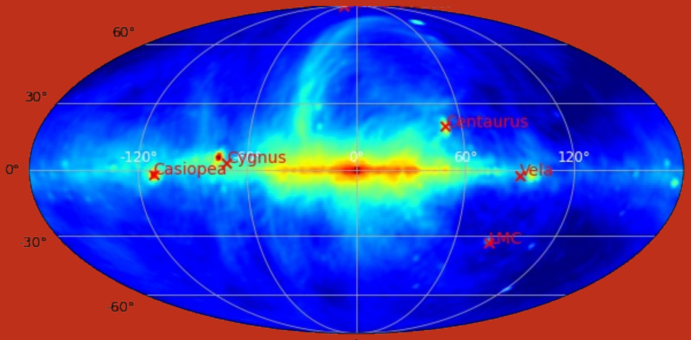
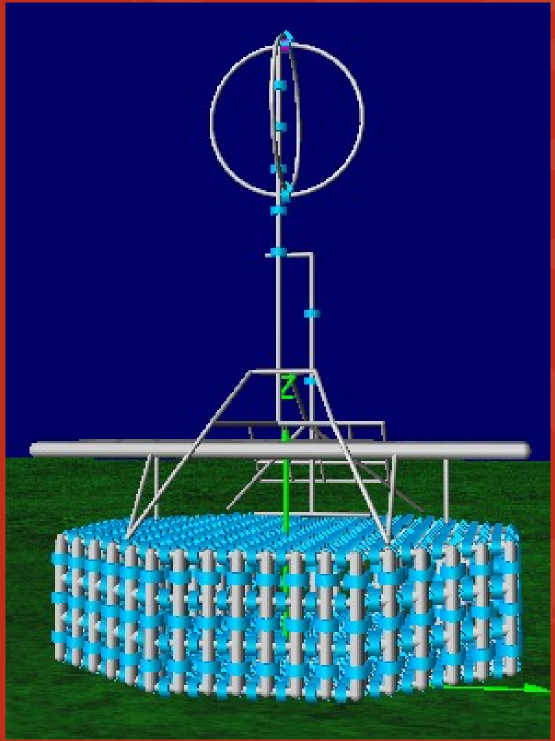
AugerPrime Radio Detector
Antenna Uncertainty





Supported by:

European Research Council

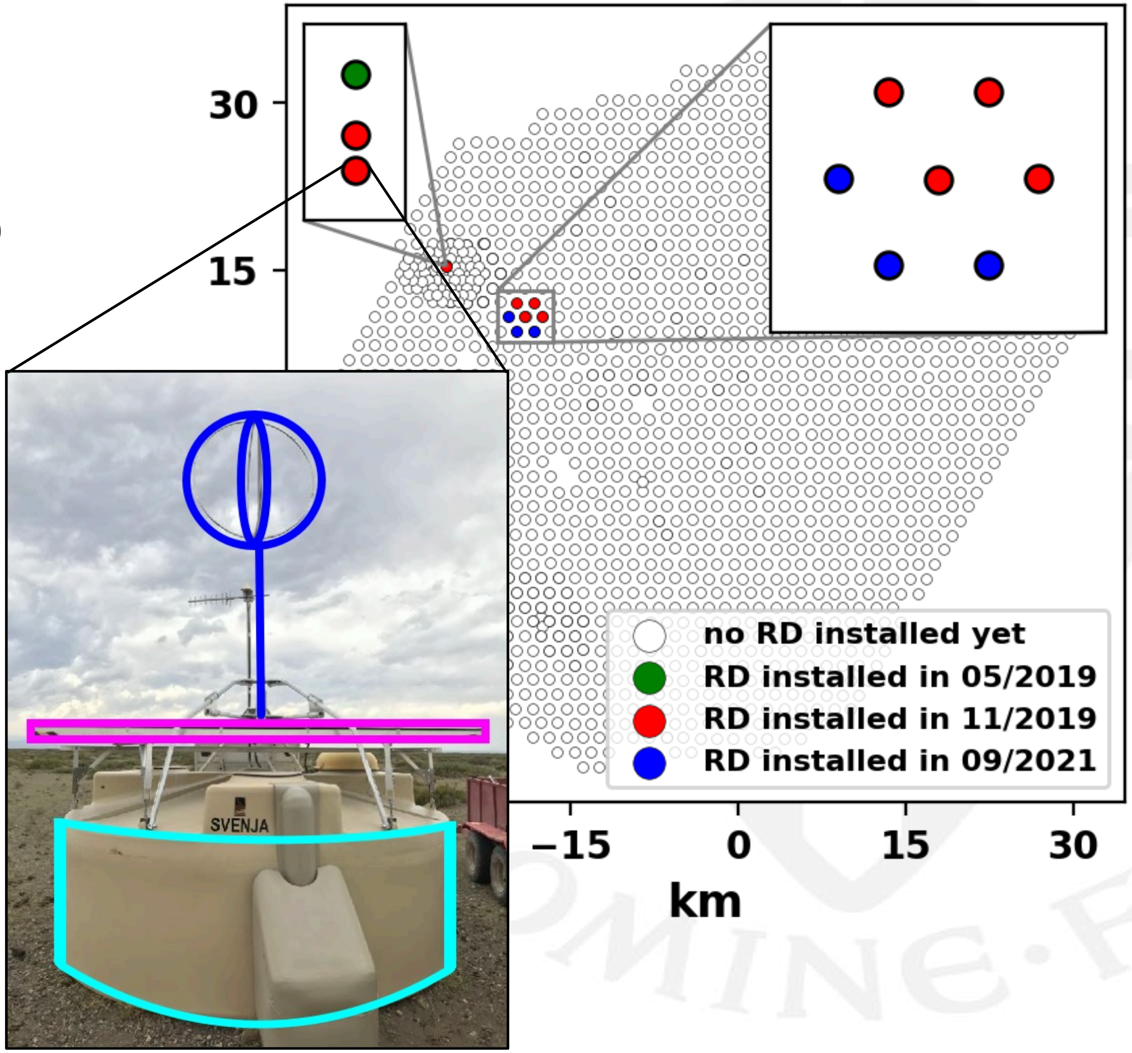
project number 787622

Tomáš Fodran for the Pierre Auger Collaboration

Pierre Auger Observatory upgrade - AugerPrime

- **AugerPrime upgrade - the Surface Detector stations will get a:**
  - ✓ Radio Detector (RD) antenna
  - ✓ Surface scintillator detector (SSD)
  - ✓ Small photo-multiplier tube to the water-Cherenkov detector (WCD)
- **Main Goal:** Primary particle mass decomposition.
- **RD purpose:** electromagnetic energy measurements above 60° zenith angles.
- **Current status:** 10/1661 RD antennas are installed and ongoing mass production.

- **For technical details on RD see Julian Rautenberg's slides:** https://indico.cern.ch/event/826366/contributions/4885838/
- **For details on RD antenna pattern see Ugo Giaccari's slides:** https://indico.cern.ch/event/826366/contributions/4880758/
- **For expected performance of the RD see Felix Schlüter's slides:** https://indico.cern.ch/event/826366/contributions/4880764/



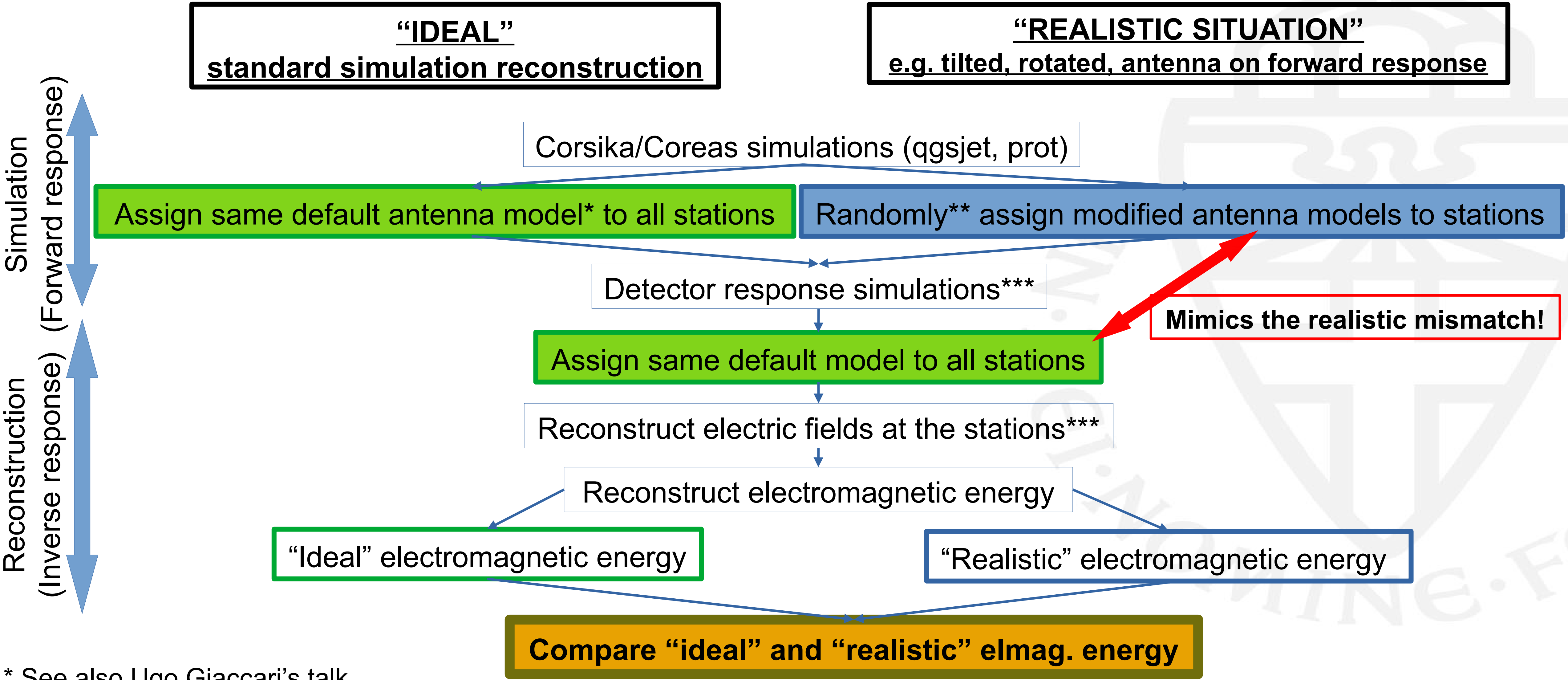
Upgraded SD station. The RD antenna is in blue, the SSD in pink, the WCD is turquoise

AugerPrime Radio Detector uncertainty

- Event-to-event reconstruction antenna uncertainty
  - Mismatch between the antenna model and the real construction.
  - How to objectively quantify propagated effect of this mismatch to the reconstructed electromagnetic energy?
- Absolute antenna uncertainty
  - Calibration using the Galactic radio emission.
  - Calibration depends on choice of radio sky map, antenna model and fitting method.

