CMB-CAL 2024

A workshop on calibration methods for
Cosmic Microwave Background polarimeters

FUNDED BY

POLOCALC

Dept. of Physics,
University of Milano-Bicocca
Milan, Italy
November 4th – 8th, 2024

Università degli Studi di Milano Bicocca

European Commission

European Research Council
Established by the European Commission

CMB-CAL 2024 is
funded through the
POLOCALC
ERC Adv. Grant
from the
European Commission

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A workshop on calibration methods for
Cosmic Microwave Background polarimeters

LOC
Federico Nati
Mario Zannoni
Gabriele Coppi
Nadia Dachlythra
Rachele Branca (Administrative Coordinator)

SOC
Alexandre Adler
Gabriele Coppi
Nadia Dachlythra
Rolando Dünner
Cristian Franceschet
Federico Nati
Tomotake Matsumura
Alessia Ritacco
Sara Simon
Shun Adachi
Mario Zannoni

The ambitious scientific goals of current and next-generation Cosmic Microwave Background experiments demand exceptional calibration accuracy.

This workshop will explore the current state and future directions of calibration methods.

Topics will include **gain calibration, telescope pointing, beam characterization, polarization angle, detectors, bandpass calibration, as well as the challenges posed by galactic foregrounds and the potential to measure Cosmic Birefringence. Special emphasis will be placed on calibration technologies such as far-field sources, wire grids, holography setups, and their interplay.**

The workshop will feature a rich schedule with a combination of talks and hands-on sessions.

The CMB-CAL 2024 Workshop is entirely funded by the *EU ERC Adv. Grant POLOCALC (101096035)*

https://cmbcal24.polocalc.eu/

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LOCAL ORGANIZATION

LOC: Federico Nati, Mario Zannoni, Gabriele Coppi, Nadia Dachlythra, and Rachele Branca.

For information about the workshop and other related topics please write to *cmbcal24@polocalc.eu*

Website: *https://cmbcal24.polocalc.eu/*

VENUE INFORMATION

The Workshop takes place in the U6 building (**Room U601F**), in Piazza dell'Ateneo Nuovo, 1, Milano

Close to Workshop's room, the additional **Room U601D** is available to work and meet independently on Day 2 and Day 3 from 16:30 to 19:00.

For those interested, we will organize some visit to the Experimental Cosmology Lab, located at the Department of Physics (**U2 building**) of the University of Milano-Bicocca is located in Piazza della Scienza, 3. *Please contact directly Federico Nati, Mario Zannoni or Gabriele Coppi.*

WIFI

Eduroam will work in all the University buildings

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FOOD

Breakfasts and Coffee Breaks will be served close to the Workshop area in U6 Building.

Lunch on Day 1 will be also served close to the Workshop area in U6 Building.

Lunches on Day 2, 3, and 4 will be served at the SottoSopra Restaurant, Viale Piero e Alberto Pirelli, 16.

Social dinner on Day 3, Wed. Nov. 6th, is at Ristorante "La Bicocca", Viale Sarca, 179.

There are several coffee shops, bars and restaurants in the area you can choose from, please visit the Workshop website for suggestions.

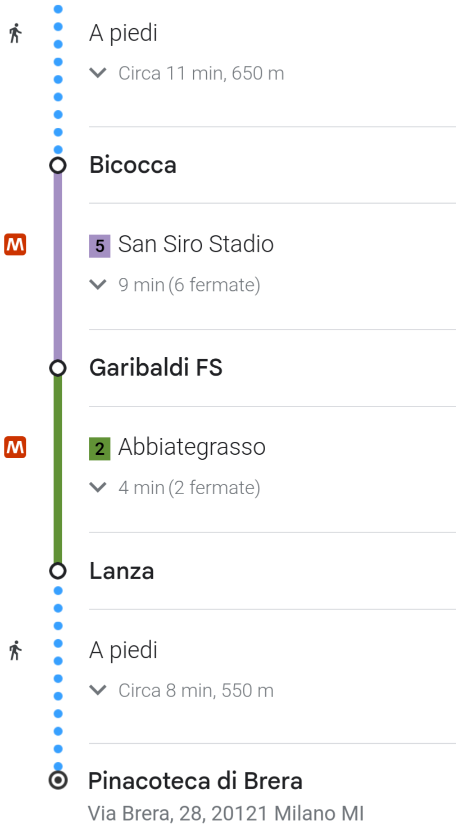
Organized Visits to Pinacoteca di Brera

When:
- Day 4 – Thursday, Nov. 7th
- Arrive at the Museum ticket office 15 minutes before your visit. Visits will be divided into four slots (please follow your assigned slot communicated via email):
  - 15:30
  - 16:00
  - 16:30
  - 17:00

If you need to request any changes to your assigned slot, please contact us at cmbcal24@polocalc.eu.

