, in order to obtain a high signal-to-noise ratio, we employed a Ha-lamp as reference source instead of the disc of Eccosorb AN72. Spectra were acquired at altitude angles ranging from \(-10^\circ \) to \(10^\circ \). We also explored altitude angles lower than \(0^\circ \) and higher than \(90^\circ \) to check the consistency and the repeatability of the performance. Interferograms were recorded in fast-scan mode (see Section 4.5.2) with a 5-KHz scan rate, performing the time average over an acquisition time of about 7 min for altitude values ranging from \(30^\circ \) to \(60^\circ \) (lower instrumental efficiency), and of 5 min for the others (higher instrumental efficiency). In Fig. 4 the two ZPD output signals are...
plotted versus the altitude angle, with error bars given by the standard deviation. At zenith, Channel 1 is proportional to $\Delta^+ + \Delta^-$, instead, while the telescope is pointing at an altitude angle of $0^\circ$ (i.e. when it is in the horizontal position), the contribution of $\Delta^-$ is opposite because of the rotation of the last wire grid, WG3. The red points represent the polarized signal detected by Channel 2: as expected, the trend is symmetrical with that of the other channel. Data points are well-fitted by the $\pm \cos 2\alpha$ function predicted by equation (12) (see the residuals in the bottom panel of Fig. 4).

The loss of efficiency, owing to the change of WG orientations along different zenithal angles, means that there is an altitude range within which the signals are negligible.

In order to determine the width of this altitude range where the instrument has low efficiency, the so-called ‘blind’ observational range, we estimated $\alpha_{\min}$ and $\alpha_{\max}$ corresponding to a signal-to-noise ratio $\leq 3$. An emission atmospheric spectrum, as derived by ATM with a PWV = 1 mm, was assumed as source. The vertical dot–dashed lines in Fig. 4 delimit the ‘blind’ orientation directions: $43^\circ < \alpha < 47^\circ$.

This is a restriction on the CASPER2 performance, but it has few consequences for our purposes because the minimum altitude explored by the MITO telescope is $42^\circ$. This operational limit for the MITO telescope is dictated by low atmospheric contamination requirements and by dome constraints. However, CASPER2 can point at lower altitudes, where the signal-to-noise ratio increases, allowing a complete angular range of skydips.

The expected variation in the atmospheric emission during skydips, owing to the decreasing opacity with altitude, has to be added to the instrumental efficiency. Each detector records a signal that can be expressed as

$$ I_{\text{out},1,2} = \Delta^+(\alpha) \pm \Delta^- a(\alpha) f(\alpha), \quad (13) $$

where $a(\alpha)$ is the atmospheric dependence and $\Delta^-$ is the difference of the input signals at the zenith position. We note that, because of the different spectral bands, $\Delta^+$ and $\Delta^-$ have to be distinguished between the two channels. In a simple optically thin atmospheric layer model we can assume that

$$ a(\alpha) = \exp(-\csc(\alpha)) \quad (14) $$

normalized at the zenith position.

### 4.3 The subinterferometer: Mickey

A Michelson subinterferometer, named Mickey, ensures the monitoring of the movements (position and velocity) of RM1 during fast-scan measurements. The movable mirror is mounted on the back of RM1. The source is a laser (Imatronic, Sigma 650/3) centred at $\lambda = 650$ nm. Interference maxima are detected by a photodiode (Osram, SFH203) and then processed by a peak-counter circuit. Accuracy on the mirror position depends on the distance between the peaks generated by Mickey, equal to $\lambda = 325$ nm.

The Fourier transform of the signal detected by Mickey along a return double-sided interferogram shows two maxima, corresponding to a backward and forward scan velocity difference of about 70 $\mu$m s$^{-1}$. The peak-counter circuit is employed to produce a trigger signal for data collection. In this way all fast-scan interferogram points are acquired with the same distance between them, independently of velocity changes due to the step motor.