Event-to-event reconstruction antenna uncertainty

Event-to-event reconstruction antenna uncertainty - Method



* See also Ugo Giaccari’s talk

** 5 different random seeds are used each time

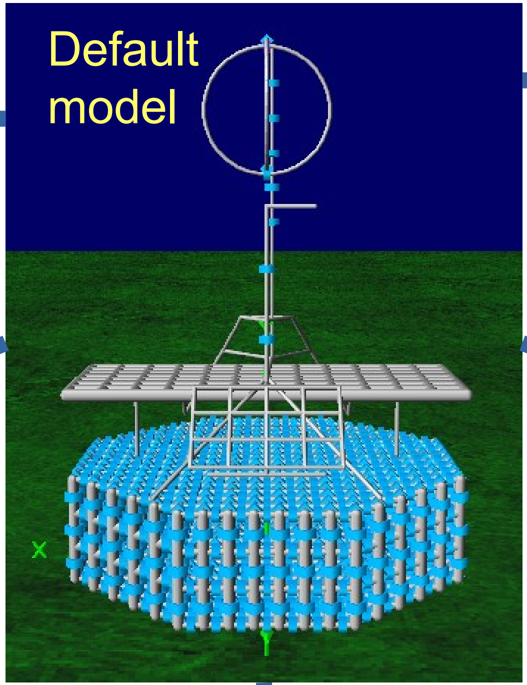
*** MC shower direction is always used!

Antenna Model modifications

- In total 91 modified antenna models were produced.
- Different random seeds were used to generate arrays with modified models.
- The following modified models were used:

Tilted antenna by 1, 2, 3, 4, 5 degrees to cardinal and intercardinal directions*. (8x5=40 models)

Rotated antenna by +/- 1, 2, 3, 4, 5 degrees. (2x5=10 models)

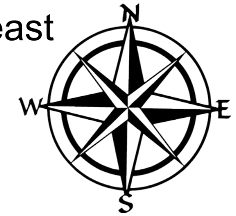


Tilted station by 1, 2, 3 degrees to cardinal and intercardinal* directions (8x3=24 models)

Shifted SSD and SP to east, west, north, south and “up” (2x5=10 models)

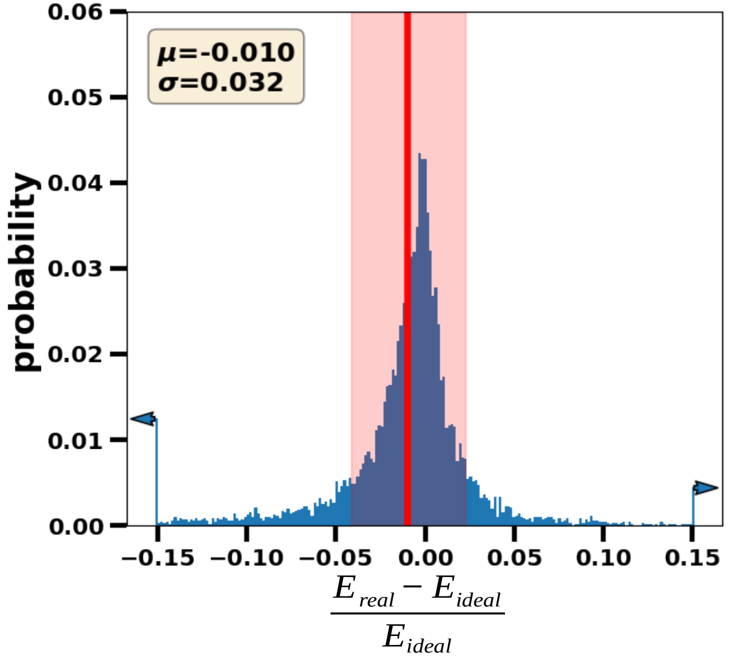
Different grounds (7 models)

