HoverCal + PoloCalC

Millimeter-Wave Polarization Angle Calibration Using UAV-Based Sources

For Cosmic Microwave Background experiments

Rolando Dünner (PUC)

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Cosmic Birefringence

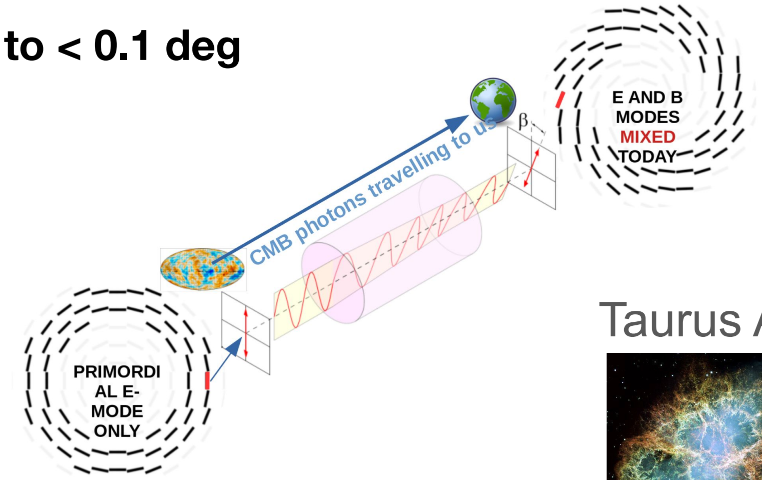
Need to calibrate the absolute polarization angle to < 0.1 deg

$$\mathcal{L} = \mathcal{L}_{EM} + \mathcal{L}_{CS} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}p_\mu A_\nu \widetilde{F}^{\mu\nu}$$

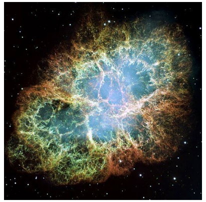
Chern-Simons Term

Parity breaking

$$\begin{aligned}
C_\ell^{TT,obs} &= C_\ell^{TT}, \\
C_\ell^{TE,obs} &= C_\ell^{TE}\cos(2\alpha), \\
C_\ell^{TB,obs} &= C_\ell^{TE}\sin(2\alpha), \\
C_\ell^{EE,obs} &= C_\ell^{EE}\cos^2(2\alpha) + C_\ell^{BB}\sin^2(2\alpha), \\
C_\ell^{BB,obs} &= C_\ell^{BB}\cos^2(2\alpha) + C_\ell^{EE}\sin^2(2\alpha), \\
C_\ell^{EB,obs} &= \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right)\sin(4\alpha),
\end{aligned}$$



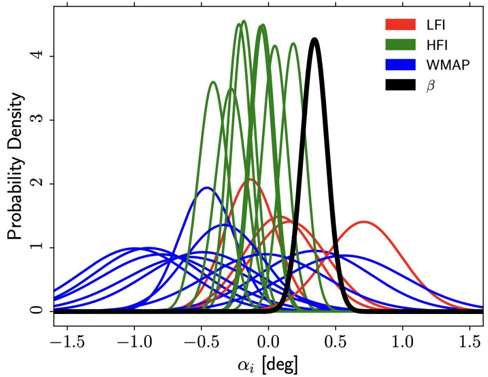
Taurus A



case	α [deg]
PR3 Commander	0.27 ± 0.05 (stat) ± 0.28 (syst)
PR3 NILC	0.26 ± 0.05 (stat) ± 0.28 (syst)
PR3 SEVEM	0.27 ± 0.05 (stat) ± 0.28 (syst)
PR3 SMICA	0.24 ± 0.05 (stat) ± 0.28 (syst)
NPIPE Commander	0.33 ± 0.04 (stat) ± 0.28 (syst)
NPIPE SEVEM	0.33 ± 0.04 (stat) ± 0.28 (syst)

Bortolami et al. 2022

Eskilt and Komatsu 2022



HoverCal+POLOCALC

Polarized Calibrator for CMB Telescopes

FONDEF ID21I10236

Accuracy 0.1 deg

New CMB Experiments

In CHILE

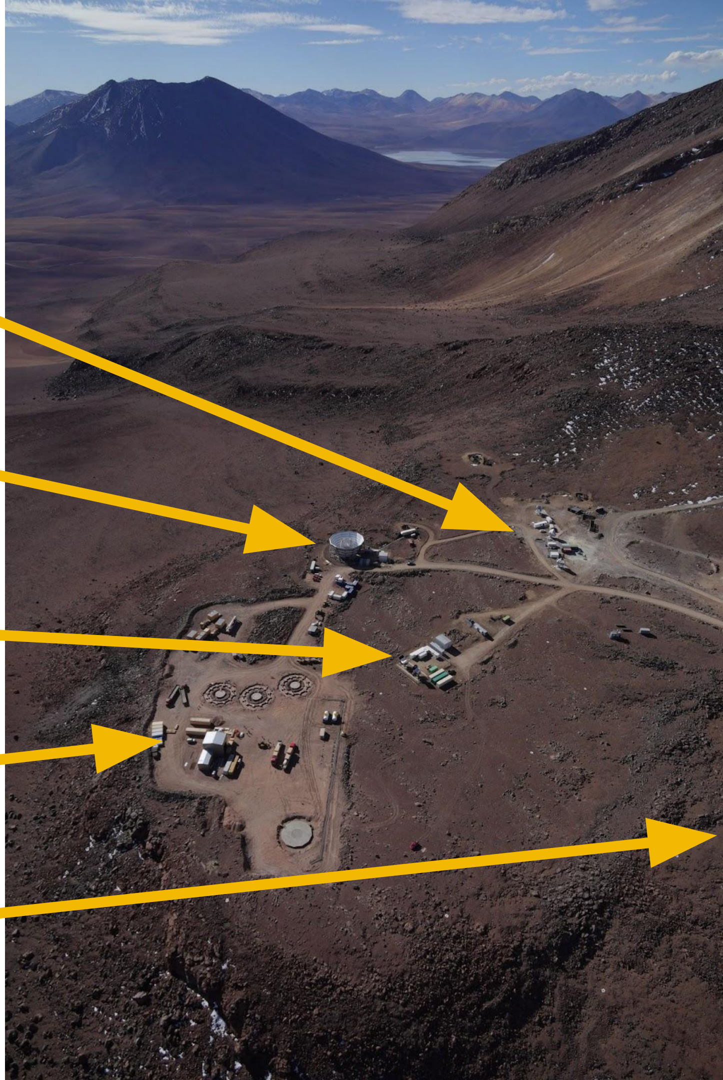
POLARBEAR - Simons Array

Atacama Cosmology Telescope

CLASS

Simons Observatory

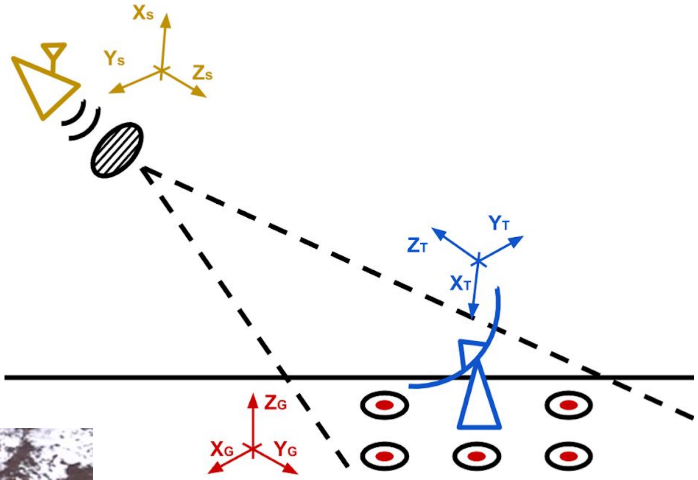
CCAT



Photogrammetric attitude reconstruction

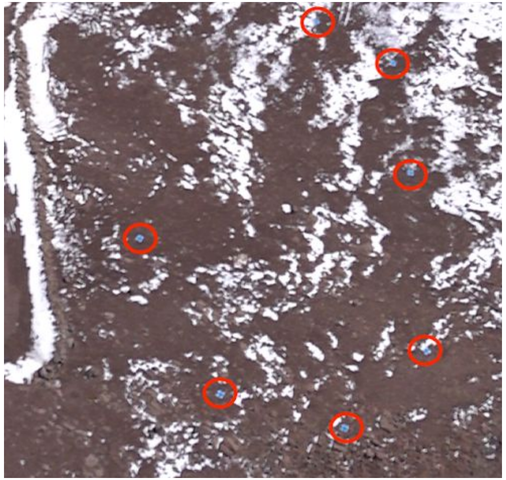
- We use photogrammetry to measure the time varying position of the source with high accuracy.
- The camera position and angle can be precisely reconstructed from fiducial marks on the ground.
- The polarization angle of the source, defined by a wire grid polarizer, is referenced to the angle of the camera.
- The source and camera are held on a rigid frame, and their relative angles are calibrated in the laboratory.
- The landmark system is based on a 3D reconstruction of the site, including the exact location of the telescopes.

Determine camera coordinates and angles: (x,y,ζ,θ,ϕ, ψ)

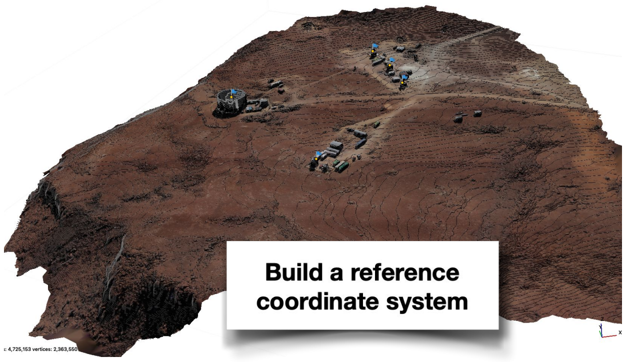


High precision in-time metrology

4K video, 30 fps

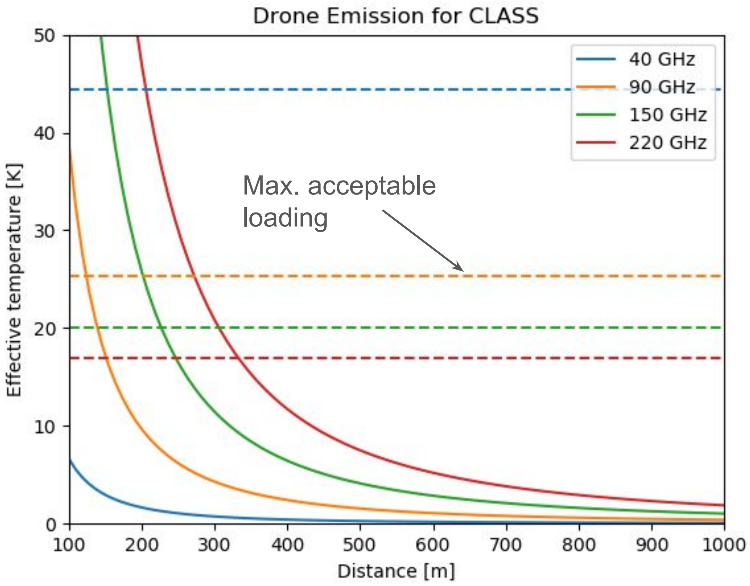


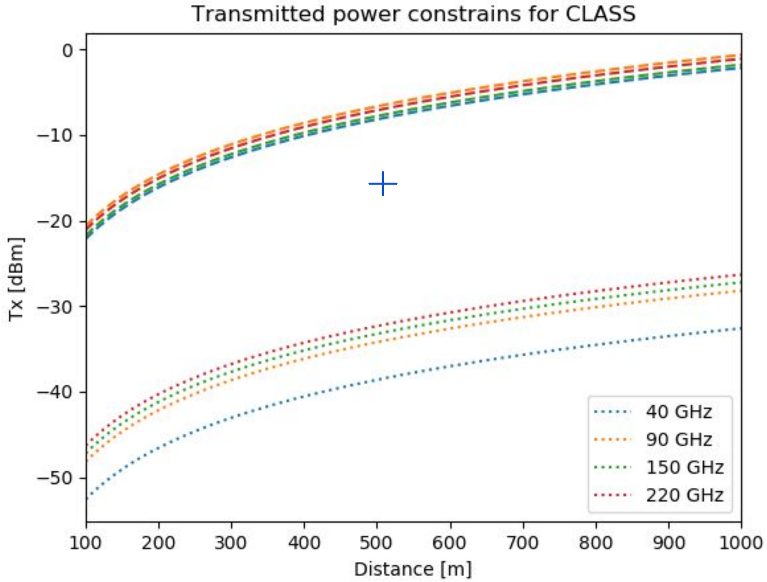
WGS-84



Thermal loading and power constraints

Using CLASS as reference



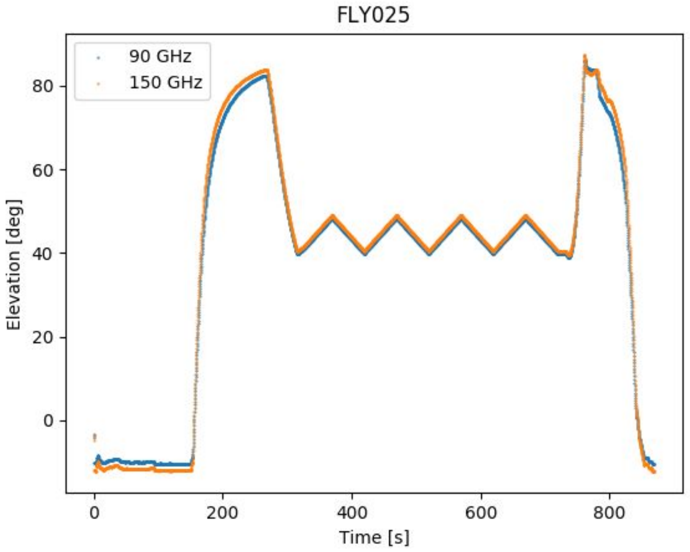


- The diluted temperature of the drone sets a limit to the minimum distance, which is more stringent at higher frequency bands. We will consider 500 meters to be our nominal distance.
- For direct beam measurements, we estimate that a forward transmitted power of -18 dBm will suffice all distances and frequency bands.

