Far infrared polarimeter with very low instrumental polarization

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ABSTRACT
After a short analysis of the main problems involved in the construction of a Far Infrared polarimeter with very low instrumental noise, we describe the instrument that will be employed at MITO telescope to search for calibration sources and investigate polarization near the CMB anisotropy peaks in the next campaign (Winter 2002-03).

Keywords: cosmology: cosmic microwave background — instrumentation: polarimeters — instrumentation: interferometers — telescopes

1. INTRODUCTION
Since the detection of the CMB anisotropy by COBE1 and the further characterization of its Doppler peaks by Boomerang2 and Maxima,3 extensive calculations and simulations have been performed to predict the degree of polarization of the CMB foreseen by Rees4 that later had been upper limited (0.1mK) by Caderni et al..5 By introducing the Stokes formalism and the elements of polarization genesis in the Microwave Background, in this work we analyze the various contributions to an expected polarized signal that is to be measured from ground experiments (N.Gnedin and N.A.Silant’ev 19976). We stress the importance of accurate removal of instrumental spurious polarization and propose a possible technique of data analysis to reduce systematic effects mostly related to atmospheric contamination in small-beam (4′ ÷ 5′ ) Far Infrared ground based experiments.7 We then describe our MITO-Pol experiment (working at 120−360 GHz) and its forthcoming upgrade in detector sensitivity, installation at MITO telescope, and the first light of the instrument with beam calibration before the planned campaign, during Winter 2002-2003, for measurements of polarization field near high peaks of CMB anisotropy as predicted by Arbuzov.8

2. SEARCHING FOR CMB POLARIZATION
As radiation decouples from matter (redshift z ∼ 1000 ), the intensity of photons arriving to us from the Last Scattering Surface(LSS), after Thomson scattering, is peaked in the direction normal to the initial propagation, and with the residual polarization parallel to the incident one.9 We see then that in an isotropic context contributions of polarized radiation scattered by LSS electrons cancel out two by two, leaving only quadrupole distributions of intensity as possible "source" of polarized (linear) radiation.

Theoretical frameworks for the origin of polarized radiation have been numerous throughout the years. By giving a complete description of radiative transfer following Boltzmann’s equation,10 or by describing in terms of Stokes Parameters the expected Polarization of the Cosmic Microwave Background (CMBP),11 important cosmological informations can be obtained. Particularly interesting is the study of the power spectra of the possible polarization modes, E-modes and B-modes,12 and the correlation of the temperature density spectrum

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Isotropic distributions cancel out by 90 degree contributions, while dipole intensity cancel out 4 by 4 summing mutually opposed contributions and cancelling with the orthogonal ones. A quadrupole anisotropy is necessary to observe a degree of linear polarization.

with them. The E-modes spectrum, essentially deriving from scalar density perturbations on LSS, is expected to be well correlated with the temperature spectrum while B-modes spectrum is not. Vector perturbations due to the vortical motions of the matter, generate mainly B-modes while tensor perturbations, which can be associated to gravitational waves, generate both E-modes and B-modes. A detection of the CMBP can be helpful in order to remove some still existing degeneracies in the determination of the cosmological parameters. The polarization spectrum is sensitive to the presence of gravitational waves at a wider angular scale range than the temperature spectrum. Furthermore a CMB polarization characterization can tell us informations on the duration of the recombination era and can give light on the reionization process which can not be studied solely by temperature spectrum. The expected polarization level is of the order of 10% of the anisotropies. Anyway, as Arbuzov et al. has predicted, we expect local polarization maxima of $\sim 30 \div 45\%$ around $3\sigma$-peaks of anisotropies mainly between the cross-levels $1.5\sigma$ and $2.5\sigma$, shaped as rings around the peaks themselves.

Let us refrain from going deep in all the possible cosmological scenarios that can be favored by detection of polarization of the CMB, to concentrate on the upper limits that have been recently set on this foreground. In table 1 we have summarized some of the currently undergoing experiments that should be able to give further information on microwave sky polarization or to set more stringent upper limits on the E and B modes power spectrum.

Generally experiments can be roughly divided as investigating in small and large angular scales. At low frequencies (i.e. $\nu < 100\text{GHz}$) very stringent upper limits have been posed: $\sim 10\mu K$ at both large and small angular scales. Considering the frequency dependence of the expected CMB polarization compared with the expected foreground emission (see §5), the best frequency range to perform CMB polarization measurements seems to be above $100\text{GHz}$. Furthermore, given the perspective of having a polarized intensity of a peak of E-mode polarization at a few $\mu K$, we choose to follow a less global approach of sky coverage in favour of a detailed analysis of temperature anisotropy peaks present in existing CMB maps.