*Cardinal: north, south, west, east
Intercardinal: NW, NE, SW, SE

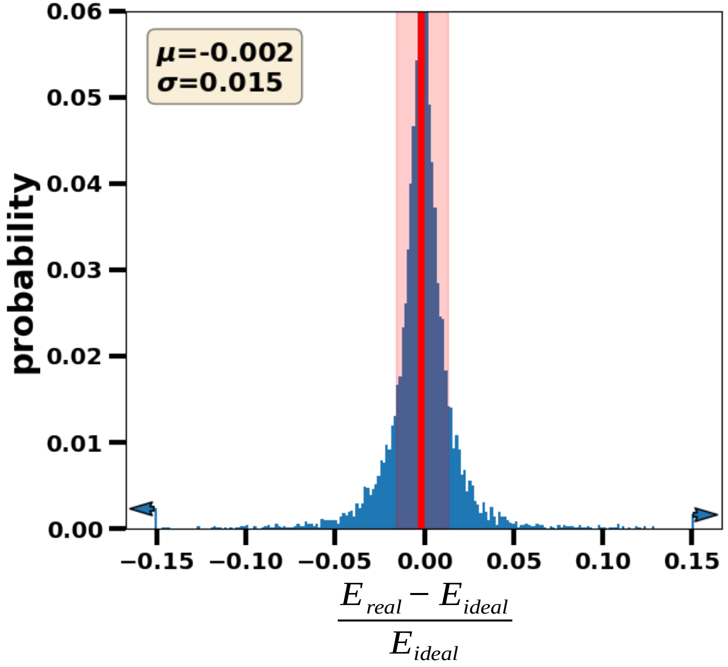


Results – arrays with variously modified models

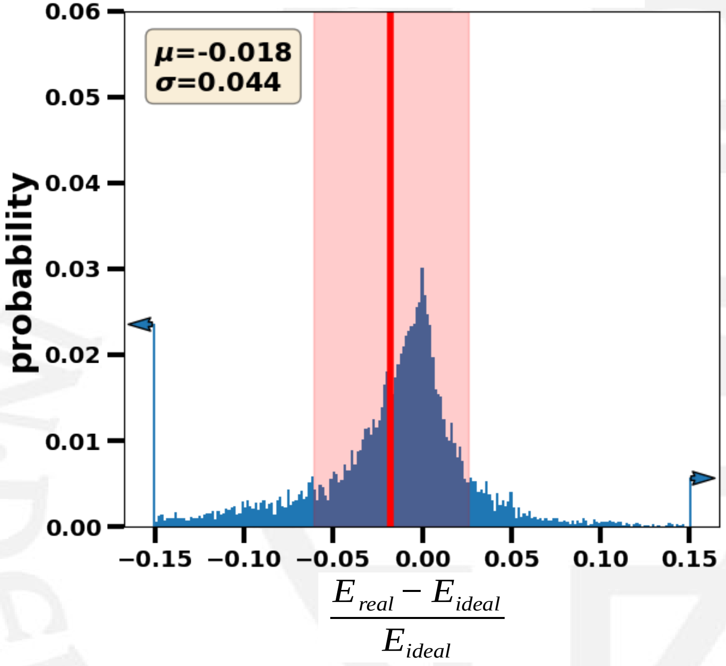
All modified models are used



Only models with modified geometry



Only modified with changed ground



- Histograms indicate differences of reconstructed electromagnetic energy between arrays with forward:default<->inverse:default and forward:modified<->inverse:default models.
- Ground (~4% uncertainty) seem to be more important factor than the geometry (<2% uncertainty)
- With increasing zenith angle, the uncertainty caused by deviated geometry becomes smaller.
- Very conservatively, the error caused by the antenna modeling should not be bigger than 5%.

Absolute antenna uncertainty

Absolute galactic calibration – method & results

Method

1) **Simulate galactic signal seen by the radio station using the galactic map, antenna model and measured HW response**

2) **Fit the simulated galactic signal with the measured noise to derive the calibration constant**

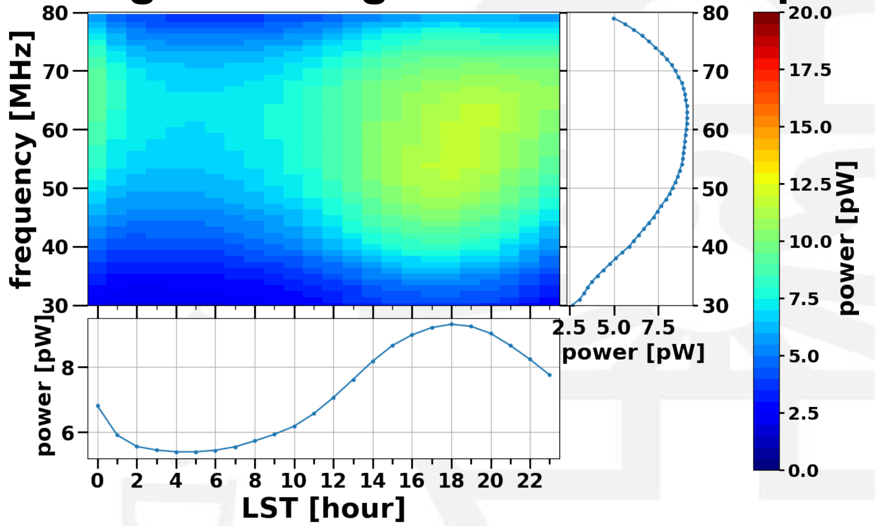
   (for details on the fitting methods see Rogerio Menezes de Almeida's slides: https://indico.cern.ch/event/826366/contributions/4877946/)

- **We used 5 different maps, <u>17 different antenna models</u> and 4 different fitting methods; this gives in total 340 constants which we then smeared by the underlying uncertainty of the map**

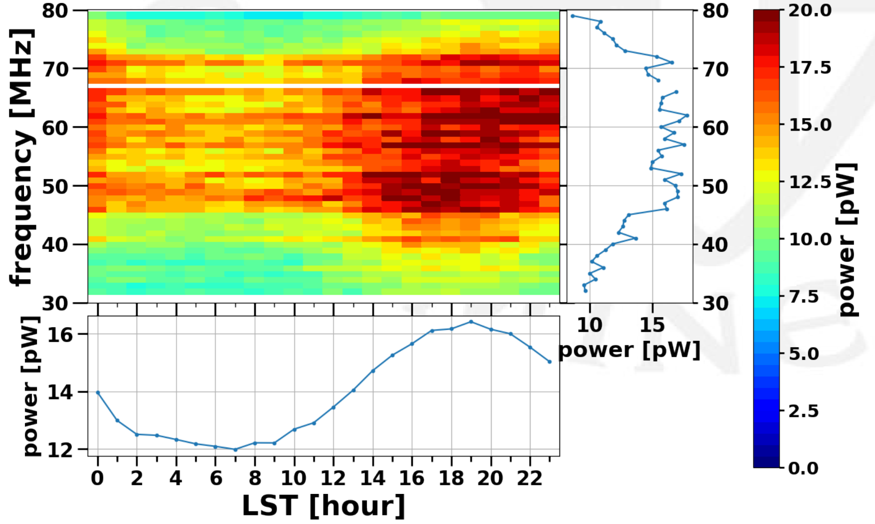
Results

- **EW calibration constant: 1.03 ± 9.6% ± 2%**
- **NS calibration constant: 0.96 ± 9.7% ± 2%**
- **<u>Uncertainty caused by the Antenna model: max 1.5%</u>**
- **For more details see this proceeding: https://pos.sissa.it/395/**