### 4.4 Thermal monitoring

An AD590 temperature sensor is used to monitor the absolute temperature of the reference load. The reference source passively follows the ambient temperature as well as the whole instrument. The MPI box and the primary mirror are also monitored to estimate possible differential emission in the instrument as a result of temperature gradients. The AD590 is a temperature transducer producing an output current proportional to the absolute temperature, and is suitable for our purposes: wide temperature range ($-55$ to $150$ C), high calibration accuracy ($\pm 0.5\%$) and excellent linearity ($\pm 0.3\%$ C over the full range).

### 4.5 Signal modulation techniques

The peculiarity of CASPER2 is its ability to perform, with the same interferometer, three different signal modulations: amplitude modulation (AM), fast-scan (FS) and phase modulation (PM). The OPD variation with time for the three options is shown in Fig 5. Many fast-scanning FTs are built so that the ZPD position lies close to one edge of the moving stage path, in order to maximize the dynamic range of the OPD and consequently the spectral resolution. Because one-sided interferograms transform into real spectra, no information on the phase is available, although phase problems do show up as baseline anomalies. Two-sided interferograms, in contrast, transform into complex spectra (they have two pieces of information per frequency), allowing phase errors to be directly measured as a function of frequency. This permits checking for optical misalignments and other potential instrumental problems through the level of asymmetry on the two sides of the interferograms. Because a high spectral resolution is not necessary when measuring the continuum level of the atmospheric emission, CASPER2 adopts a two-sided interferogram sampling, with the ZPD located half-way along the moving mirror path. To reduce the effect of measuring the interferograms with a limited mechanical path difference, the interferogram lobes are weighted with a triangular apodization function, at the expense of decreasing the spectral resolution to about 8.6 GHz.

#### 4.5.1 Amplitude modulation

The AM technique is fulfilled by a chopper-wheel modulator placed in front of the cryostat, performing a synchronous demodulation of the signal and a step-by-step movement of RM1. The step length is equal to 100 $\mu$m, ensuring a Nyquist frequency, $f_N = 750$ GHz,
higher than 450 GHz (see Table 2). The chopper blades, coated with Eccosorb AN72, act as a reference source at ambient temperature. The two modulated signals feed the two lock-in amplifiers. Because the chopper is kept at room temperature, the large brightness temperature gradient between the two sources means that the faint signal fluctuations are difficult to detect. In addition, the AM procedure has the disadvantage that half of the observation time is spent on the reference source. The AM procedure represents a reliable tool useful for characterizing the performance of the whole instrument, working both with stable sources in laboratory tests and instrument calibration over bright sky signals.

### 4.5.2 Fast-scan

The FS technique consists in sweeping the range of available OPDs through a rapid movement of the translating stage at constant velocity. The recorded time-domain signal is therefore trivially related to the interference pattern thanks to a simple time/position conversion through the stage velocity, and the Fourier analysis yields directly the necessary information about the spectrum of the incoming radiation beam. A carefully selected velocity may shift the electrical frequencies of interest away from potentially troublesome low-frequency components or line features in the system noise, allowing for a cleaner reconstruction of the optical power in the passband. Moreover, because the scan can be repeated an arbitrary number of times, the short integration time per unit OPD can be increased to hit the photon noise limit with almost no additional effort in the instrumental setup. On the other hand, apart from mechanical limitations, an intrinsic upper limit to the value of the translation velocity is determined by the time constant of the detectors and by the highest frequency in the instrument bandwidth: in order to be able to discriminate between two consecutive fringes in the interference pattern generated by radiation at frequency \( v_{\text{max}} \), the fringes must be scanned over a time interval longer than the detector time constant \( \tau_d \), thus determining the limit velocity

\[
\nu_{\text{lim}} \leq \frac{1}{\tau_d v_{\text{max}}}.
\]

(15)

Fast-scanning interferometers are usually operated well below this limit, and signals are de-convolved from the detector time-response before further data-processing to avoid residual artefacts. This is also the case for CASPER2, for which the time constant of the detectors is \( \tau_d = 10 \text{ ms} \) and the translation velocity of the moving roof mirror is set to 0.86 cm s\(^{-1}\) (i.e. 1.72 cm s\(^{-1}\) lag velocity). Under these conditions, a time of 3.8 s is needed to perform one scan. An average of several scans on the same source is needed to improve the signal-to-noise ratio of the observations (see Section 4.7).