Flight programs

Measuring telescope optics in nominal observing conditions

- The drone is flown 500 meters away, at nominal elevation as seen by the telescopes.
- The drone moves up and down forming an arc, at constant distance from the telescopes.
- Meanwhile, the telescopes scan in azimuth, similar to their normal CMB observations.
- The gimbal keeps the source pointing to a fixed POI, strategically located at the center of site, not in any particular telescope.
- The drone batteries allow for 7-10 minutes of useful flight time, which translates into 3-5 up-down scans, producing 300-500 useful detector crossings.
- The drone's launch point and trajectory is always kept away from people and equipment at the site, performing the high altitude program when already far from the telescope site for safety reasons.

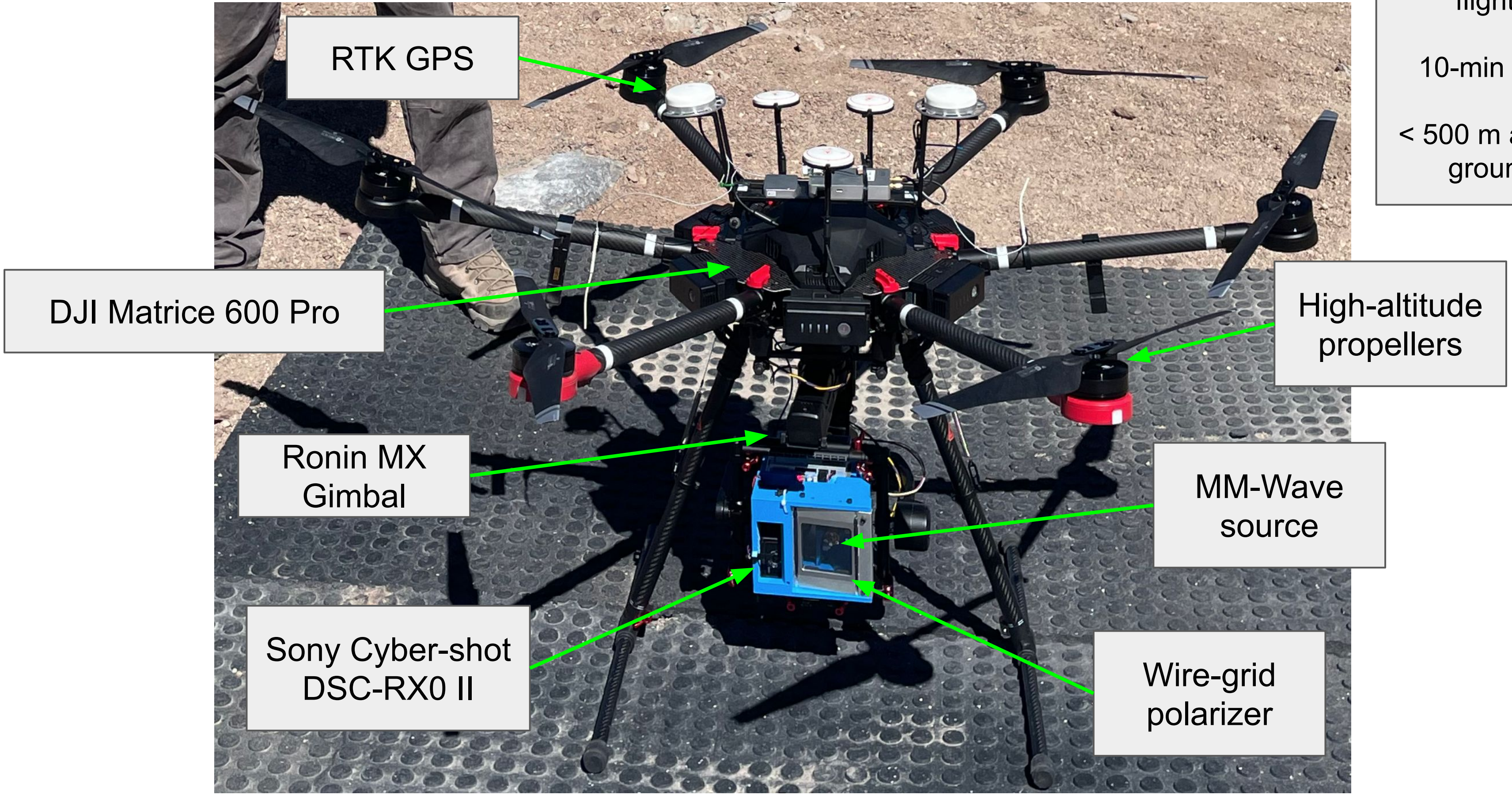


HoverCal + PoloCalC

Automatic flights

10-min long

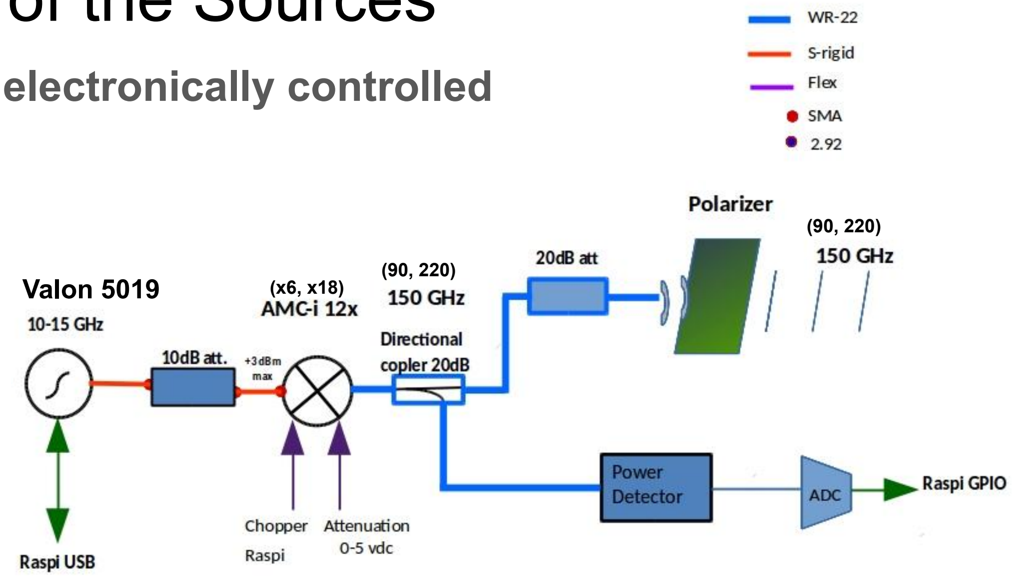
< 500 m above ground



Radio-Frequency Design of the Sources

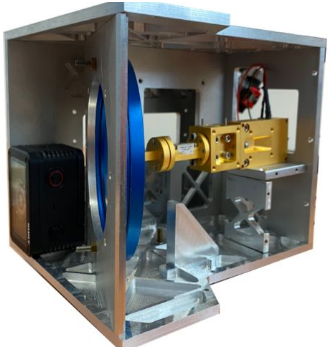
Lightweight, tunable, modulated and electronically controlled

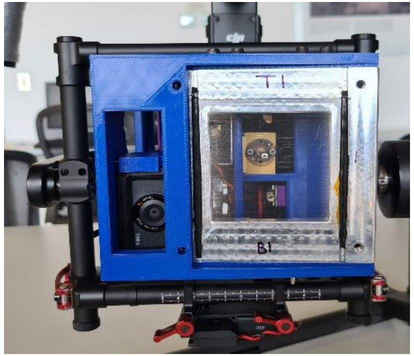
- Three coherent sources, operating at 90, 150 and 220 GHz, base on a Valon PLL and VDI frequency multipliers.
- Tunable between 75-115, 110-170 and 220-300 GHz respectively.
- Active attenuation.
- Electronically chopped at 47 Hz.
- Low directivity output feed.
- A wire grid polarizer with 99.9% degree of polarization.
- System control and communications provided by a Raspberry PI 4.
- Custom made auxiliary power and sensor boards complete the control electronics.
- Additional GPS (timing), inclinometer and weather sensors are included.



150 GHz

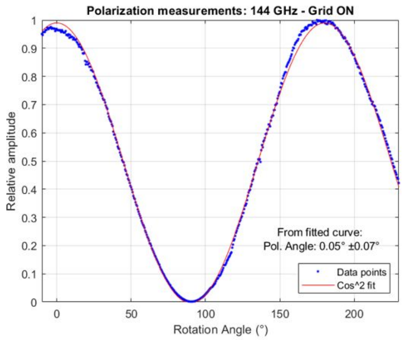
90 GHz

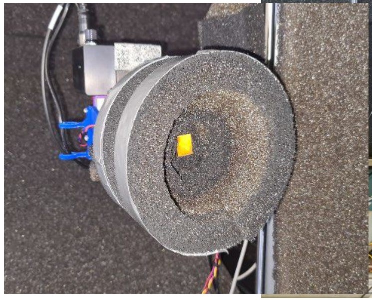


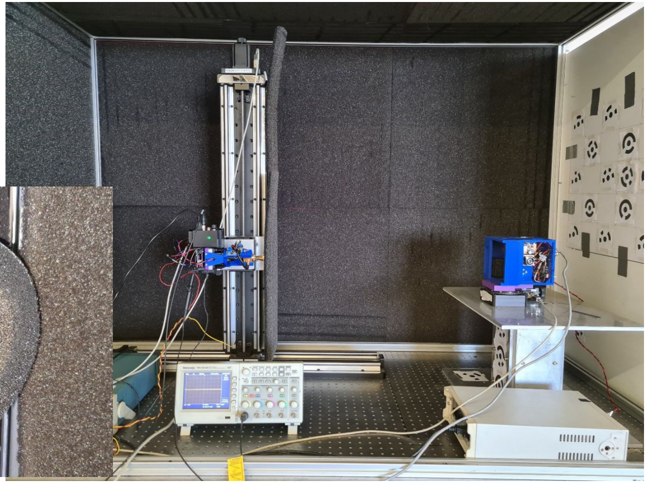


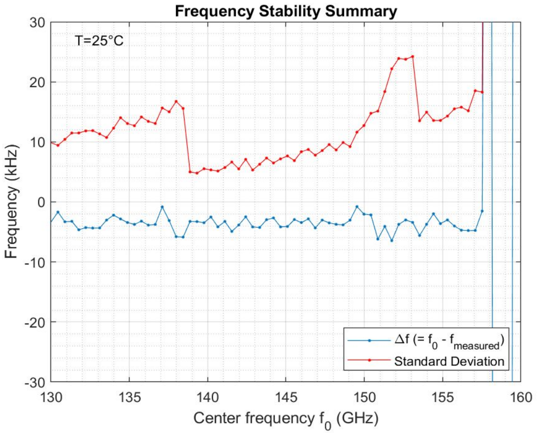
RF source characterization

We characterized the RF properties of the source, including frequency and power stability, beam pattern and polarization degree.