Simulated galactic signal in the EW loop

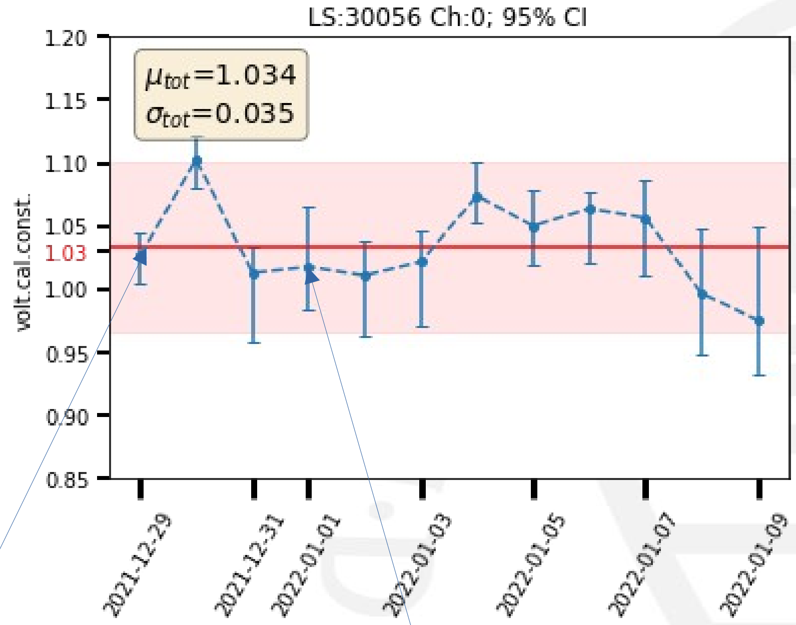


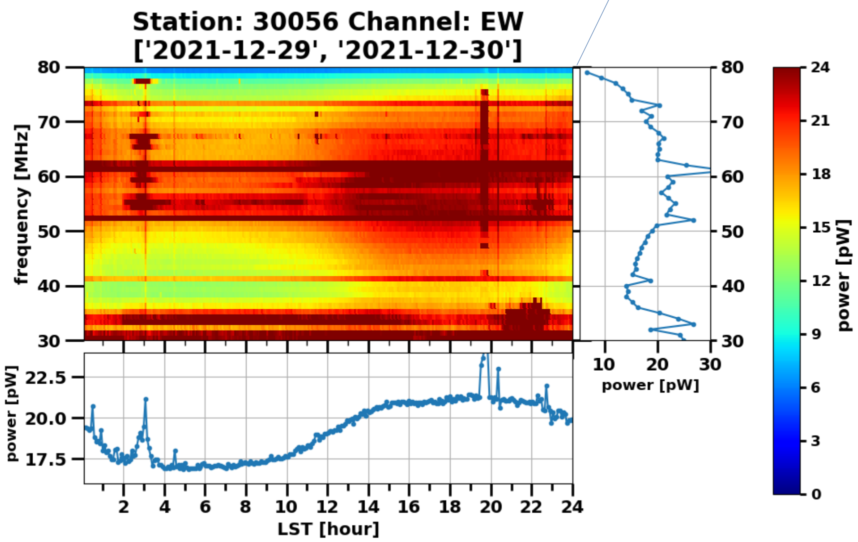
Measured noise & galactic signal in the EW loop

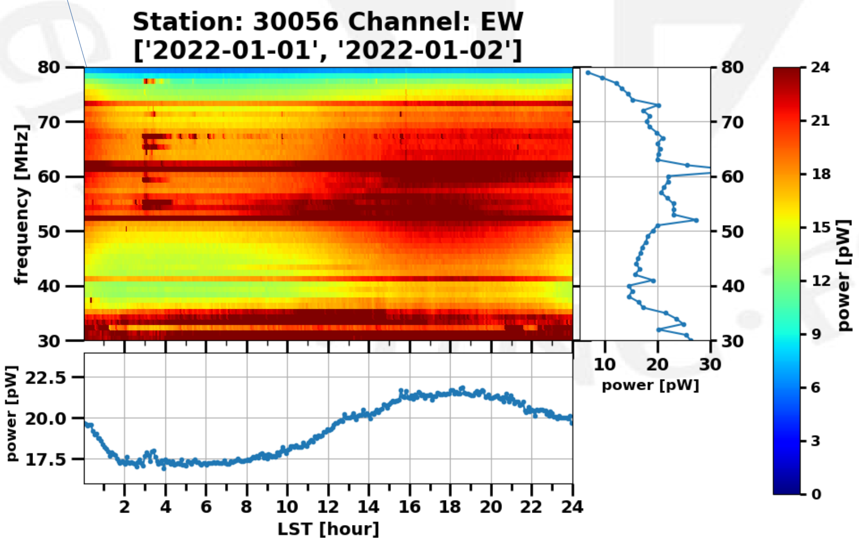


Towards the Daily Absolute Galactic calibration

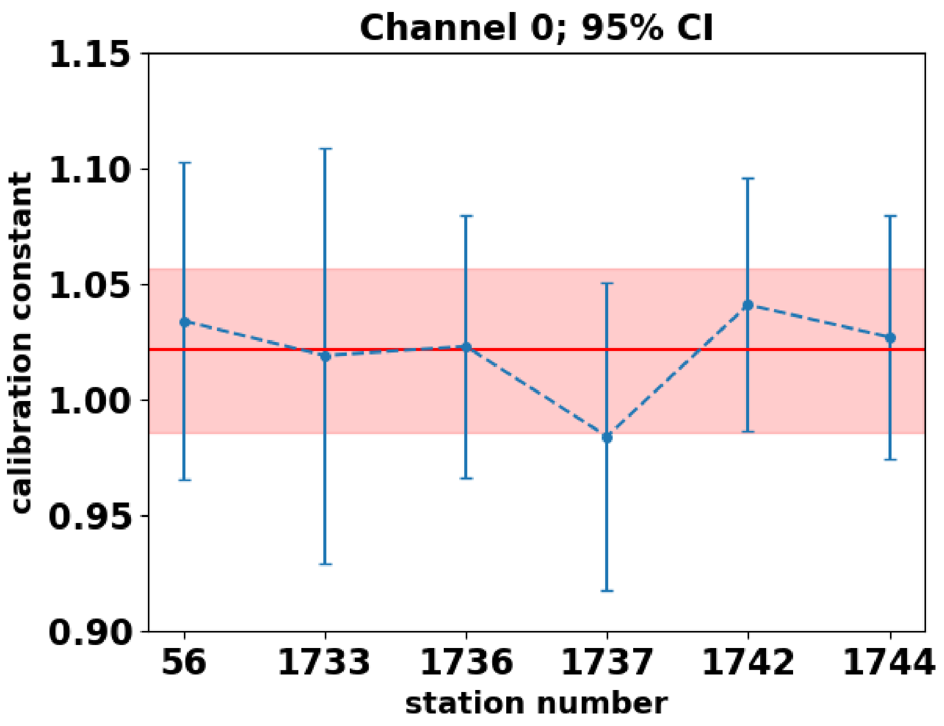
- Online rapid spectra averaging done directly in the FPGA (Field Programmable Gate Arrays)
- Every 5 minutes thousands of spectra are averaged
- Daily datasets are still better in compare to what we had after 4 months with triggered data.
- Data are suitable for a daily calibration.