3. MITO-POL: A POLARIMETER WITH LOW INSTRUMENTAL POLARIZATION FOR THE VERY FAR-INFRARED REGION

The MITO polarimeter, to be mounted at the MITO telescope on Italian Alps, employs two bolometric detectors, separated by a polarizing wire-grid, to perform continuous monitoring of modulated polarized signals incoming at the focal plane of the telescope after passing in a double-Fresnel rhomb and a modified Martin-Puplett interferometer. This composed modulation allows us to extract a fixed polarized signal supposed to exist "behind" any spurious and non-constant polarizing foreground.

3.1. MITO: Millimetre Infrared Testagrigia Observatory

Located in the highest reaches of the Alps, at $3480\text{m}$ a.s.l., the observatory is devoted to Far Infrared measurements of cosmological interest. The contents of precipitable water vapour have been computed by HITRAN
Table 1. Recent and future experiments of CMB polarization measurement.

| Name         | ν/∆ν(GHz)   | Beam   | Sensitivity       | Coverage     | Polarimeter   | Upp.limit     |
|--------------|-------------|--------|-------------------|--------------|---------------|--------------|
| CBI          | 26 – 36     | 3’ – 30’ | 20 (µK/night)    | -            | Interferometer | -            |
| ATCA         | 8.7         | 2’      | -                 | 6 pix        | Interferometer | ≤ 11µK       |
| POLATRON     | 90/20       | 2.5’    | .7 (mK/√Hz)      | 850 pix      | OMT           | -            |
| PolKa        | 350         | 10'' – 1’ | -                | -            | rotating analyzer | ≤ 300µK     |
| MITE-Pol     | 150 – 350   | 5’      | 2 (mK/√Hz)       | 10° × 10°    | d.F.r.+M.Puplett | -            |
| PIQUE        | 40,90 /16   | 14’     | 2 (mK/√Hz)   | ~ 25 pix     | OMT           | ≤ 10µK       |
| MilanoPol    | 33/1.5      | 7° – 14° | 1 (mK/√Hz)     | -            | correlator    | -            |
| MilanoPol2   | 33/1.5      | 15’     | 1 (mK/√Hz)     | -            | correlator    | -            |
| POLAR        | 26 – 36.90 – 100 | 7°         | 1 (mK/√Hz) | 1844°      | OMT           | ≤ 10µK       |
| COMPASS      | 26 – 36.90 – 100 | 10’-20’     | 1 (mK/√Hz) | -          | OMT           | -            |
| MAXIPOL      | 150,240,410 | 10’    | .041 (mK/√Hz) | 10⁶ pix     | grid.pol.+HWP | -            |
| Boom2K       | 90,150,240,410 | 10’    | 200 (µK/√Hz) | 10⁶ pix     | polarization abs. | -            |
| BAR-Sport    | 32.90       | 30’/12’ | .5 , .7 (mK/√Hz) | 20° × 20°    | OMT           | -            |
| MAP          | 22,30,40,60,90 | 13’ – 56’ | 35 (µK/pix) | full        | OMT           | -            |
| Planck-HFI   | 6Ch ∈ 100 – 857 | 5’ – 33’ | 6 (µK/pix) | full        | -            | -            |
| SPORT        | 22,32,60,90/10% | 7°      | 1 (mK/√Hz) | 82%         | OMT           | -            |

and the observational results confirm a low level in pwv, reaching peaks of antarctic level for the last months of Winter. The telescope is a 2.6m primary Cassegrain in altazimuthal configuration, the secondary mirror with wobbling capabilities will remain fixed on-axis while modulation with the polarimeter will be obtained by a rotating double Fresnel rhomb (see § 3.2). Measurement of CMB anisotropy and SZ-effect⁷⁻¹⁵ have already proven the efficiency and reliability of the telescope.