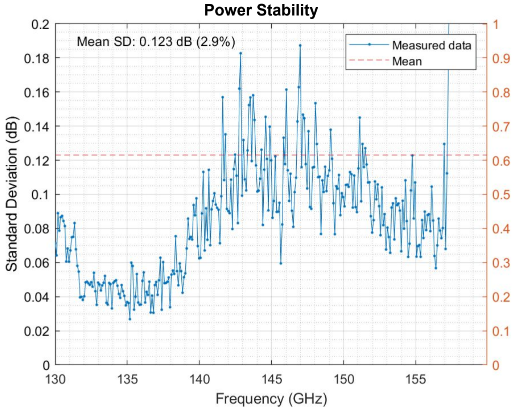




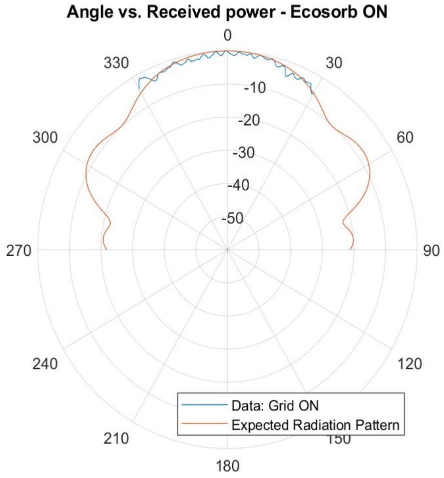




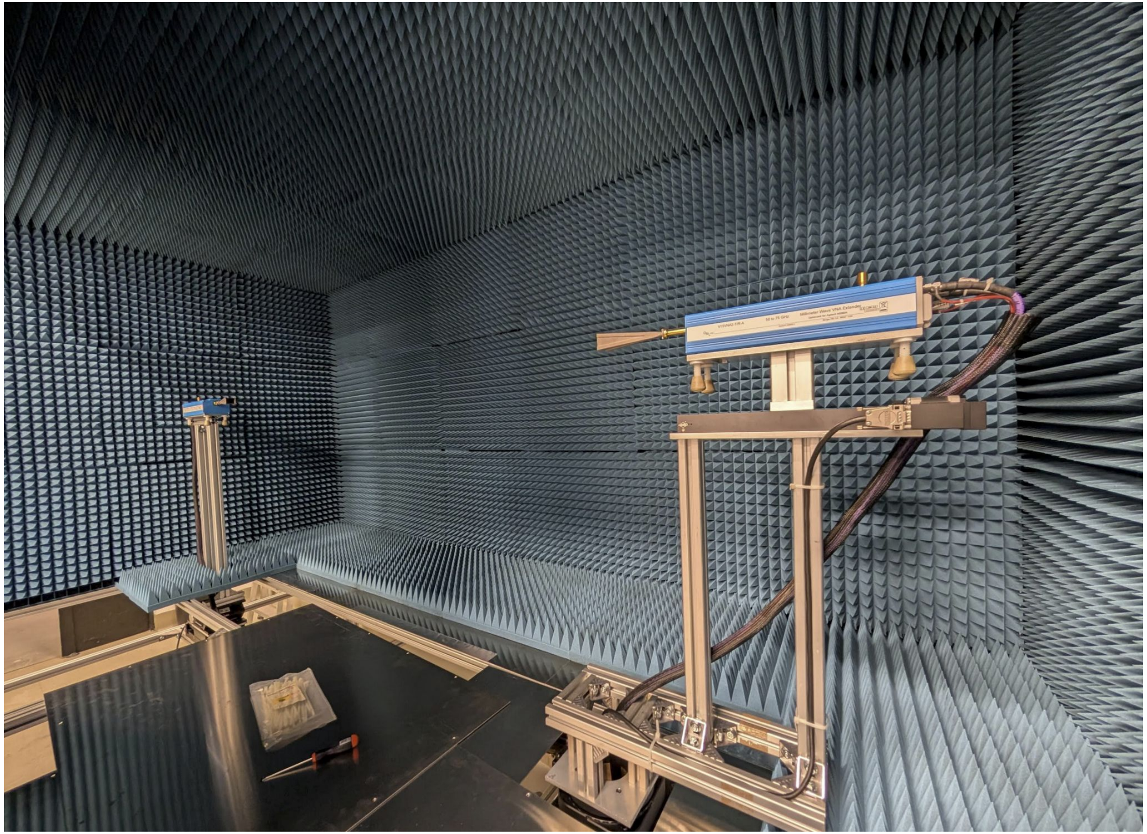
Average frequency stability (SD) of the RF source is ~0.1 ppm.
Average frequency offset of the RF source is ~3.5 kHz.



Average Stability (standard deviation) of the RF source power through the usable frequency range (130 to ~157 GHz) is estimated at 0.106 dB.



New Anechoic Chamber at Milano-Bicocca

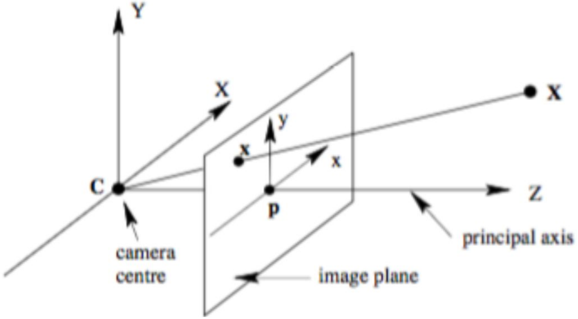


Photogrammetry

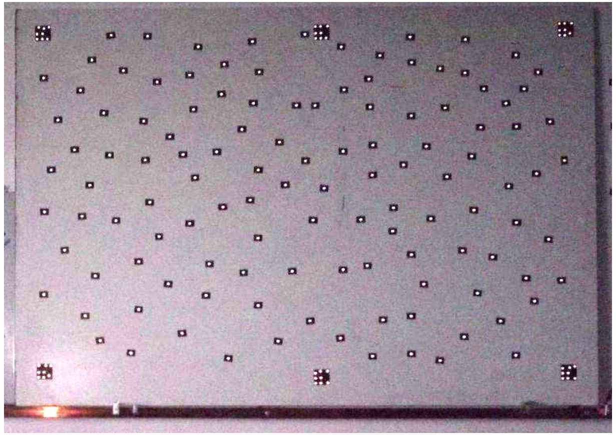
Camera calibration

- The photogrammetry camera optics are calibrated using reference targets.
- This is done using nominal camera settings, in 4K video mode, infinity focus and same exposure configuration than used during flight.
- The primary optical parameters (focal length, pixel size, and image center) are critical for the photogrammetric reconstruction, as they scale and shift the result.
- The secondary optical (radial and tangential distortions), are also measured, but their overall effect in the camera position and aim determination are small compared to our needs.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ a & f_y & c_y \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

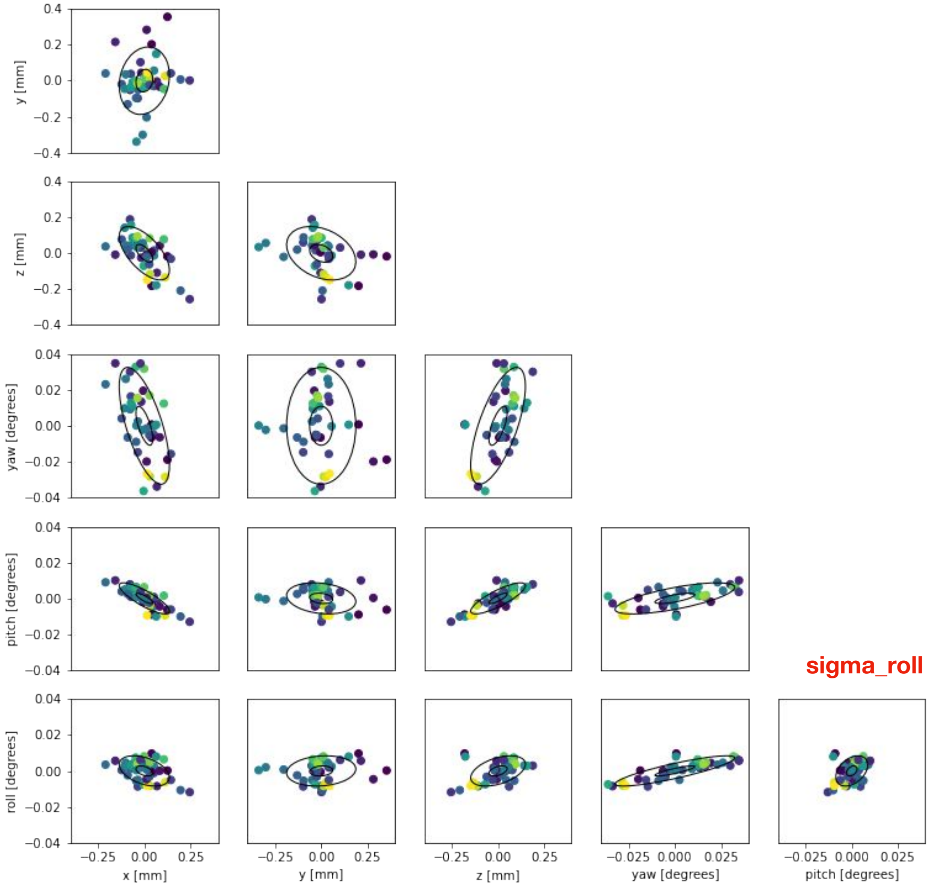


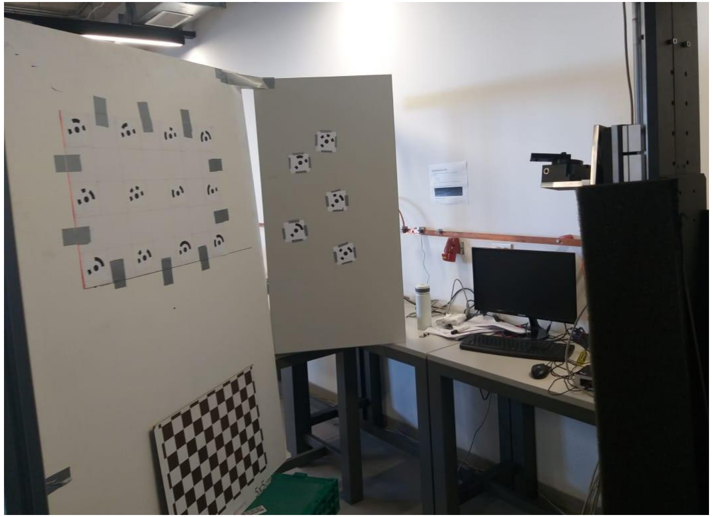
$$\begin{aligned} \tilde{x}_i &= x_i(1 + k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6 + 2 p_1 y_i + 3 p_2 x_i) + p_2 y_i^2 \\ \tilde{y}_i &= y_i(1 + k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6 + 2 p_2 x_i + 3 p_1 y_i) + p_1 x_i^2 \end{aligned}$$



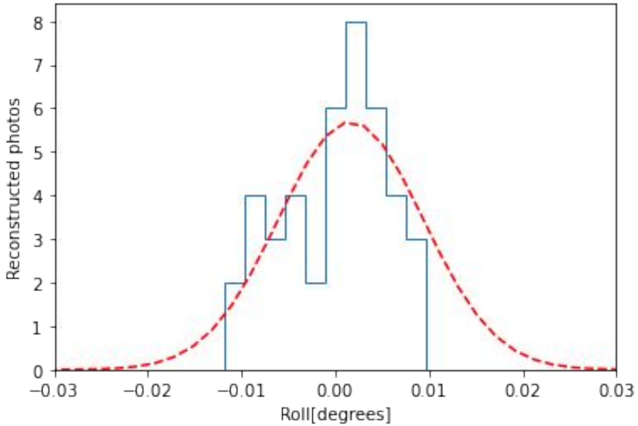
Params.	mean (mu)	error (std)
fx	2569.61	8.64
fy	2568.58	8.33
cx	1881.57	8.61
cy	1087.14	3.53
k1	0.0195	0.0057
k2	-0.0420	0.0232
k3	0.0306	0.0271
p1	-0.00027	0.00046
p2	-0.00108	0.00097