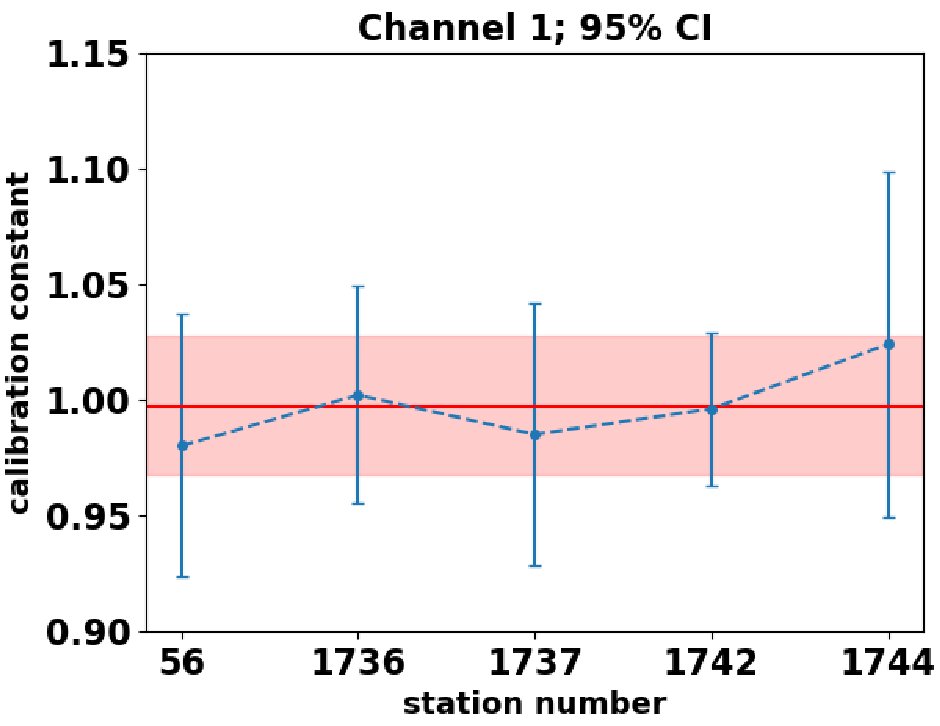






Station-to-station fluctuations





- Here we averaged the daily stations calibration constants (12 days)
- Red horizontal line is average calibration constant of all stations
- All stations are within the 95% confidence interval
- No outliers

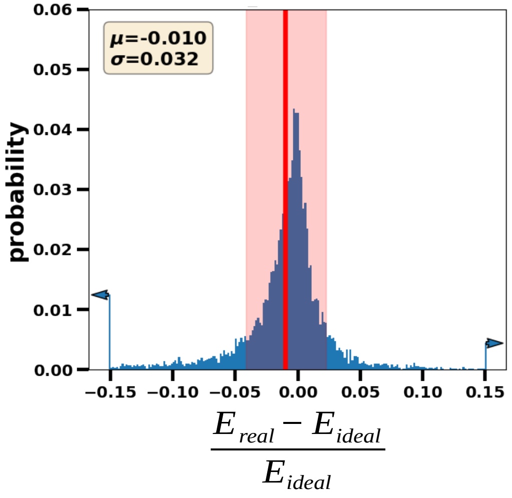
Conclusion

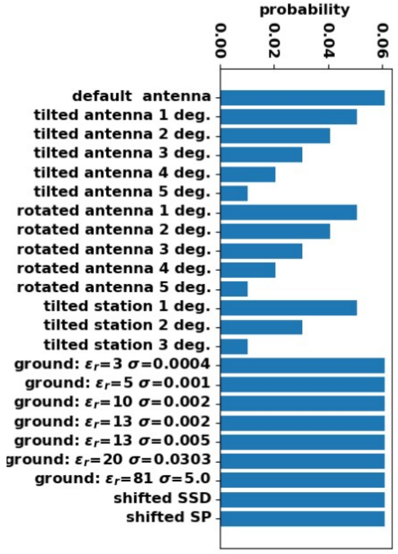
- ✓ **Ground is the most significant factor in the modeling (~4% deviation)**
- ✓ **Geometric antenna uncertainties are less relevant than ground (<2% deviation)**
- ✓ **Geometric antenna uncertainties decrease with increasing zenith angle**
- ✓ **Very conservatively, the uncertainty caused by the antenna modeling should not be bigger than 5%.**
- ✓ **In the absolute galactic calibration, the antenna model causes an uncertainty of less then 1.5%.**
- ✓ **Daily galactic calibration looks promising; double use: both as a <u>calibration</u> tool and as a <u>monitoring</u> tool.**