Where:
- *Pinacoteca di Brera*
  Via Brera, 28, Milano

How to get there:
- From U6 or SottoSopra Restaurant, walk to Metro Station **Bicocca**, take **M5 - Purple line**, Direction “San Siro Stadio”
- Get off at **Garibaldi FS** stop (10 min, 6 stops)
- Take **M2 - Green Line**, direction “Abbiategrasso/Assago”
- Get off at **Lanza** stop (4 min, 2 stops)
- Walk (8 min, 550 m) to *Pinacoteca di Brera*, Via Brera 28




Sposalizio della Vergine
Raffaello Sanzio


Cena in Emmaus
Caravaggio (Michelangelo Merisi)


Cristo morto nel sepolcro e tre dolenti
Andrea Mantegna


Il bacio
Francesco Hayez

About POLOCALC: Some history...

2015

Journal of Astronomical Instrumentation, Vol. 4, Nos. 3 & 4 (2015) 1550007 (18 pages)

DOI: 10.1142/S2251171715500075

World Scientific
www.worldscientific.com

A CubeSat for Calibrating Ground-Based and Sub-Orbital Millimeter-Wave Polarimeters (CalSat)

Bradley R. Johnson[*,‖], Clement J. Vourch[†], Timothy D. Drysdale[†], Andrew Kalman[‡], Steve Fujikawa[§], Brian Keating[¶] and Jon Kaufman[¶]
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New York, NY 10027, USA
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Glasgow, Scotland G12 8QQ, UK
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Received 2015 May 26; Revised 2015 August 20; Accepted 2015 August 24; Published 2015 October 2

We describe a low-cost, open-access, CubeSat-based calibration instrument that is designed to support ground-based and sub-orbital experiments searching for various polarization signals in the cosmic microwave background (CMB). All modern CMB polarization experiments require a robust calibration program that will allow the effects of instrument-induced signals to be mitigated during data analysis. A bright, compact and linearly polarized astrophysical source with polarization properties known to adequate precision does not exist. Therefore, we designed a space-based millimeter-wave calibration instrument, called CalSat, to serve as an open-access calibrator, and this paper describes the results of our design study. The calibration source on board CalSat is composed of five "tones" with one each at 47.1, 80.0, 140, 249 and 309 GHz. The five tones we chose are well matched to (i) the observation windows in the atmospheric transmittance spectra, (ii) the spectral bands commonly used in polarimeters by the CMB community and (iii) the Amateur Satellite Service bands in the Table of Frequency Allocations used by the Federal Communications Commission. CalSat would be placed in a polar orbit allowing visibility from observatories in the Northern Hemisphere, such as Mauna Kea in Hawaii and Summit Station in Greenland, and the Southern Hemisphere, such as the Atacama Desert in Chile and the South Pole. CalSat also would be observable by balloon-borne instruments launched from a range of locations around the world. This global visibility makes CalSat the only source that can be observed by all terrestrial and sub-orbital observatories, thereby providing a universal standard that permits comparison between experiments using appreciably different measurement approaches.

2016

International Journal of Modern Physics D
Vol. 25, No. 10 (2016) 1640012 (13 pages)

DOI: 10.1142/S0218271816400125

World Scientific
www.worldscientific.com

Cosmic microwave background and cosmic polarization rotation: An experimentalist view