Camera reconstruction uncertainties



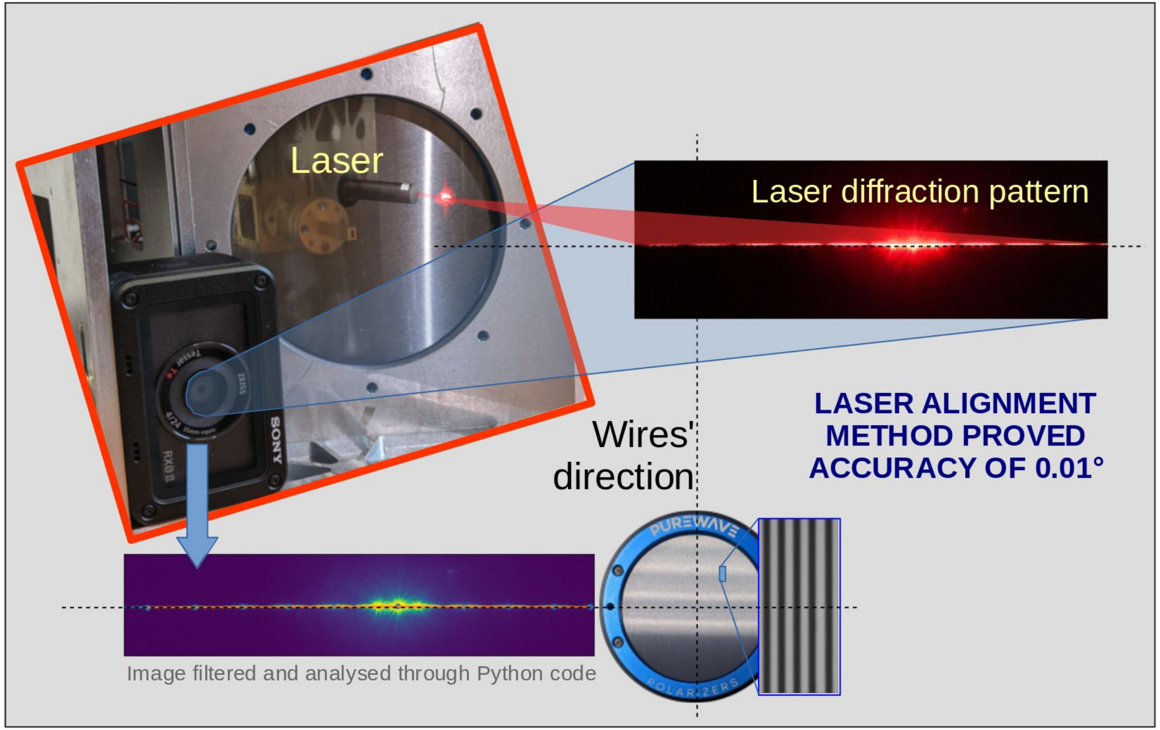


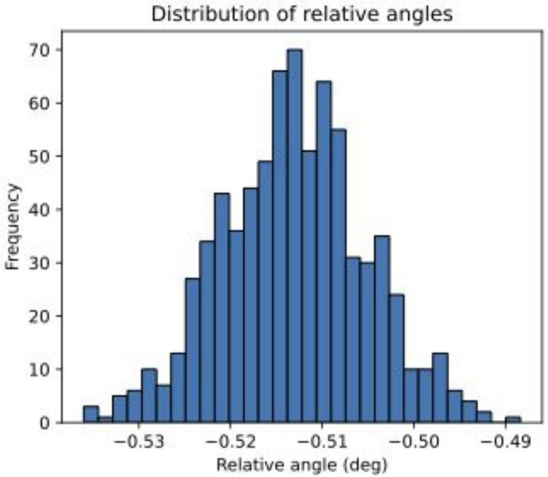
sigma_roll < 0.01 deg!



Camera - Wire Grid Alignment

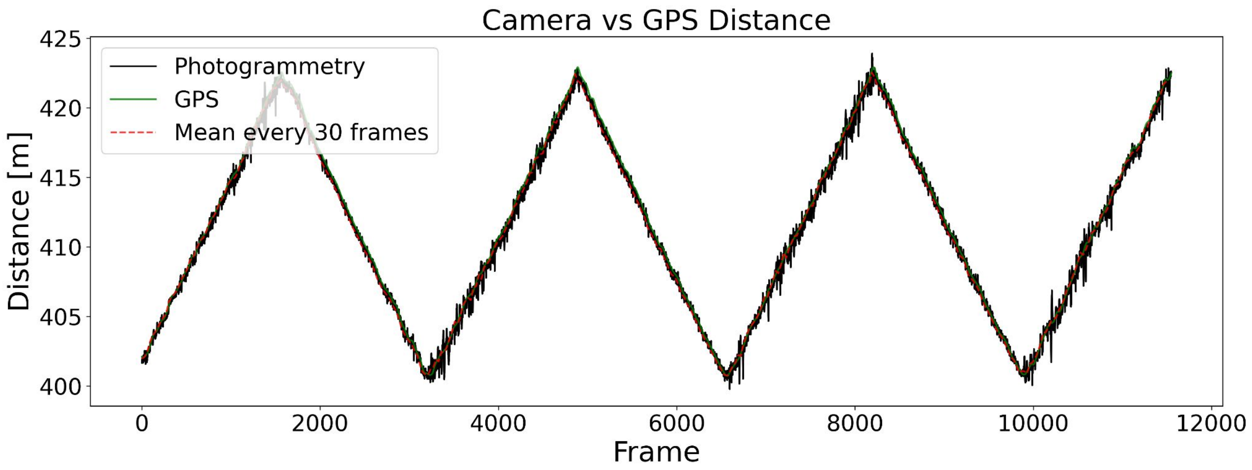
Using laser diffraction pattern

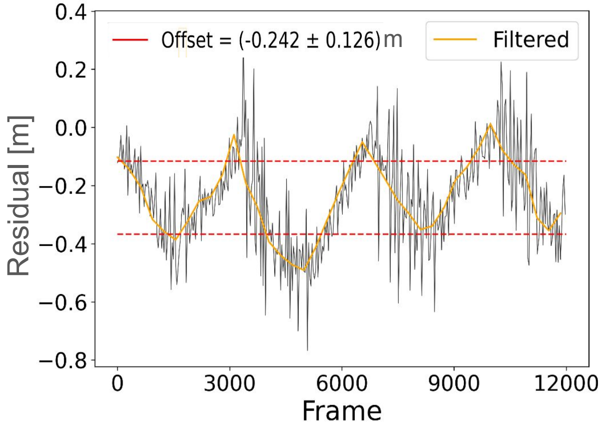


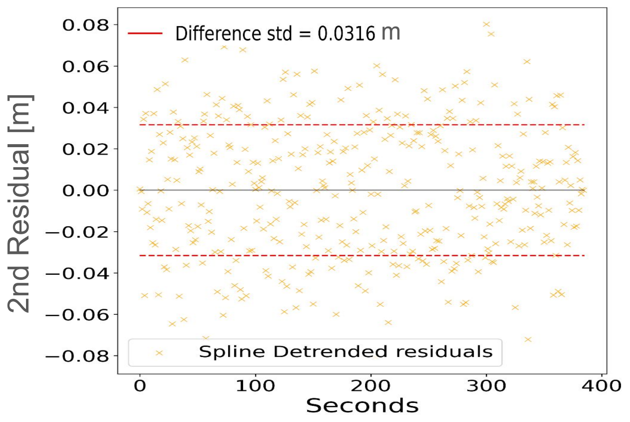


- The camera and the polarizing grid must be carefully aligned in the laboratory previous to the experiment on the field.
- The angle is determined with a dispersion of less than 0.01 deg.

Photogrammetric reconstruction of the source position



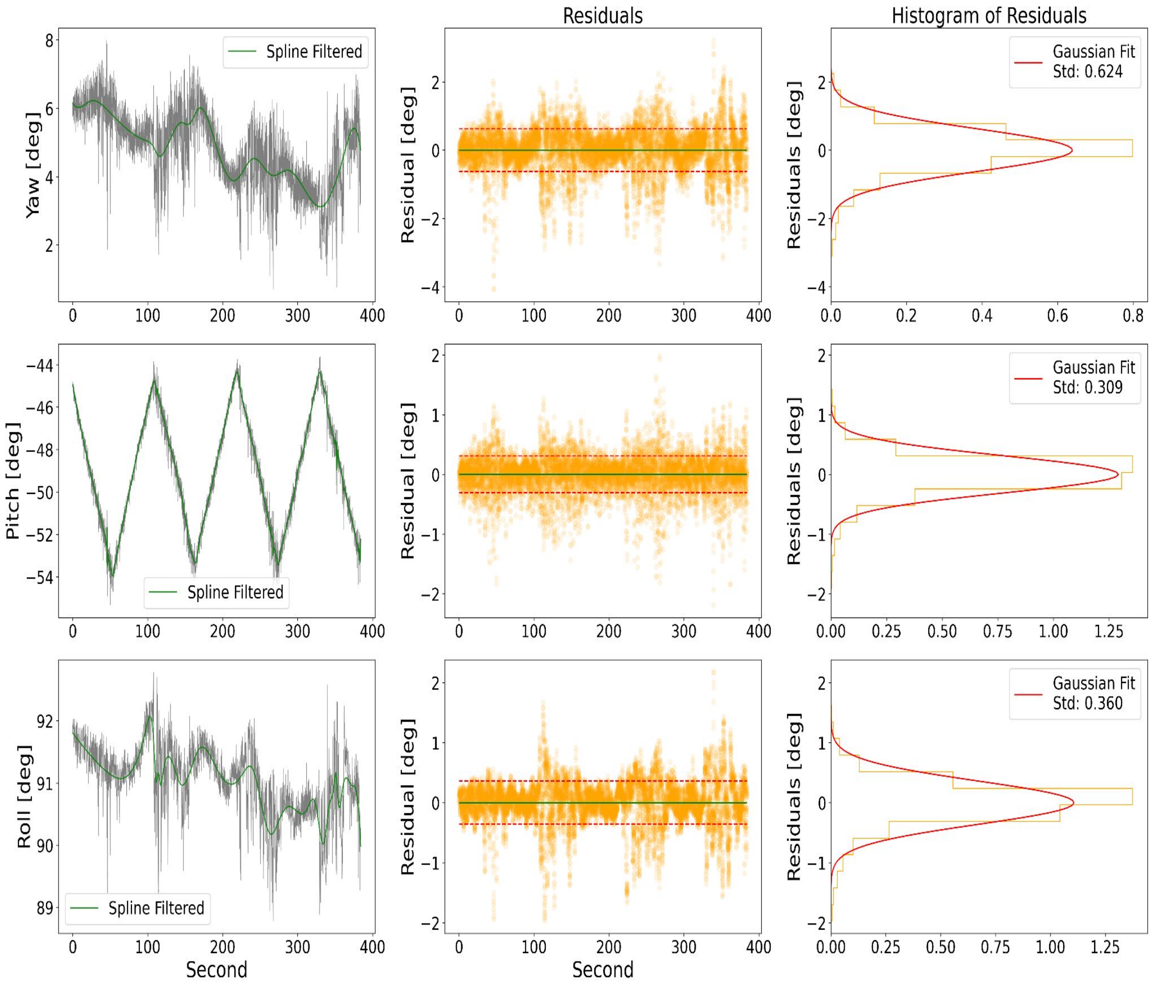




- We compare the photogrammetric reconstruction camera position to the (more accurate) GPS position.
- The mean offset in distance is less than 24 cm.
- The slow position-dependent drift is due to residual miss-calibration of the camera optics, with an std. of 13 cm.
- After removing the slow drift (averaging every 30 frames), the remaining residuals have an std of 3 cm.
- These residuals may still contain real motions of the source with respect to the drone.