3.2. The instrument

Radiation focused by the telescope enters the rotating double Fresnel-rhomb that has been adopted to modulate a polarized signal, leaving the non-polarized background (or foreground) untouched. The double rhomb is made of high-density polyethylene with a refractive index selected to obtain total internal reflection of the focused rays with minimal dispersion. On reflection, linearly polarized signals are phase-shifted by π/4 through each rhomb, obtaining the equivalent of a half-wave retarder by employing two rhombs like in fig.3. The polarized signal will thus rotate at an angular speed double than the physical speed ω of the double rhomb. If we adopt Stokes parameters, we can express this element with the following Mueller matrix:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos 4\omega t & \sin 4\omega t & 0 \\
0 & -\sin 4\omega t & \cos 4\omega t & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]

On exiting the double-rhomb, radiation enters the Martin-Puplett interferometer and passes through a 45° * axis wire-grid that splits polarized radiation in its two orthogonal components, along with acting as a beamsplitter of unpolarized radiation. These two separate components, travel towards two roof-shaped mirrors (see fig.3), one of which shifts to change the path-length of the beam introducing a phase shift \( \phi = 2\pi l/\lambda \), where

*with respect to the interferometer axis.
Figure 2. Left: MITO telescope with ground shields on the Plateau Rosa site (3480m). Right: Mito-POL cryostat mounted with the interferometer and the double-Fresnel rhomb at the focal plane of the telescope.

Figure 3. Section of final instrument setup.

\( l \) is the increase of the path and \( \lambda \) is the wavelength. The two beams recombine and enter the photometer after being refocused, to be splitted by a final wire-grid (positioned on the cold flange), at the entrance of the two radiation collectors (i.e. two \( f/4 \) Winston cones that concentrate the radiation on the detectors). If we compose the Mueller matrices of the optical elements employed, given an entrance signal \((I, Q, U, V)\) we obtain an output on the detectors:
\[
S_{Ch1/Ch2} = \frac{1}{2} \left( \begin{array}{cccc} 1 & \pm 1 & 0 & 0 \\ \pm 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right) \left( \begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & \cos \phi & 0 & \sin \phi \\ 0 & 0 & -1 & 0 \\ 0 & \sin \phi & 0 & -\cos \phi \end{array} \right) \left( \begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & \cos 4\omega t & \sin 4\omega t & 0 \\ 0 & \sin 4\omega t & -\cos 4\omega t & 0 \\ 0 & 0 & 0 & -1 \end{array} \right) \left( \begin{array}{c} I \\ Q \\ U \\ V \end{array} \right) \right)
\]

so as to have on the two channels, separated from the last wire-grid:

\[
S_{Ch1} = \frac{1}{2} [I + (Q \cos 4\omega t + U \sin 4\omega t) \cos \phi - \sin \phi]
\]

\[
S_{Ch2} = \frac{1}{2} [I - (Q \cos 4\omega t + U \sin 4\omega t) \cos \phi + \sin \phi]
\]

We see how subtraction of channels, normalized with the sum, yields a good indication of polarized signals with modulation of Q and U Stokes parameters at a frequency 4 times that of the mechanical rotation of the Fresnel-rhombs. This would avoid spurious polarized signals originating by slight-misalignment of the rhomb, rotating with \(\omega\) frequency, to give an unpolarized asymmetric contribution.

![Figure 4. The detectors employed are composite bolometers with NTD-germanium as thermistors.](image)

The detectors that we are employing at the moment are composite bolometers with NTD-germanium as thermistors (see fig.4). Their operating temperature in the cold flange of the HDL-8 model Infrared Labs Inc. \(^3\)He cryostat is of \(300 \div 305\) mK reached\(^\dagger\) with a \(~4\) hours procedure, and has a time duration working cycle of \(~18\) hours. The NET of these detectors is \(2mK\sqrt{s}\) in laboratory conditions (higher background and working temperature). If we consider this minimum signal as a final operational value, we need an integration time of about twenty minutes per pixel (\(1.7\) obtained by a beam of \(5\) \(FWHM\)) to obtain a \(S/N\) ratio greater than 1 (for signal amplitude as the one predicted by Arbuzov\(^8\)). In future campaigns we will employ spider-web bolometers\(^16\) which will reduce NET to BLIP (Background Limited Infrared Photodetection) conditions allowing us to compute a better analysis of sources either by obtaining a higher \(S/N\) ratio, or by allowing us to map sources in a considerably shorter integration time.