A critical source of systematics in fast-scanning FTSs is the non-uniformity of the scan velocity: because interferograms need to be uniformly sampled in the space-domain, rather than in the time-domain, any fluctuation in velocity at a fixed scan rate converts into a local ‘stretch’ of the OPD scale, resulting in artefacts in the frequency domain in both line and continuum interferometry. In CASPER2, this issue is solved by monitoring the stage position through the optical subinterferometer (see Section 4.3), whose fringes provide a position reference for each data point. The interferograms are highly oversampled (5000 samples s\(^{-1}\)), with an electrical Nyquist frequency of 2.5 kHz (or an equivalent optical bandwidth of 43.6 THz). After Fourier transformation, the high-frequency components of instrument noise are discarded and the signal in the optically meaningful band is extracted to observe the sky brightness and PWV information.

One of the advantages of FS interferometry over step-by-step interferometry (or slow scan) is that no chopper is used to modulate the radiation (see Section 4.5.1). A disadvantage in FS interferograms is that slow drifts in the intensity of the source can result in variations of the baseline of the interferogram that can be of the same frequency as modulations from the longest wavelength being measured. This affects the performance at low optical frequencies.

#### 4.5.3 Phase modulation

A third signal modulation technique, available with CASPER2, is PM. This technique, proposed by Chamberlain (1971), allows the replacement of AM and FS, implying a modulation of the OPD when recording the interferogram. The insensitivity to slow fluctuations in the intensity of the source plus the full time on source observations make PM very attractive for atmospheric measurements.

Operatively, modulation is performed by periodically wobbling RM2 while the detector signals are lock-in demodulated. We can rewrite the Muller matrix for the MPI as in equation (6):

\[
\mathbf{M}_\text{MPI} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \delta' & 0 & \sin \delta' \\
0 & 0 & -1 & 0 \\
0 & \sin \delta' & 0 & -\cos \delta'
\end{pmatrix},
\]

(16)

where \( \delta' = \delta + \delta_M \) with \( \delta_M = 2\pi M(t)/\lambda \), the modulation of the OPD obtained by periodically oscillating RM2 with amplitude \( A \) and frequency \( v_0 \). In Fig. 5 the OPD is plotted against time for all three observation modes.

The amplitude of the phase modulation has to be carefully chosen to fit the spectral band of the instrument. In our case, with a sinusoidal modulation function, \( A = 0.5 \nu_{\text{c}}/v_{\text{max}} \). For \( v_{\text{max}} = 450 \text{ GHz} \), the highest frequency in the two bands, this corresponds to 840 \( \mu \text{m} \).

The wobbling frequency is chosen to be equal to 12 Hz so that the effect of low-frequency source variations is essentially eliminated using PM techniques. At the same time, by avoiding a direct current (DC) component the acquisition dynamic range is well fitted to the interferogram range.

RM2 is wobbled by a linear actuator driven by a waveform generator using a feedback loop based on a position transducer and a proportional-integral-derivative circuit. A linear variable differential transformer (LVDT) (Solartron Metrology, model SM/1) is used.
as position transducer for the mirror. The accuracy in oscillation amplitude and frequency was checked and found to be 2 per cent in amplitude and 1 per cent in frequency. The requirements on the stability of the oscillation amplitude were estimated by simulated observations. Changes in the amplitude result in a different weighting along the spectrum affecting the inferred PWV, as derived by the fit of ATM synthetic spectra. The constraint on PWV respecting the uncertainty on the RM2 oscillation amplitude turns out to be 2 per cent, estimated assuming several PWV average values in the range of 0.1 to 6 mm.