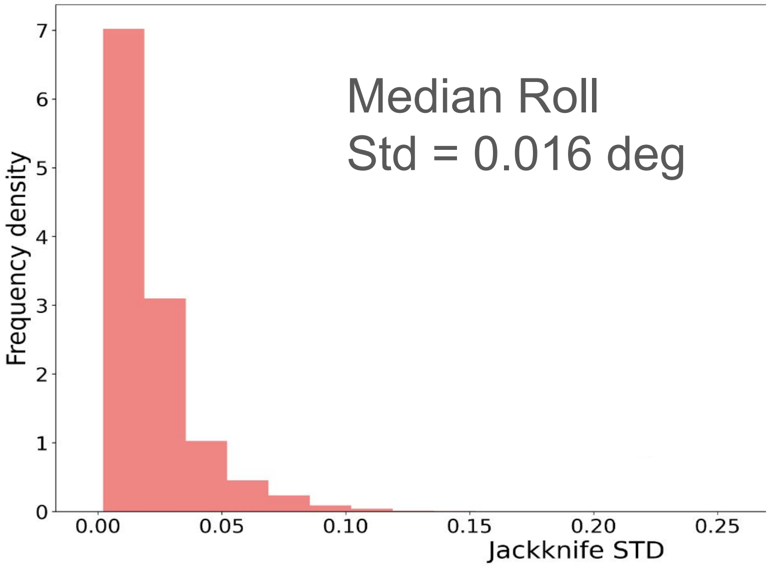
Source attitude and “vibrations”

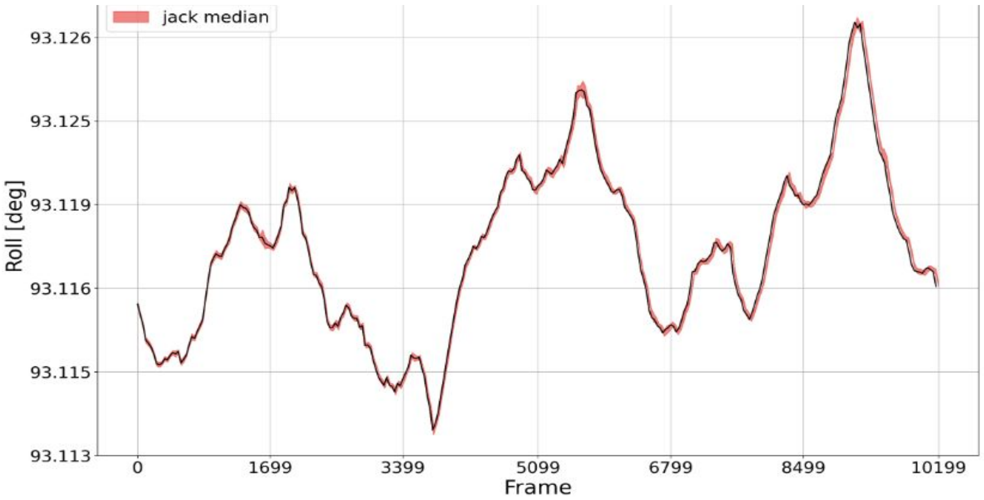
- The source is actively pointed towards the POI during flight.
- Slow attitude corrections compensate the drone motion during the flight.
- The drift residuals are indicative of source fast “vibrations”, combined with measurement errors.
- The dispersion of the attitude angles is less than 0.4 deg. for roll, being an upper limit to the precision of the roll angle measurement.

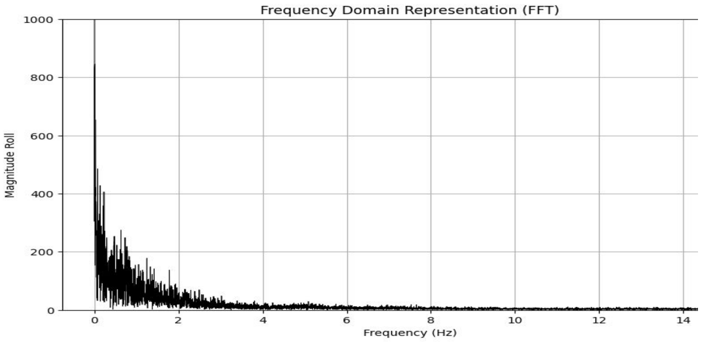


Photogrammetry Roll Angle Jackknife analysis

- Measurement errors are dominated by target centroid determination
- We compute the roll angle dispersion repeating the solution after randomly removing 1 target at a time.

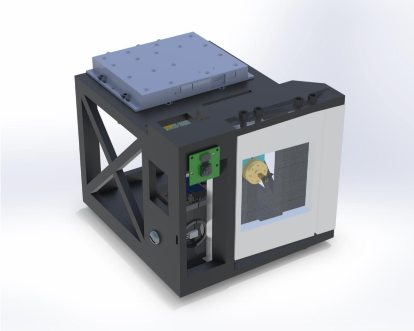


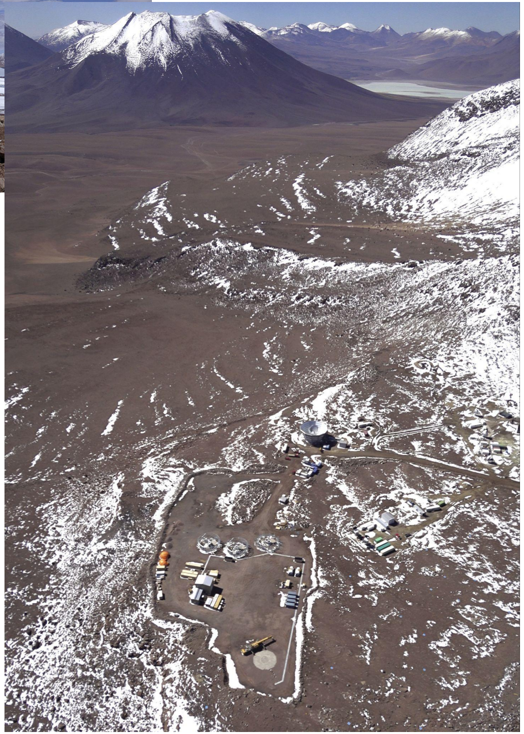




Site Campaigns

- April 2022
  - 11 flights
  - 90 and 150 GHz sources
  - CLASS, Simons Array (PBa), ACT
  - Tested different flight strategies
  - Tested source power and thermal loading
- February 2023
  - 10 flights
  - 90 and 150 GHz sources
  - CLASS
  - Tested the new control system and auxiliary inclinometer
- April 2024
  - 17 flights
  - 90 and 150 GHz sources
  - CLASS, SO, ALMA
  - ALMA green light
  - Completed CLASS boresight angles
- December 2024: full calibration flights



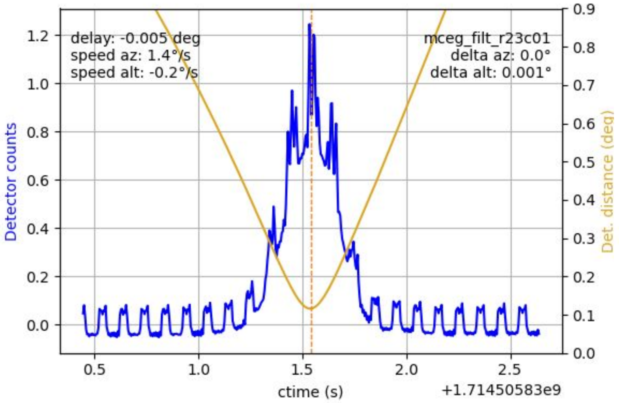


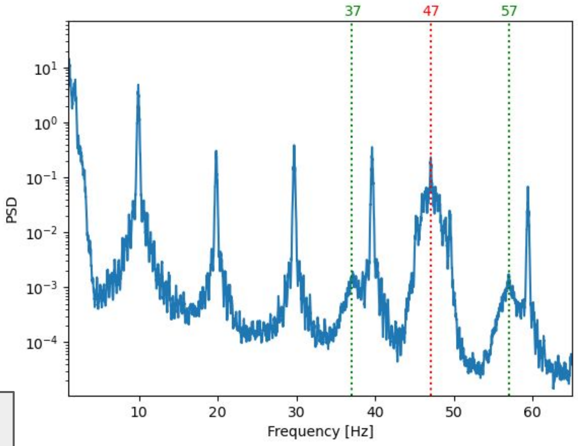
Time-Ordered Data

- The detector TOD show the instant when a detector sees the drone.
- The source signal is chopped at 47 Hz, producing a spectral line in the TOD.
- Both CLASS and SO-SAT have polarization modulators, operating at 10 and 8 Hz respectively.
- The signal is thus double demodulated, appearing at both sides of the main 47 Hz carrier.
- The double demodulated signal is purely polarized.

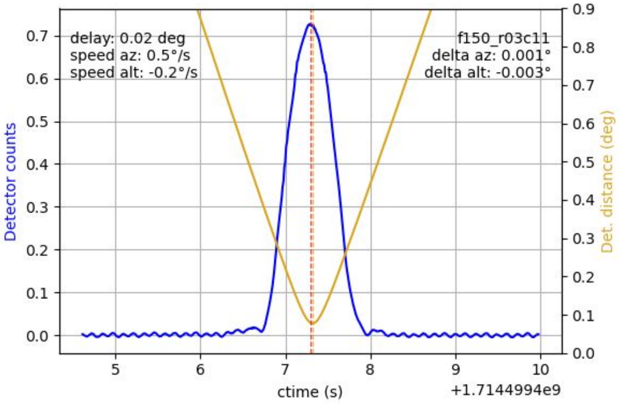
T signal ~ Jupiter in 6m telescope

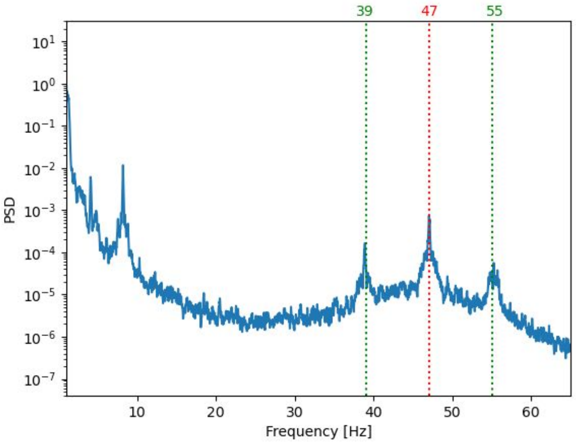
CLASS 150





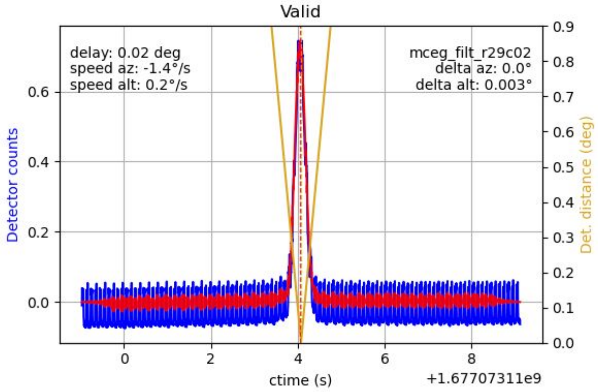
SO-SAT1 150

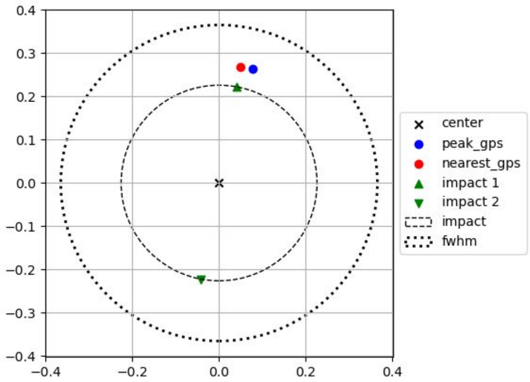


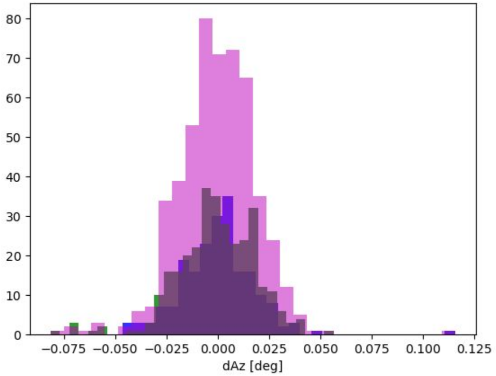


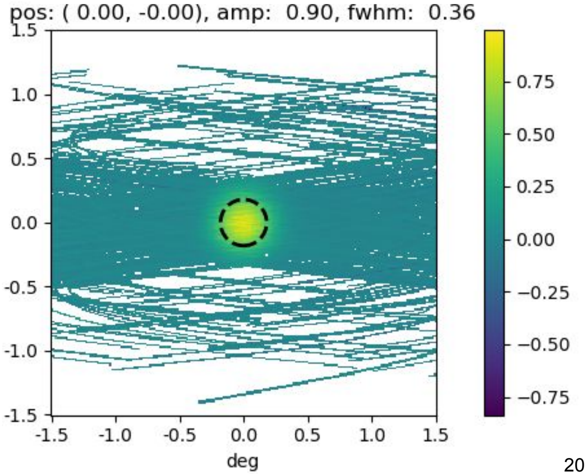
Pointing reconstruction from telescope data

- CLASS and SO-SAT TODs where analyzed to determine the pointing accuracy of the system.
- We measured the time delay and pointing error of every event in which a detector beam crossed the drone.
- A Gaussian beam model was used to reconstruct the crossing event and find the pointing errors.
- The azimuth errors are better constrained by the telescope scan.
- The pointing dispersion is close to 0.01 deg (0.6 arcmin)