The frequency band selection and the reduction of the background on the bolometers have been performed employing a filters sequence anchored at the various thermal shields of the photometer. The first filter is the \(z\)-cut quartz \(4mm\) vacuum window which is characterized by high transmission up to \(100cm^{-1}\). At the \(N_2\) stage, at \(77K\), we have used again a quartz filter with antireflecting coating obtained by means of diamond powder on a side and black polyethylene on the other side. Black poly removes radiation above \(400cm^{-1}\) (NIR and visible) while the diamond powder cuts the UV radiation. Two Yoshinaga filters have been placed at the \(^4\)He stage at \(1.6K\). These produce an electro-magnetic cut above \(55cm^{-1}\). Two further Yoshinaga filters (one per winston cone) have been placed at the \(^3\)He stage at \(300mK\) just at the Winston cone inputs so to block possible residual IR radiation that would saturate the bolometers. The final band selection is performed by means of two embedded mesh filters placed again at the cone inputs. Mesh filters allow a very sharp selection with a

\(^\dagger\)After \(^4\)He transfer and thermalization.
cut-off frequency $\nu_{\text{cut-off}} = 12 \text{cm}^{-1}$. The low frequency band threshold is determined by the diameter of the output holes of the Winston cones which behave as high-pass filters with a cut-on frequency $\nu_{\text{cut-on}} = 4 \text{cm}^{-1}$.

Signal amplification and bolometer bias supply have been performed in order to reduce the high detector impedance, to produce an amplification of the order of 1000 and to keep as low as possible the receiver noise. The first requirement has been satisfied by using a JFET amplifier in a common drain configuration (characterized by a very high input impedance) directly installed on the $^4\text{He}$ flange. The second requirement has been obtained by means of a operational amplifier in a non-inverting configuration. A detailed study has been performed in order to reduce the electronic noise of the amplification system as well as of the bolometer bias supply. The overall system noise has been estimated and experimentally confirmed to be of the order of $5 \mu \text{V}/\sqrt{\text{Hz}}$.

MitoPol experiment has been installed at MITO telescope during the last FotoMito campaign for SZ-Effect measurements (Winter 2001-2002), to verify mechanical matching to the telescope, optical coupling, operational procedures in measurement conditions, and possible electronic problems in situ. A preliminary test of the instrument without the double Fresnel-rhomb has been done to measure the beam of the instrument as a photometer. The first light allowed us to understand how important is a good optical alignment as well as the reduction of electric cross-talk between the channels. This last problem, for instance, has induced us (also considering the imminent detector change) to move into differential amplification system. Several calibrations by chopping two blackbodies (77 and 300K) behind a polarizer have been performed. Tests and further calibrations are going on, in particular in order to solve all the problems connected to the installation of the new detectors.

### 4. INSTRUMENTAL POLARIZATION AND SPURIOUS ATMOSPHERIC POLARIZATION

In order to detect faint polarized signals, in the presence of a much greater unpolarized background, it is necessary to reduce at minimum level all possible contributions to spurious polarization effects (which can result in an additional polarized signal or in reducing a present polarization (i.e. de-polarization)). First of all, in the selection of the spectral region of observation, filters employed must be carefully chosen to avoid materials or components that have oriented structures or that have been machined with a final preferential axis. Metal meshes and grids must be avoided, and similarly powder-pressed filters that undergo baking may retain a global anisotropy in grain-orientation (i.e. fluorogold). Also, thin polymer films that are "stretched" may contribute to partial polarization along the tension axis.

The other important issue that must be considered is polarization (or de-polarization) induced by oblique reflection from good conductors as is the case of aluminum alloys (i.e. mirrors). From this point of view, Winston cones have been shown to be strongly de-polarizing so that they cannot be used before the splitting of the two polarizations.\(^{18}\) This overall effect, that has been modeled precisely in geometric terms for optical astronomy, can cause spurious polarization as far as $10^{-4}$ for a non-polarized point source at 1 arcminute from the optical axis in a $f/10$ Cassegrain configuration telescope.\(^{19}\) At larger wavelengths the effect decreases due to change in the complex refractive index of the surface. Renbarger et al.\(^{20}\) have practically measured spurious polarization of this kind for large reflection angles ($15 \div 45^\circ$)\(^{1}\) (for $\lambda \sim 250 \div 1000\mu\text{m}$), finding a value of a few tenths of percent for multiple reflections at $45^\circ$ angles. Calculations at much smaller angles to determine the level of spurious polarization introduced by a Cassegrain $f/4$ telescope at millimeter wavelengths have been made with a ray tracing program\(^{17,18}\) giving a level just short of $10^{-6}$ for spurious polarization inside a 5 arcminute beam. Much care must be anyway taken in dealing with off-axis sources (for instance in drift scan procedure), this is one of the reasons why we have chosen a 5′ beam.