BACKUP

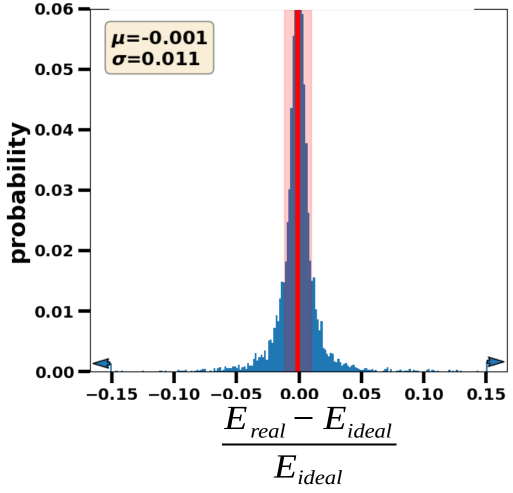
Results – arrays with variously modified models

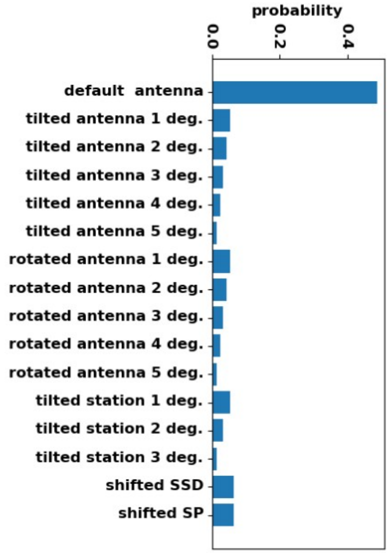
All modified models are used

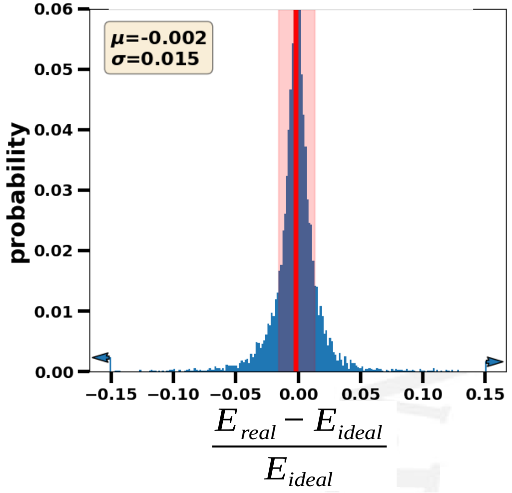


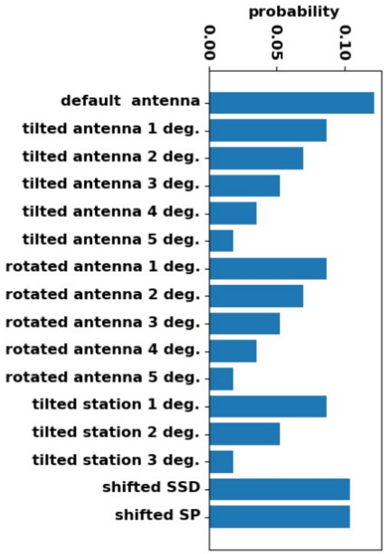