Paolo de Bernardis[*] and Silvia Masi[†]
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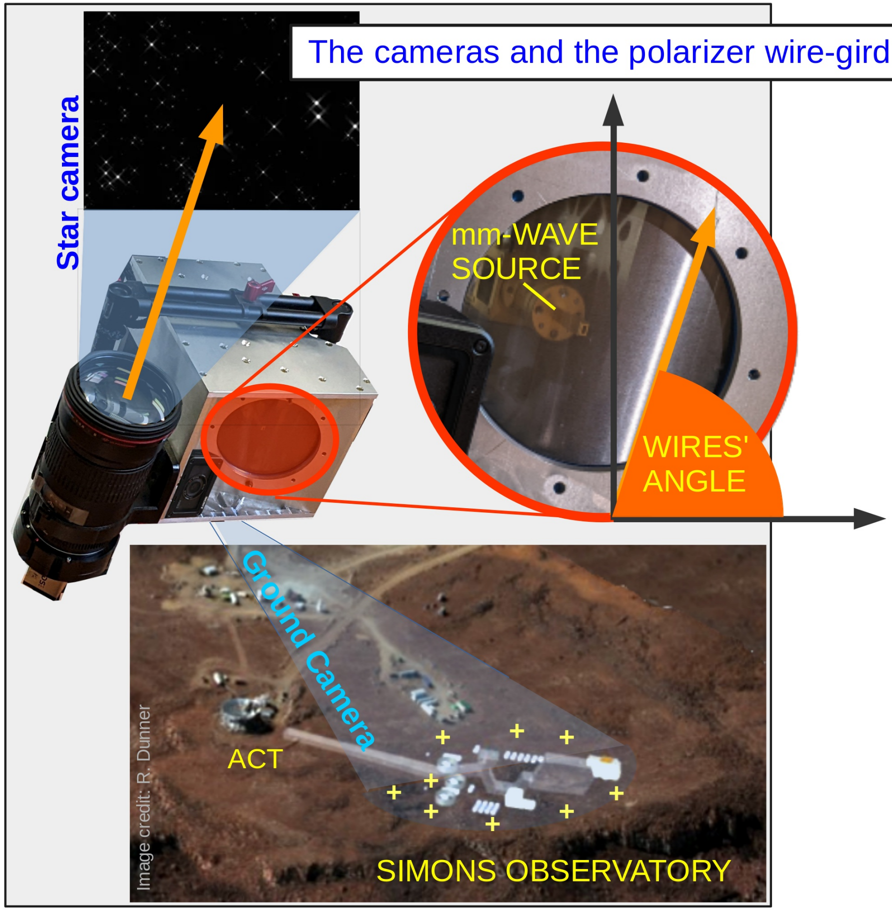
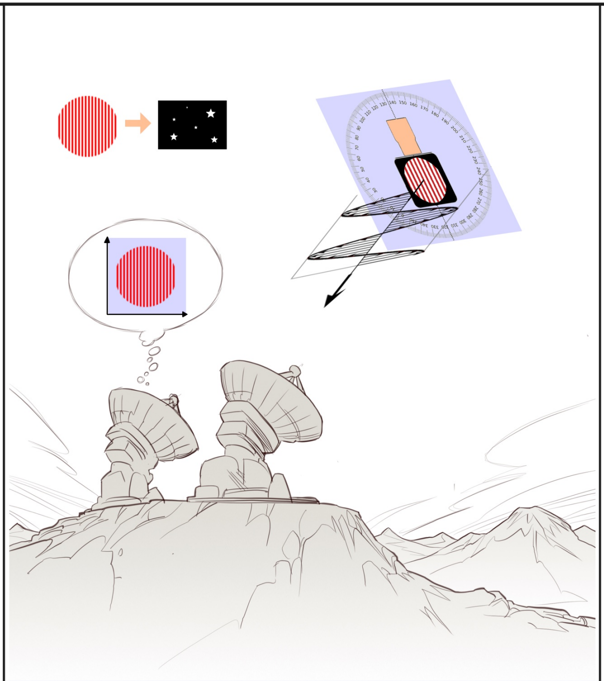
Received 20 March 2016
Revised 10 April 2016
Accepted 14 April 2016
Published 26 May 2016

In this note, we discuss the prospect of accurate measurements of cosmic microwave background (CMB) polarization rotation with future surveys. We focus on instrumental issues, analyzing the required improvements in detection methods and calibration procedures, and discuss the impact of these requirements in the design and optimization of forthcoming CMB polarimeters.