Instrumental spurious polarization can therefore be drastically reduced by employing on axis telescope configurations and arranging the optical layout in such a way that the various channels have exactly the same beam. Unfortunately this symmetry requirement cannot always be exactly obtained to the required level. For a ground based experiment one has to take into account the atmosphere emission that, even if unpolarized, has an intensity much higher than the signal we want to detect. A polarization induced by not perfectly symmetric

\(^{1}\)The measurements had the intent of demonstrating low ($10^{-4}$) spurious polarization for off-axis telescopes measuring polarized emission by dust, possibly correlated with galactic magnetic fields.
reflections could thus simulate a polarization signal. On the other hand one of the main advantage of polarization experiments with respect to photometric experiments is the possibility to reduce atmospheric fluctuations by differencing the two polarization states of the same sky region.\textsuperscript{21} The atmospheric fluctuations cannot anyway be totally removed by simply subtracting the signals of the two channels if the two beams are misaligned. This effect is much larger for point-like sources in comparison with extended sources which completely fill the beams. The not perfect beams alignment results in the presence of non-gaussian atmospheric fluctuations, observed at "large" $\sigma$. These can be eliminated in data analysis by filtering the signal fluctuations (beyond $n\sigma$) with an appropriate filter (with $n$ to be found by maximizing the signal to noise ratio). A similar analysis has been applied to Fotomito SZ data and has shown best values for $n$ of a few units giving the highest signal to noise ratios.

5. FOREGROUNDS AND SYSTEMATICS IN THE DETECTION OF CMBP

As for the search of CMB anisotropies in the far-infrared region, polarization measurements require a detailed knowledge of foregrounds and how to remove them. The advantage of having some non-polarized foregrounds, is leveled by the lack of information regarding the expected polarized fraction of single contributions. Apart from the atmosphere, other important foregrounds that must be taken into account are dust contamination due to emission of aligned small particles and grains in primordial or galactic magnetic fields,\textsuperscript{22} galactic free-free emission that can give a 10% contribution concentrated in HII regions (due to Thomson scattering), and synchrotron emission, both galactic and extra-galactic, the former of course depending on galactic latitude, dominating at low frequencies but with a significant contamination at mm wavelengths.\textsuperscript{23} Some of these foregrounds can be efficiently removed if measurements at different frequencies are provided, others (as in the case of polarized dust emission) can be compared to consistent patterns of galactic magnetic field when mapping, so that these can be ignored in the presence of expected anisotropy ring patterns inconsistent with magnetic field lines if present.\textsuperscript{24} Thus, by performing observations in sky regions which are particularly clean from foregrounds, studying the detected polarized signals and the dependence on the frequency and on the sky coordinates, foregrounds can be drastically reduced and finally eliminated from the CMB polarization measurements.

\textbf{Figure 5.} Expected polarized foregrounds, with corresponding frequency bands of some of the Table1 experiments.

Polarization patterns of ISM clouds are also studied for what concerning star-formation process for the full understanding of which, a deep study of present magnetic fields (which align dust grains) is necessary. This is for instance what SCUBA does at James Clerk Maxwell Telescope on Mauna Kea, Hawaii. Greaves et al.\textsuperscript{25}
have observed polarized thermal emission from the aligned dust grains in the central region of M82. 850µm polarization image of the star-formation region W3 has also been taken and compared with observation made by Hildebrand et al.26 showing a remarkable similarity. DR21 is also a widely studied region both from photometric and polarimetric point of view.27 Thus, if more then one observation is taken on a single source, these sources could become efficient calibrators and sources used to test the polarimeter efficiency.

6. CONCLUSIONS

The main characteristics of our experiment MITO Pol have been presented. Problems connected with spurious polarization removing have been analyzed and a method for non-gaussian atmospheric fluctuation has been presented. This will be applied on MITO Pol data and will reduce atmospheric contamination that all ground-based experiments necessary undergo. We think that our polarimeter could give a contribution to the still open problem of the detection of CMB polarization and polarized foregrounds. First step of MITO Pol will be the observation of foreground sources in order to be able to create a catalogue of polarized sources to allow cross-check between various polarization experiments and to be useful for specific CMB polarization space mission as MAP, SPOrT or Planck.

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