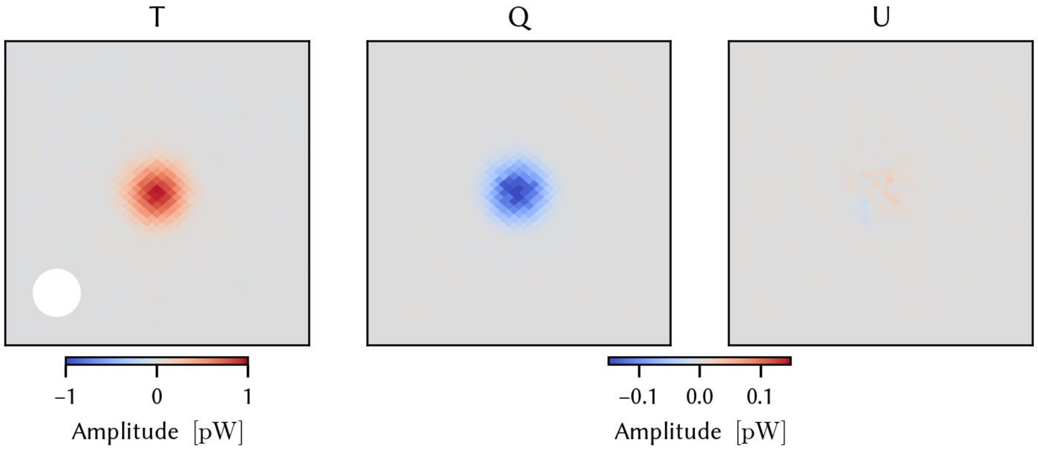


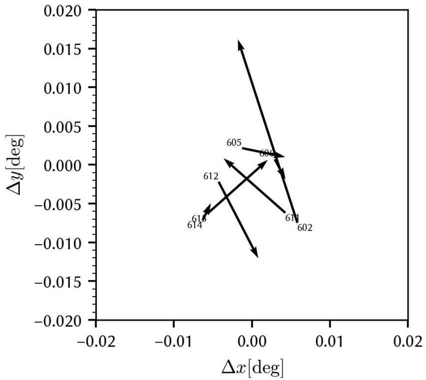


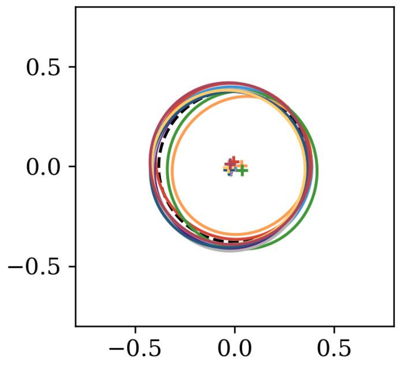




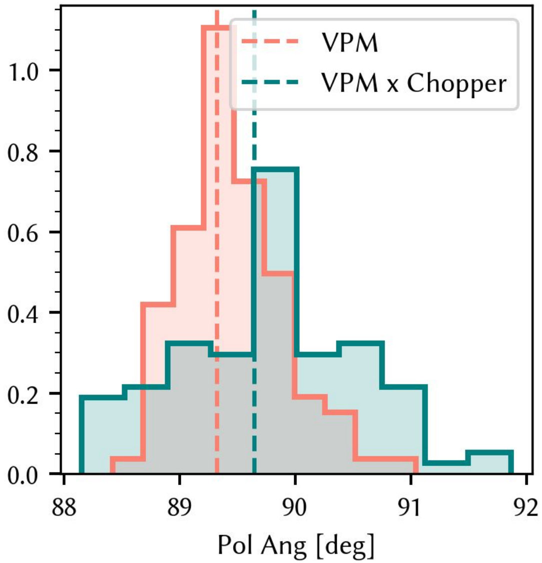
CLASS Maps (Work in progress)



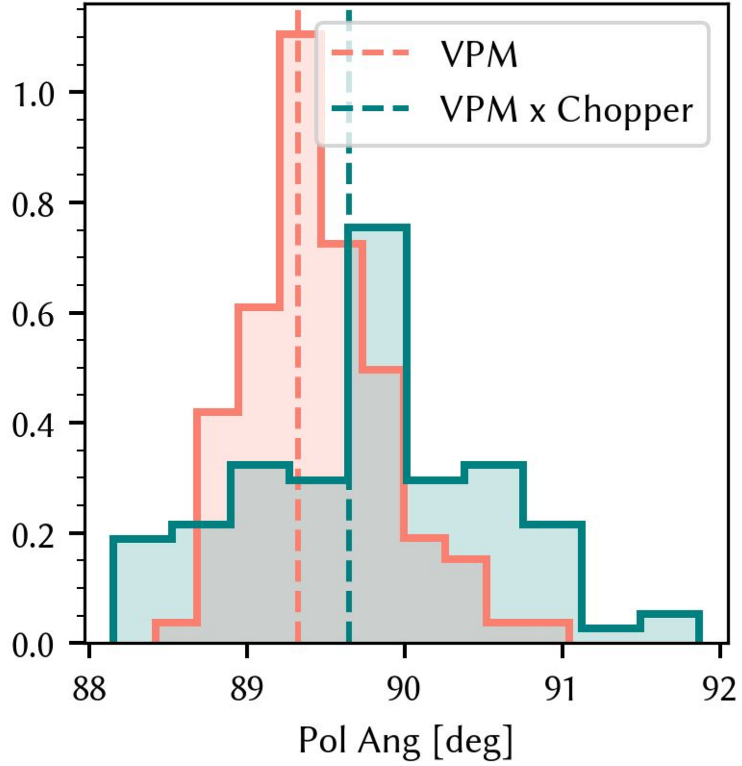




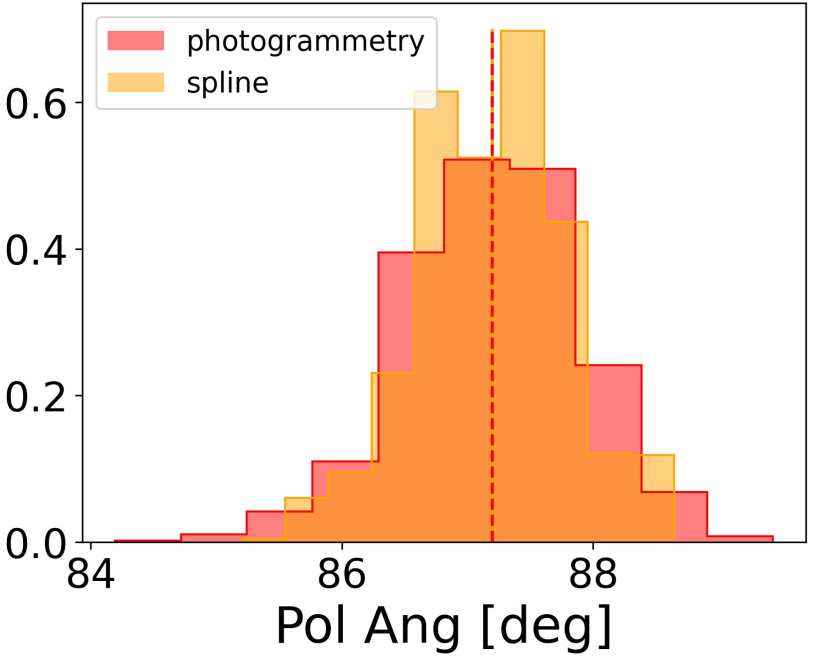
Photogrammetry corrections are not included yet in this result



CLASS polarization measurement dispersion consistent with motions of the source during the flight

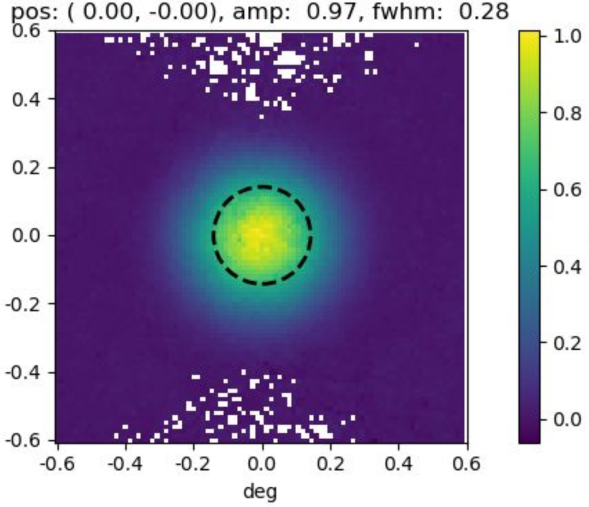


It is still pending to correct these motions when determining the polarization angle

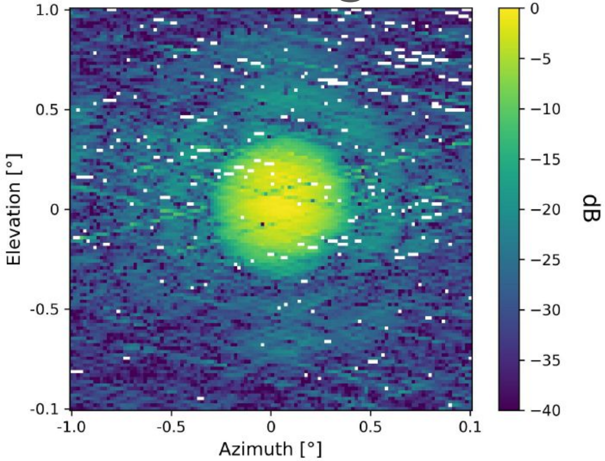


Simons Observatory SAT beam maps

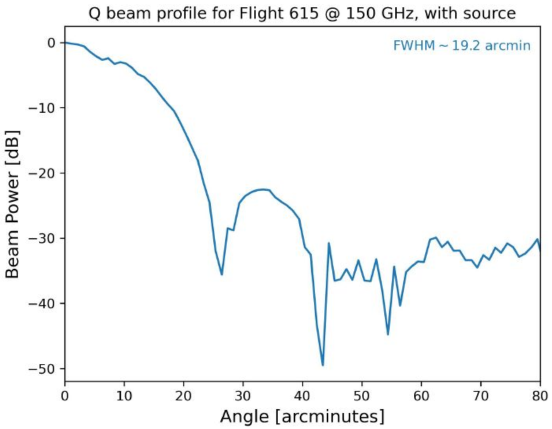
SAT3



Q beam for SAT1 @ 150 GHz



FWHM ~ 19.2 arcmin
Ideal: 17.6 arcmin



First drone maps done with SO-SAT already allow us to characterize fundamental properties of the beam and of the telescope performance.

The measured beam sizes are consistent with the expected values if the pointing errors are considered.

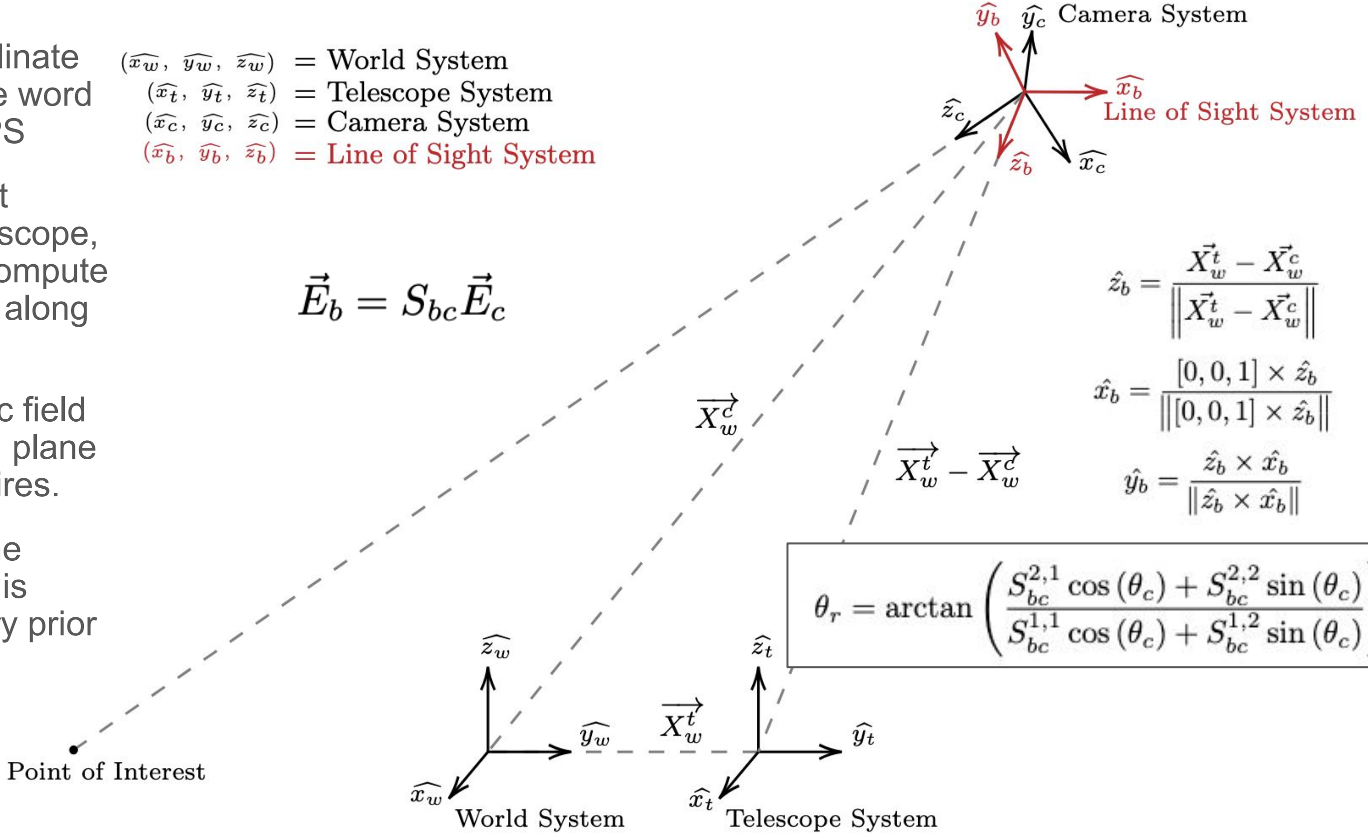
Fin

Coordinate system reconstruction

- The camera (source) coordinate system is determined in the word system provided by the GPS
- Given that the source is not pointing directly to any telescope, a correction is needed to compute the roll angle of the source along the line of sight.
- We assume that the electric field is aligned with the wire grid plane and perpendicular to the wires.
- The angle of the wires in the camera coordinate system is determined in the laboratory prior to the flight.