POLOCALC, the concept

The cameras and the polarizer wire-gird are aligned with a better than 0.1° accuracy





Absolute orientation through **sky-referenced** **polarized source**

See Rolando Dünner’s talk tomorrow and poster by Federico Astori

POLOCALC, the origins (2016)

World Scientific
www.worldscientific.com

Journal of Astronomical Instrumentation, Vol. 6, No. 2 (2017) 1740008 (13 pages)

DOI: 10.1142/S2251171717400086

POLOCALC: A Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background

Federico Nati[1,6], Mark J. Devlin[1], Martina Gerbino[2], Bradley R. Johnson[3], Brian Keating[4], Luca Pagano[5] and Grant Teply[4]

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Received 2017 April 7; Accepted 2017 April 27; Published 2017 May 22

*First submission to ERC (2017, CoG) was evaluated very well, but **failed**! (and so did the second (2019, SyG) and third one (2021, AdG)....*

ABSTRACT

[...] The POLarization Orientation CALibrator for Cosmology, **POLOCALC**, will dramatically improve instrumental accuracy by means of an artificial calibration source flying on **high-altitude balloons and aerial drones**. **Polarization angle calibration** requires observation of a well-characterized distant source at high elevation angles. [...] POLOCALC will also allow a unique method to measure the telescopes' **polarized beam**. [...]

The source will make use of both narrow and broadband microwave emitters between 40 GHz and 150 GHz coupled to precise polarizing filters. The **orientation** of the source polarization plane will be registered to absolute celestial coordinates by star **cameras and gyroscopes** with arcsecond accuracy.

[...] We will precisely characterize the microwave source in laboratory before deployment. The beam pattern of the source will also be precisely measured using rotary stages, diode sensors and lock-in amplifiers.

During the operations in the field, the microwave source power will be **modulated** for optimal signal recovery using a lock-in demodulation technique, while on the telescope side, we will also take advantage of the modulation systems such as a rotating HWP to change the polarization orientation.

Journal of Astronomical Instrumentation, Vol. 6, No. 2 (2017) 1740008 (13 pages)

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POLOCALC: A Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background

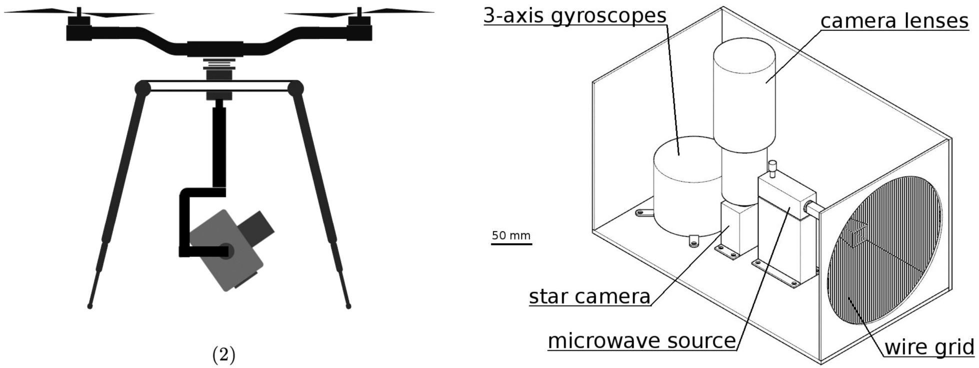

Fig. 2. A schematic representation of the essential elements of POLOCALC. From right to left: the linear polarization filter, the microwave source pointing towards the telescopes, behind it the star camera looking at the sky (oriented at 90 deg with respect to the source direction), and the three-axis high-precision gyroscopes.

ABSTRACT

[...] The POLarization Orientation CALibrator for Cosmology, **POLOCALC**, will dramatically improve instrumental accuracy by means of an artificial calibration source flying on **high-altitude balloons and aerial drones**. **Polarization angle calibration** requires observation of a well-characterized distant source at high elevation angles. [...] POLOCALC will also allow a unique method to measure the telescopes' **polarized beam**. [...]

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HoverCal

In 2017 at PUC, **Rolando Dünner** and his group started a drone calibrator project. They introduced the idea of using **photogrammetry** with landmarks to determine the roll angle, the **method to align the polarizing grid to the camera**.

They started drone flights at the Atacama site in 2017 to demonstrate the drone’s capacity and thermal emission loading.

Proceedings of the SPIE Vol. 11453, Millimeter, Submm, and Far-Infrared Detectors and Instr. for Astronomy X
114532P (2020), https://doi.org/10.1117/12.2561165

Millimeter-Wave Polarization Angle Calibration Using UAV-Based Sources

Rolando Dünner, Juan Fluxá, Sergio Best, Felipe Carrero
Instituto de Astrofísica and Centro de Astro-Ingeniería, Facultad de Física,
Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 7820436, Macul, Santiago, Chile, rdunner@astro.puc.cl

ABSTRACT

[...] We implemented a 150 GHz coherent source, with a single selectable linear polarization, fixed frequency and electronic chopper at 10 Hz. The source position is measured to better than 2 cm and 0.05 degrees using photogrammetry and a differential GPS. This source can be used to measure the polarized beam shape, relative and absolute polarization angles and map far sidelobes.