4.6 Calibration procedures

Calibrated spectra are derived by employing several considerations. The two inputs of CASPER2 differ as follows:

\[ B_{\text{in}}(v) = \epsilon_{\text{atm}}(v)BB(T_{\text{atm}}, v) + \epsilon_{\text{tele}}(v)BB(T_{\text{tele}}, v), \]  

\[ B_{\text{out}}(v) = BB(T_{\text{ref}}, v), \]

where \( \epsilon_{\text{atm}} \) and \( \epsilon_{\text{tele}} \) are the atmospheric and telescopic emissivities, respectively, while \( BB \) denotes the specific brightness of the atmosphere, the telescope and the reference load (the only one having an emissivity equal to 1), each of them at the equivalent temperatures \( T_{\text{atm}} \), \( T_{\text{tele}} \) and \( T_{\text{ref}} \). While \( \epsilon_{\text{atm}} \) is related to the atmospheric opacity, we assume \( \epsilon_{\text{tele}} \) equal to \( 3 \times 10^{-3} \) at the frequency of 150 GHz, for an aluminum mirror, and changing with the frequency as \( \sqrt{v} \) (Bock et al. 1995).

The spectra derived from equations (8) and (9), after baseline removal, are related to the spectra of the incoming sources as

\[ \tilde{I}_{\text{out}}(v) = R_i(v)\tilde{I}_{\text{in}}(v)\Delta\Omega(v)\left[B_{\text{in}}(v) - B_{\text{in}}(v)\right], \]

\[ \tilde{I}_{\text{out}}(v) = F_i(v)\left[B_{\text{in}}(v) - B_{\text{in}}(v)\right], \]

where \( F_i(v) = R_i(v)\epsilon_i(v)\Delta\Omega(v) \), the calibration function, \( F_i(v) \) for the \( i \)-channel, includes the responsivity \( R_i(v) \), the spectral efficiency \( \epsilon_i(v) \) and the throughput \( \Delta\Omega(v) \). In Fig. 6 the normalized calibration functions are shown for both channels.

The throughput \( \Delta\Omega(v) \) is assumed equal for the two inputs, being dictated only by the optical matching between the cones and the last cold lens operating as an aperture stop. A frequency dependence of it can be considered for both patterns: starting from a single-mode propagation at the cone exit apertures at the lowest frequency, and moving to a multi-mode approach at 450 GHz. For CASPER2 applications this anisotropic response of the two ports is not a technical hitch, because the diffuse sources, namely the atmosphere and the sheet of Eccosorb, totally fill both the inputs. We can easily assume that the telescope efficiency (Ruze 1966) is unitary along the whole spectral range, counting on an rms surface error of \( \sim 0.1 \mu m \) and that the wire grids behave like ideal polarizers in our bands.

The optical matching between the two inputs of the MPI and the two sources shows differences as a result of the distinct optical paths. Specifically in the case of \( i_1 \), the input port is further transformed by the primary beam telescope.

The calibration functions are estimated by filling the \( i_n \) port with a second well-modelled source, a cold blackbody, realized with an Eccosorb AN72 sheet thermalized inside a liquid nitrogen bath (77 K). Hence the atmospheric spectra are obtained from

\[ I_{\text{atm}}(v) = \frac{I_{\text{out}}(v)}{F_i(v)} + BB(T_{\text{ref}}, v) - \epsilon_{\text{tele}}BB(T_{\text{tele}}, v). \]

Any possible optical mismatch between the two input ports has to be known and taken into account to avoid consequent contamination on inferring the atmospheric spectra. The correct balance between the two inputs is checked by filling even the sky port with a room-temperature blackbody inserting an Eccosorb AN72 sheet in front of the telescope to record a null interferogram. For an ideal source coupling of the two ports, the residual signal (i.e. the difference in spectra between two identical sources) has to be zero. A potential temperature gap between the two blackbodies could also produce a non-null interferogram, but this has been monitored.

The knowledge of the null interferogram, or at least of the upper limit of the ZPD value when the signal-to-noise ratio is less than one, allows us to put a constraint on the minimum detectable contribution on the PWV content. Long acquisition of null interferograms enables us to discriminate spectra with a difference of only 0.01 mm of PWV irrespective of the PWV content, at least for PWV < 1 mm.