$(\widehat{x_w}, \widehat{y_w}, \widehat{z_w})$ = World System
$(\widehat{x_t}, \widehat{y_t}, \widehat{z_t})$ = Telescope System
$(\widehat{x_c}, \widehat{y_c}, \widehat{z_c})$ = Camera System
$(\widehat{x_b}, \widehat{y_b}, \widehat{z_b})$ = Line of Sight System

$$\vec{E}_b = S_{bc}\vec{E}_c$$



$$\hat{z}_b = \frac{\vec{X_w^t} - \vec{X_w^c}}{\left\|\vec{X_w^t} - \vec{X_w^c}\right\|}$$

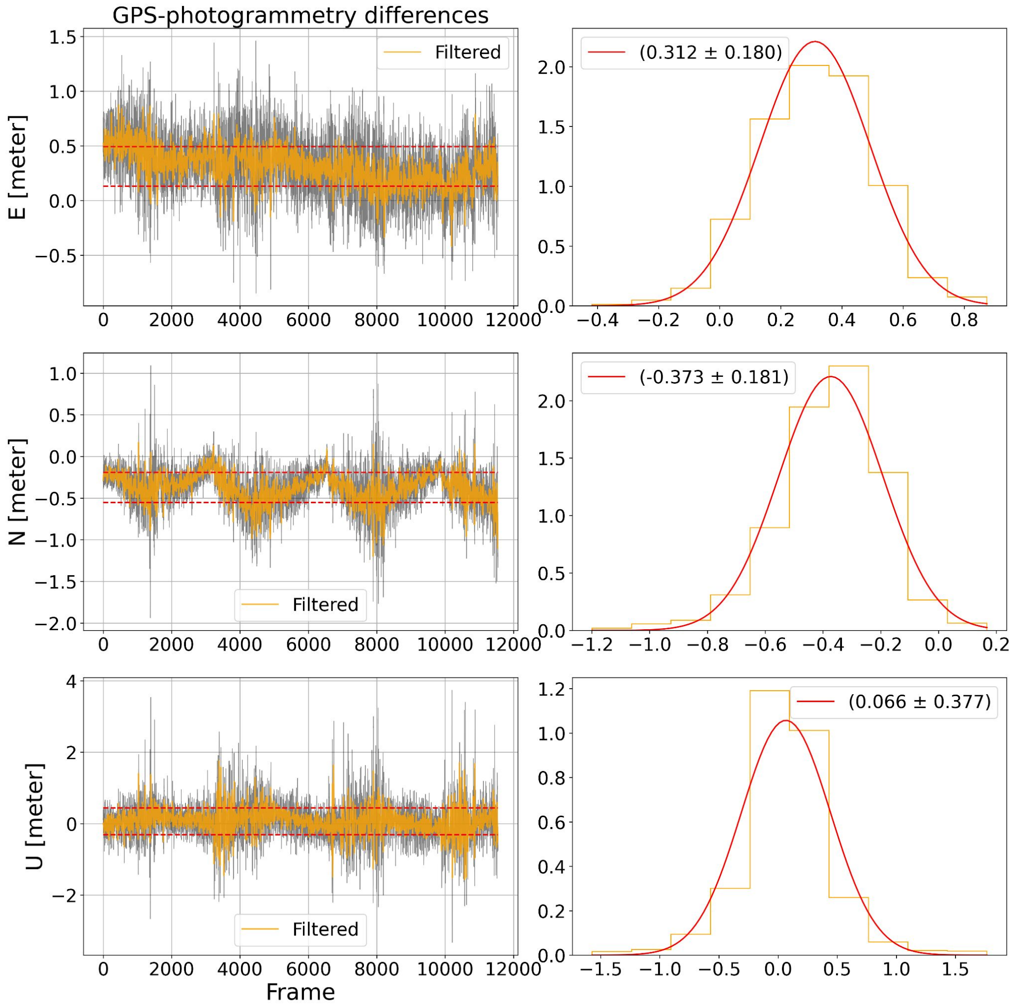
$$\hat{x}_b = \frac{[0,0,1] \times \hat{z}_b}{\left\|[0,0,1] \times \hat{z}_b\right\|}$$

$$\hat{y}_b = \frac{\hat{z}_b \times \hat{x}_b}{\left\|\hat{z}_b \times \hat{x}_b\right\|}$$

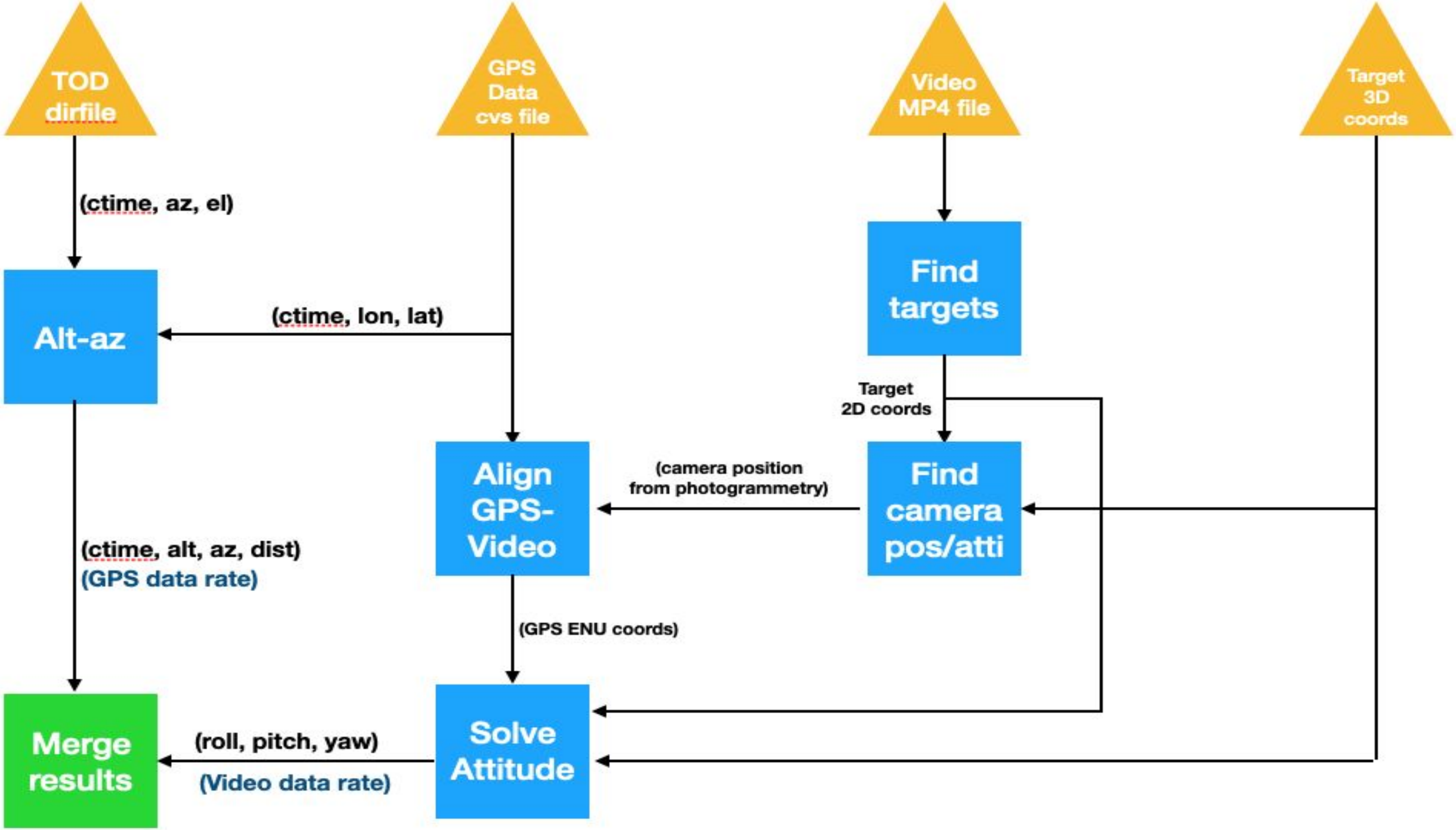
$$\boxed{\theta_r = \arctan\left(\frac{S_{bc}^{2,1}\cos(\theta_c) + S_{bc}^{2,2}\sin(\theta_c)}{S_{bc}^{1,1}\cos(\theta_c) + S_{bc}^{1,2}\sin(\theta_c)}\right)}$$

GPS - Photogrammetry difference of ENU coordinates

- We repeat the previous analysis on the ENU cartesian coordinates of the source
- The orange lines is the average every 10 points.
- The mean and standard deviation are shown both in the right panels and in the left.
- The position error, including systematic effects, is less than 40 cm.



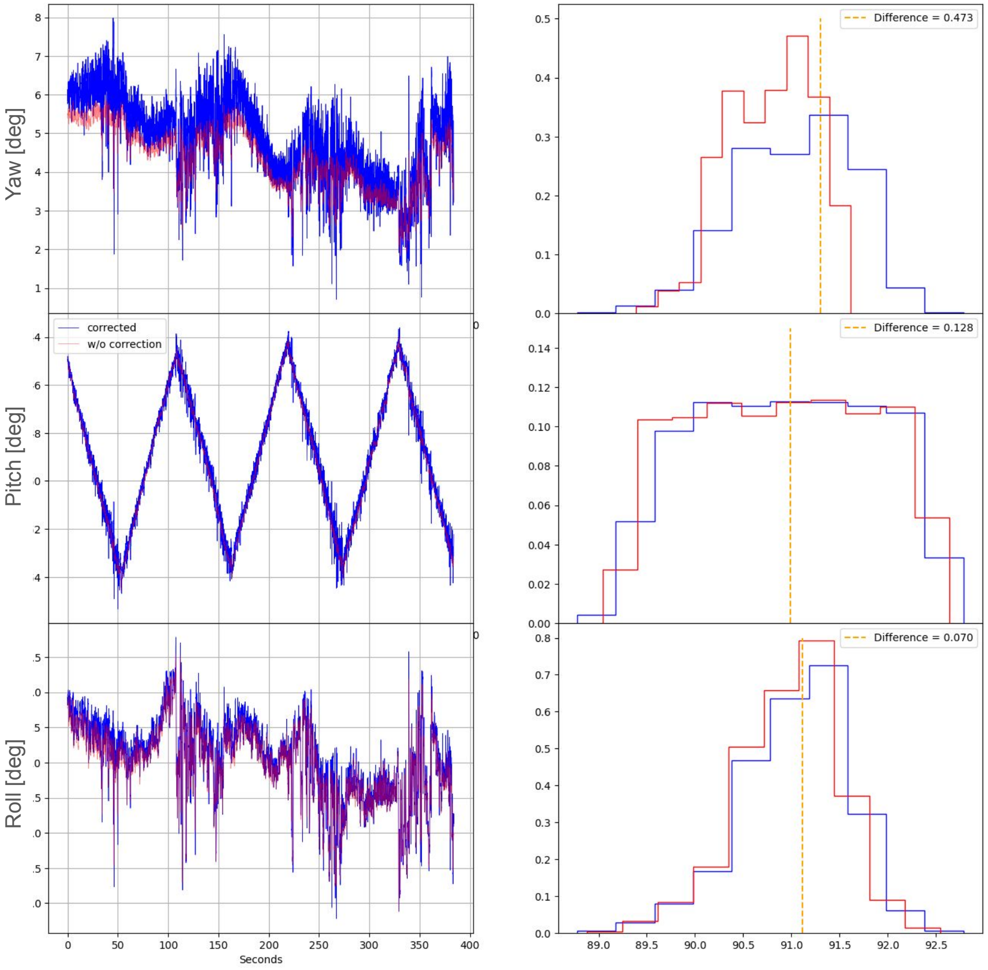
Data reduction pipeline



GPS - Photogrammetry incidence on attitude determination

Compare the attitude obtained using photogrammetry alone vs forcing the position to be determined by the GPS

- Photogrammetry suffers from a strong correlation between angles and position.
- This is solved by forcing the solver to use the GPS position in the photogrammetry fit.
- The effect in the attitude is small, less than 0.5 degrees in yaw, and less than 0.07 degrees in roll.