PRELIMINARY TESTS

We have performed several flights at the telescope site, demonstrating that the drone can lift a 4 kg payload up to 500 m above the ground (software limit for commercial drones), in 10 minute flights. We modeled the drone's thermal emission and measured the polarized response through the sidelobes.

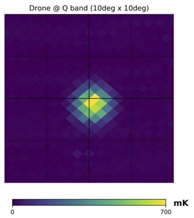
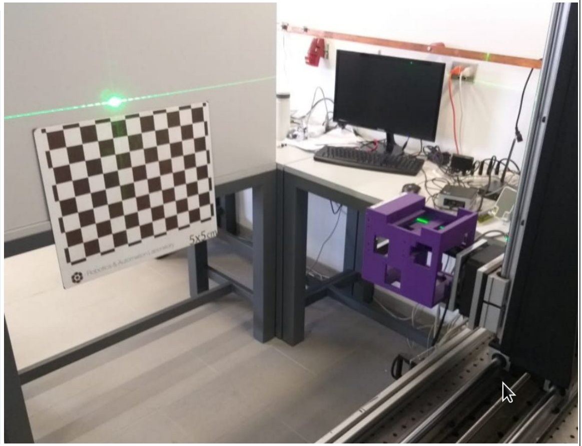


Fig. 4: The thermal emission of the drone is crudely equivalent to a 290 K blackbody with circular section of 24 cm in diameter, producing a 4 K load at 150 GHz when located 500 m away from a small aperture telescope like CLASS. This is low enough for not saturating the detectors.



2019: PROTOCALC

funded by Marie S. Curie Action, **Gabriele Coppi (Supervisor Federico Nati, HI Milano-Bicocca)**

European Commission
Marie Skłodowska-Curie Actions
Research Fellowship Programme

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Proceedings of the SPIE, Volume 12190, id. 1219015 9 pp. (2022).
DOI: 10.1117/12.2628312 - 10.48550/arXiv.2207.07595

PROTOCALC: an artificial calibrator source for CMB telescopes

Gabriele Coppi[a,b], Giulia Conenna[a], Sofia Savorgnano[a], Felipe Carrero[c], Rolando Dünner-Planella[c], Nicholas Galitzki[c,d], Federico Nati[a,b], and Mario Zannoni[a,b]

[a]Department of Physics, University of Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
[b]National Institute for Nuclear Physics (INFN), Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
[c]Instituto de Astrofísica and Centro de Astro-Ingeniería, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 7820436, Macul, Santiago, Chile
[d]Department of Physics, University of California San Diego, La Jolla, CA 92093, USA

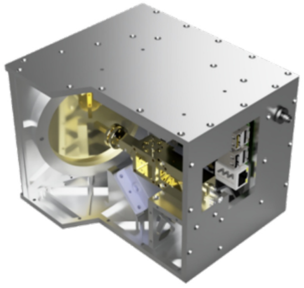


Figure 1. Rendering of the PROTOCALC payload.

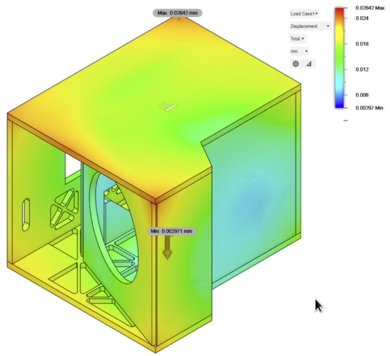


Figure 2. Displacement due to thermal contraction as simulated using Autodesk Fusion360.

[...]PROTOCALC (PROTOtype CALibrator for Cosmology) is a project funded as a Marie-Curie Fellowship under the Horizon-2020 Program. The goal of the project is to develop a **90 GHz polarization calibrator for CMB** Telescopes with a polarization angle accuracy of 0.1°.

[...] Between the end of April 2022 and the beginning of May 2022, we performed our first flight above the Cerro Toco Plateau in Chile. We did several tests with multiple telescopes (CLASS, Polarbear2 and ACT) observing the source.