4.7 The Allan variance

The instability of the atmospheric emission in the mm/submm spectral region has to be carefully taken into account when the observational goal is to achieve frequent and independent spectra with high signal-to-noise ratios. The time dedicated to performing a single interferogram is mainly dictated by the detector time response, while the time-scale to average several interferograms is affected by atmospheric drift. In the specific case of the FS technique, to avoid loss of observational time, the minimum number of spectra that can be averaged is constrained by the need to achieve a high signal-to-noise ratio while sampling a continuously changing atmosphere. It is clearly necessary to determine a characteristic time to indicate when an instrument is dominated only by thermal noise instead of by an atmospheric fluctuation regime. An appropriate approach to infer this time-scale is to estimate the Allan variance (Allan 1966). In a wide-band spectrometer, such as CASPER2, it is important to also check the time-scale similarity for all frequencies by investigating the noise performance in the measured spectra (Schieder & Kramer 2001).

Large fluctuations of atmospheric emission are expected in correspondence with the three ‘windows’ centred at the frequencies of 150, 270 and 350 GHz; hereafter we refer to these lines by 2, 4 and 5, respectively. In contrast, the oxygen band at 118 GHz and the
high-absorption H$_2$O band at 183 GHz, denoted as 1 and 3, should appear more stable with time. In Fig. 7, for example, 87 spectra of the zenithal atmospheric brightness recorded by the FS technique are shown for the two bands of CASPER2. Each spectrum is the average of two back-and-forth spectra acquired in 6 s. The vertical dotted lines refer to the examined frequencies.

The Allan variance is calculated, for the previous five reference lines, in the following way. The signal, $s_f(t)$, related to the atmospheric emission at frequency $f$ extracted from the FS spectra at time $t_i$, is averaged over variable time-scales, $T$, generating the new data set:

$$S_f(T, t_j) = \frac{1}{T} \sum_{i=j+1}^{i+T} s_f(t_i).$$

The Allan variance, or the two-sample variance, is estimated for the frequency $f$ as in Wiedner, Hills & Pardo-Carrión (2002):

$$\sigma_A^2(T) = \frac{1}{N-2} \sum_{j=2}^{N-1} \left( \frac{S_f(T, t_{j-1}) + S_f(T, t_{j+1})}{2} - S_f(T, t_j) \right)^2$$

(23)

In Fig. 8 the Allan variance corresponding to the five frequencies is plotted for the two CASPER2 bands. It is worth noting the expected $1/T$ dependence for short average times, corresponding to dominant thermal noise, and the slope change when atmospheric drift dominates. This behaviour is not satisfied in the case of 1 and 3, for which a strong and stable emission is present.

We can estimate, at least for this specific data set of spectra, $T \simeq 100$ s as the more suitable average time. Even if the values of the Allan variance increase for all frequencies in the high-background Channel 2, affected by a larger instrumental noise, the best average time is almost the same. We employ this time-scale to generate the spectra reported in the next section.

6 CONCLUSIONS

A double-beam FTS interferometer, installed at the focal plane of a 62-cm-diameter telescope, is devoted to monitoring atmospheric emission spectra in the mm/submm band compared to an ambient-temperature reference source. The MPI is designed to perform three independent signal acquisition procedures: fast-scan, phase-modulation and amplitude modulation. Being an ancillary instrument it utilizes an independent altazimuthal mount, allowing it to point in the same direction as a telescope dedicated to cosmological mm observations from the ground, here the 2.6-m-diameter Mito telescope in the Alps. The recorded spectra, in the 90–450 GHz spectral region, permit validation of the results of the transfer radiative code, ATM (Pardo et al. 2001), for this site and consequently to infer the PWV value as derived by fits with synthetic spectra or by skydips. The instrument has been characterized in the laboratory and was employed during the observational campaign at Mito in 2010 July. The choice of the best spectrum integration time is derived by the Allan variance estimate. Preliminary spectra recorded by fast-scan modulation are presented to show the capabilities of the instrument.

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Figure 9. Averaged atmospheric zenithal spectra recorded with the fast-scan procedure at MITO on 2010 July 16, 04:03. The red line is the best fit obtained with ATM model corresponding to PWV = 6.53 ± 0.16 mm for Channel 1 (top panel) and PWV = 6.84 ± 0.16 mm for Channel 2 (bottom panel).

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