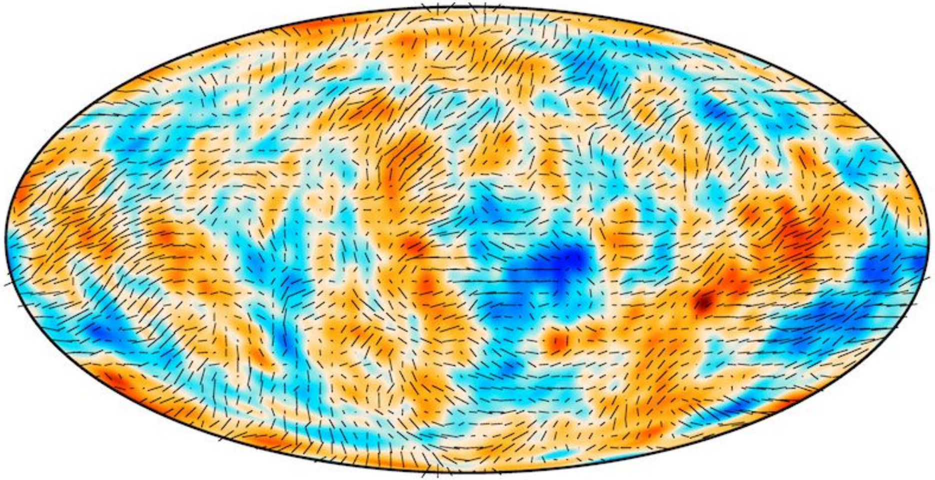


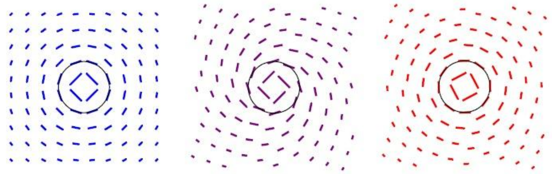
Motivation

Absolute polarization angle calibration

- Standard models predict null TB and EB power spectra.
- These correlations may provide hints for non-standard physics, or may be due to instrumental systematics.
- To detect new physics we need to calibrate the absolute polarization angle of CMB telescopes to better than 0.1 degrees.
- The lack of well suited natural calibrators justifies the development of artificial alternatives.
- Our approach is to develop a UAV-based calibration source.

Sky map of CMB polarization measured by the Planck satellite (2018).





Polarization maps illustrating the rotation of photon polarization. Credit: Liang Dai. ©2014 American Physical Society

Topics

- Scientific need for better polarization angle determination of CMB telescopes
- HoverCal + PoloCalC: general project description
  - Collaboration with SO and CLASS (ACT, Polarbear)
  - Independent measurement. Artificial source.
- Metrology system:
  - RTK GPS accuracy (pointing analysis) (Rolando)
  - Photogrammetry accuracy (errors in position reconstruction from photo vs GPS, roll, pitch, yaw from lab test, statistical analysis of photogrammetry angle reconstruction) (Federico Astori)
  - Roll angle error estimation (Gabriele)
    - Camera calibration
  - Wiregrid angle determination (laboratory tests) (Matías, Gabriele)
- Site campaigns:
  - Flight programs and methodology
  - ALMA green light
  - Future plans
- Preliminary results:
  - CLASS pointing accuracy (Rolando, Yunyang)
  - SO pointing accuracy – wobble effect discovery (Rolando, Carlos, Nadia)
  - Photogrammetry angle determination (Federico Astori, Yunyang, Rolando, Gabriele)
  - First polarization angle measurements for CLASS (Yunyang, Rolando)

Preliminary Error Budget

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

$\boldsymbol{\sigma_{align}}$ = 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

$\sigma_{beam} < 0.001°$

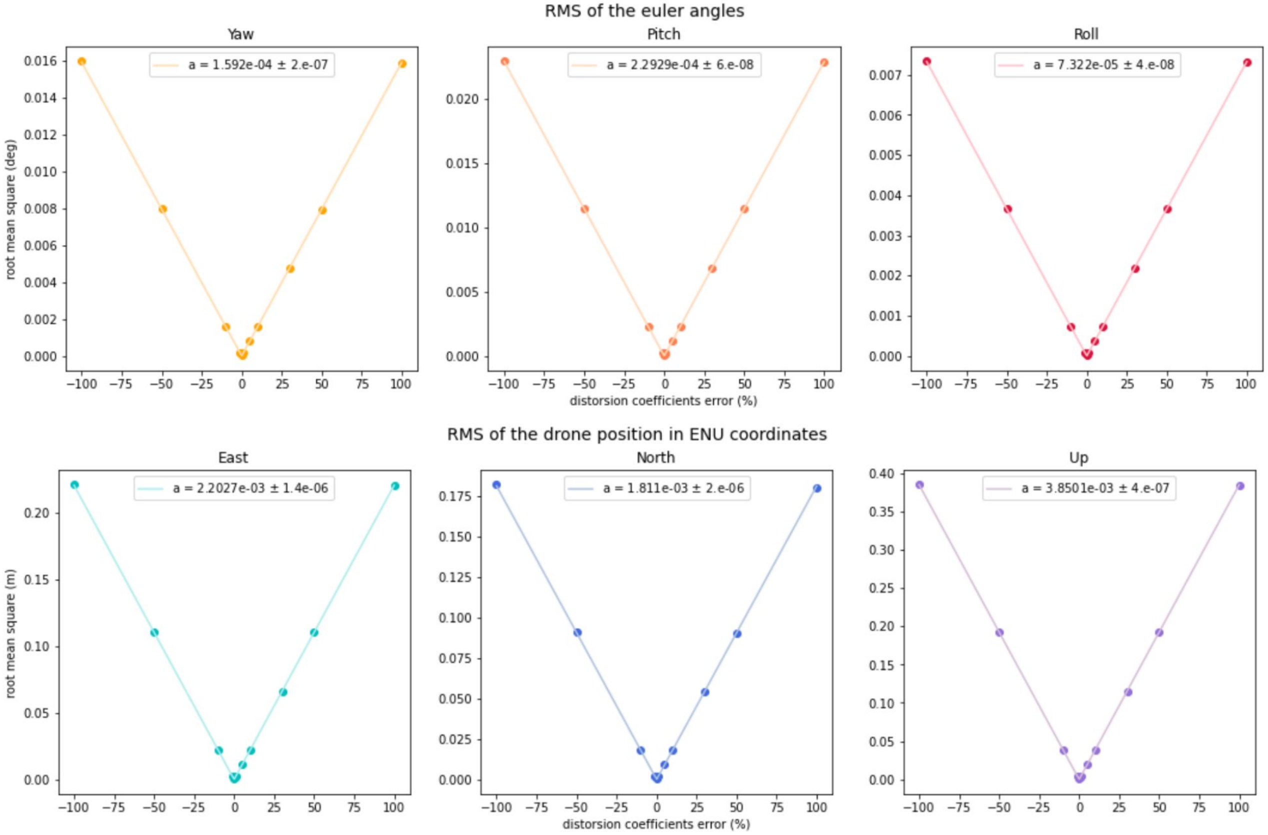
HWP position readout accuracy

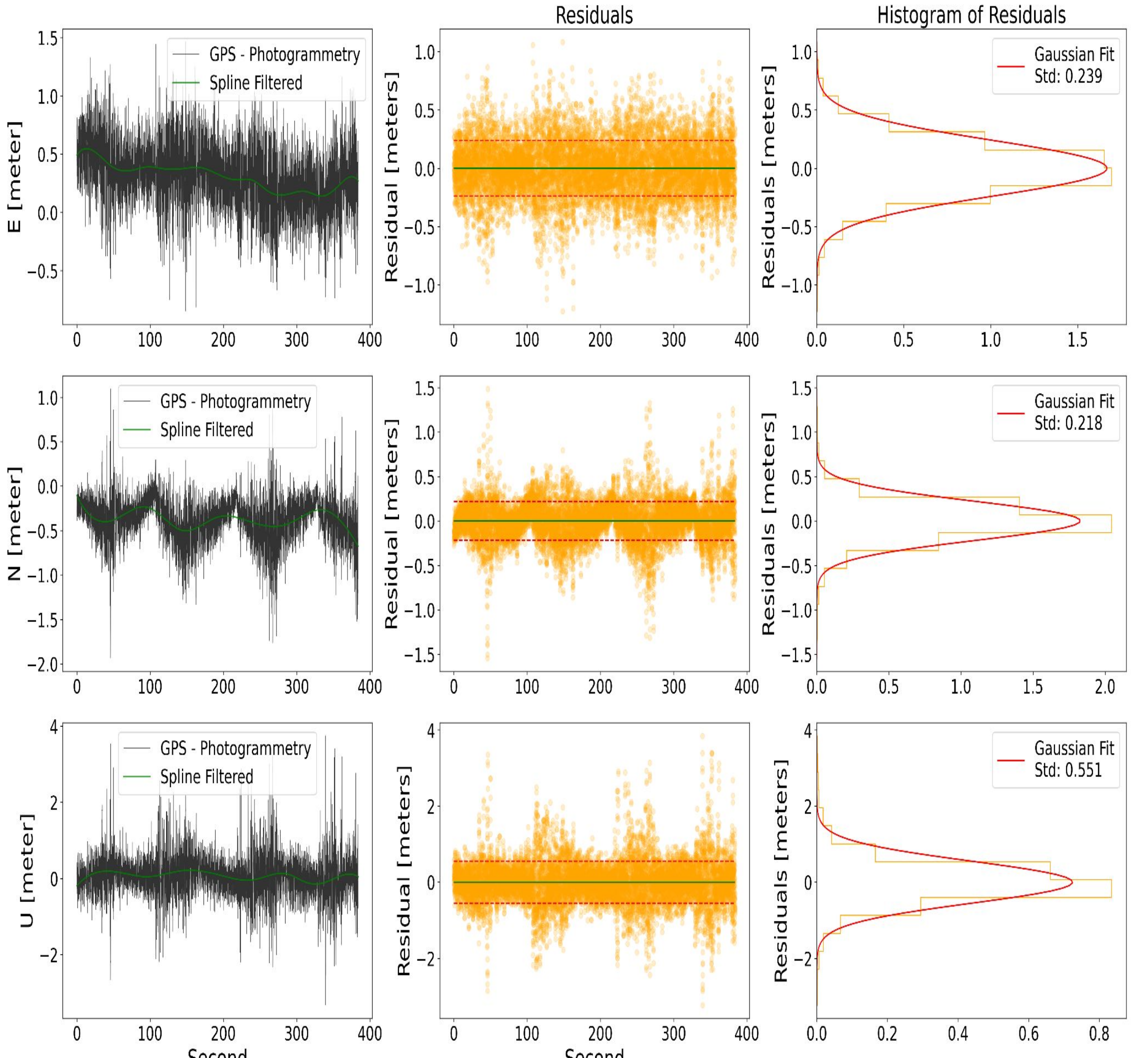
$\sigma_{HWP} << 0.001°/\sqrt{Hz}$

Radiation coupler, electronics:

$\sigma_{syst} \sim 0.001°$

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


RMS of the euler angles
Yaw
Pitch
Roll
a = 1.592e-04 ± 2.e-07
a = 2.2929e-04 ± 6.e-08
a = 7.322e-05 ± 4.e-08
root mean square (deg)
distorsion coefficients error (%)
RMS of the drone position in ENU coordinates
East
North
Up
a = 2.2027e-03 ± 1.4e-06
a = 1.811e-03 ± 2.e-06
a = 3.8501e-03 ± 4.e-07
root mean square (m)
distorsion coefficients error (%)



Residuals
Histogram of Residuals
GPS - Photogrammetry
Spline Filtered
Gaussian Fit
Std: 0.239
Std: 0.218
Std: 0.551
E [meter]
N [meter]
U [meter]
Residual [meters]
Residuals [meters]
Second