► **+ 220 GHz source from Josquin Errard**

About POLOCALC: Some history...

POLOCALC

2016... after 7 years, a lot of work and ideas (and errors!) from a lot of people (and 4 resubmissions...) **in 2023!**

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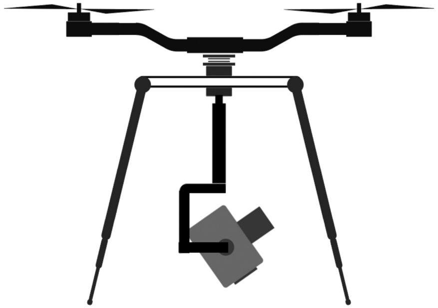

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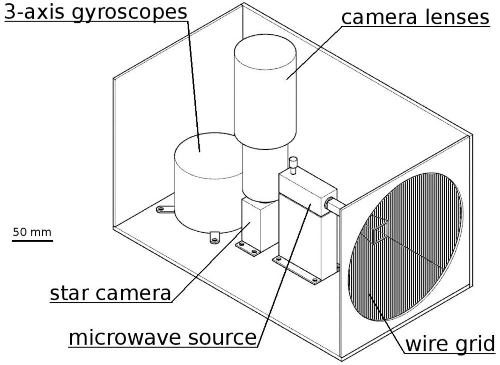

POLOCALC

European Research Council
Established by the European Commission

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

2024

The POLOCALC ERC project was awarded the ERC Advanced Grant in 2023 (and started in 2024). It partners with Rolando Dünner's HoverCal.

Scientific staff
Federico Nati (PI)
Gabriele Coppi
Mario Zannoni

Postdoc
Nadia Dachlythra
Thierry Souverin
+ WE ARE HIRING!

PhD
Ludovico Bizzarri
Federico Astori
Lorenzo Scalcinati

Staff Technicians
Andrea Passerini (eletronics)
Stefano Banfi (mechanical)

Project Admin
Rachele Branca

Master's & Bachelor
Giulia Rancati Cattaneo
Sofia Savorgano (past)
Giulia Conenna (past)
Noemi Mezzanzanica (past)

The Simons Observatory site in Atacama, as seen by the HoverCal+POLOCALC photogrammetry system.

Why this workshop?

During the ERC interview rehearsal I was asked a "simple" question:

"What is the error budget in the calibration?"

Why this workshop?

During the ERC interview rehearsal I was asked a "simple" question:

"What is the error budget in the calibration?"

My first answer: 

Why this workshop?

“What is the error budget in the calibration?”

My second answer:

Background noise

Change in atmospheric emission, drone/balloon thermal emission and ground pickup

$\sigma_{back} \sim 0.001°$

Calibration source noise & accuracy

Emitting **power stability**
Modulated, angle has very weak dependancy
$\sigma_{pow} << 0.001°/\sqrt{Hz}$

Attitude stability
-Wind speed < 5 m/s
-Gimbal stabilization
-Wide emitting beam
$\sigma_{wind} < 0.001°/\sqrt{Hz}$

Attitude Determination instant **Accuracy**
$\sigma_{ADACS} < 0.01°$ (expected ~0.001°)

Alignment between attitude sensors and polarized source
σ_{align} =
baseline: 0.1°
target: 0.01°
(or better)

Telescope noise & accuracy (from SO requirements)

Relative polarization angle accuracy: ~ 0.001°

Note that **Absolute** polarization angle accuracy from direct calibration is only ~ 1°
(Lowered by indirect model assumptions on Tau-A and TB and EB correlations)

Telescope **base** pointing accuracy
$\sigma_{base} \sim 0.001°$

Beam, optical elements, filters
$\sigma_{beam} < 0.001°$

HWP position readout accuracy
$\sigma_{HWP} << 0.001°/\sqrt{Hz}$

Radiation coupler, electronics:
$\sigma_{syst} \sim 0.001°$

$$\sigma_\alpha \sim \sqrt{(\sigma_{back})^2 + (\sigma_{pow})^2 + (\sigma_{wind})^2 + (\sigma_{ADACS})^2 + (\sigma_{align})^2 + (\sigma_{base})^2 + (\sigma_{beam})^2 + (\sigma_{back})^2 + (\sigma_{HWP})^2} \sim [0.1° : 0.01°]$$

Why this workshop?

“What is the error budget in the calibration?”

My third answer:

LET’S HAVE A WORKSHOP!

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