Only modified geometry

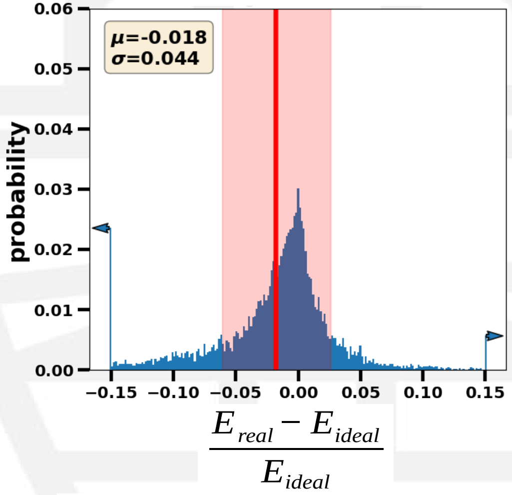


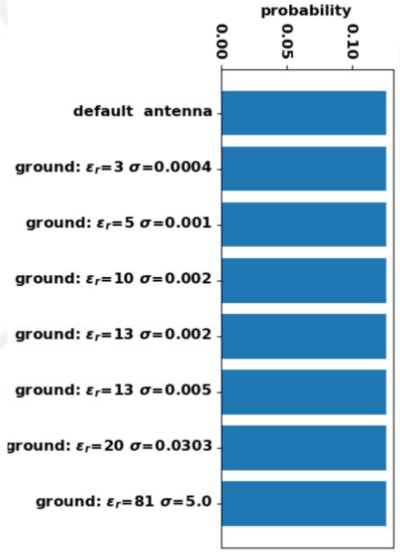




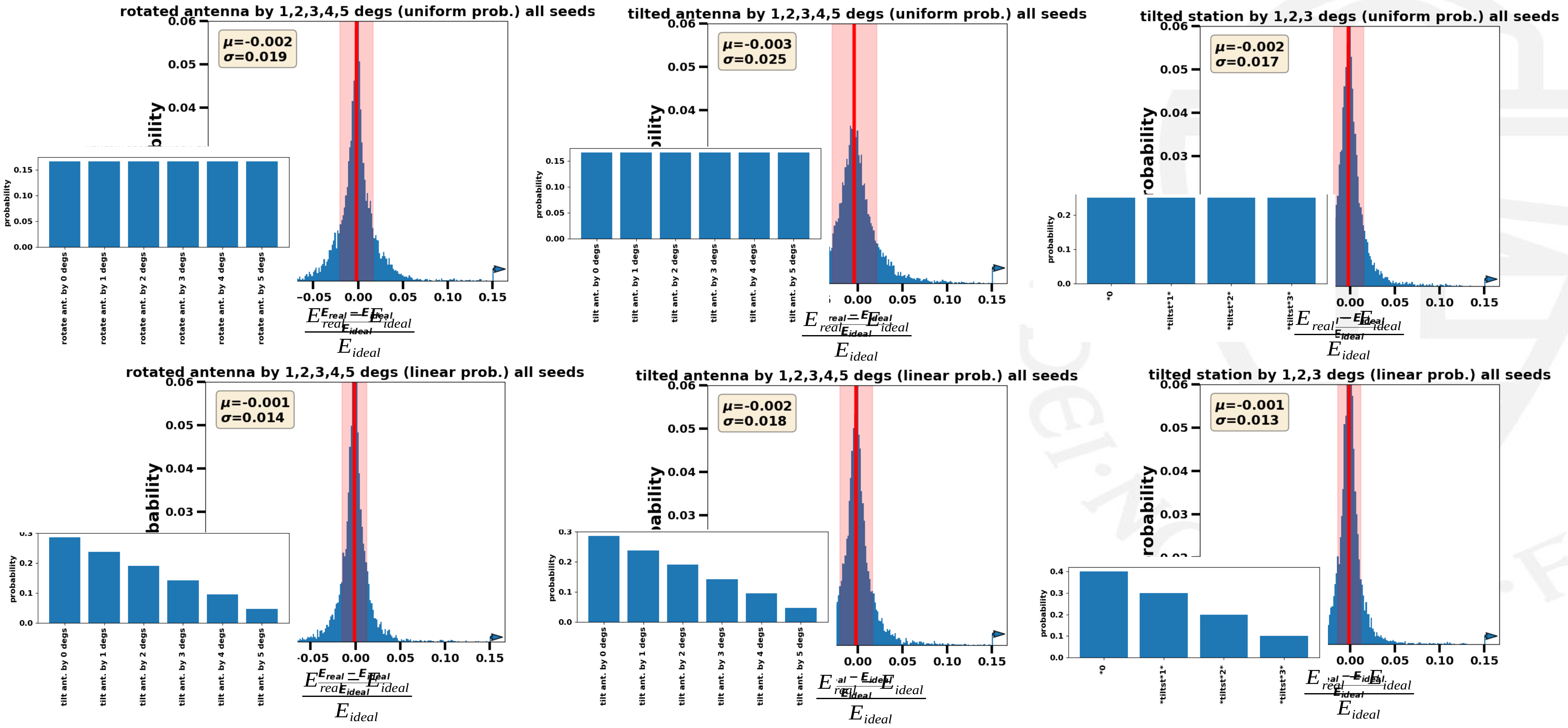


Only modified ground

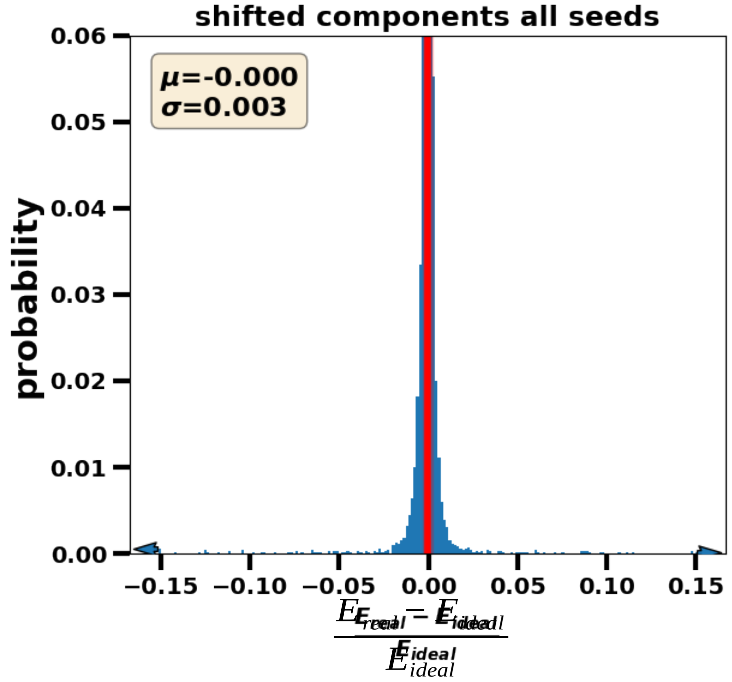


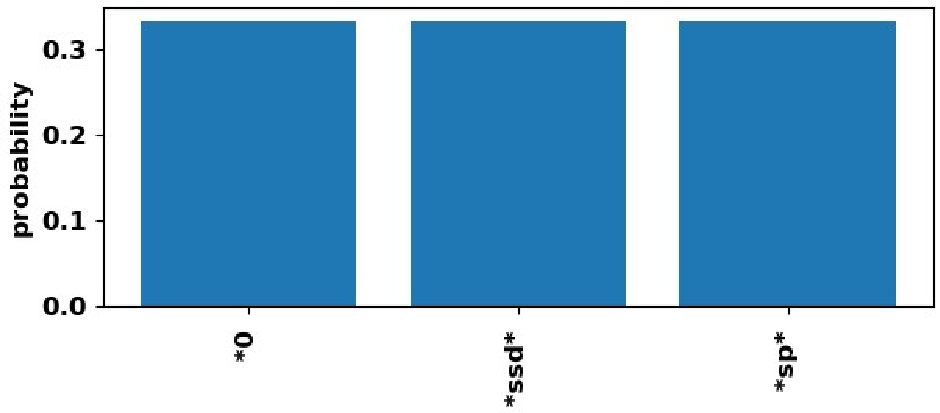


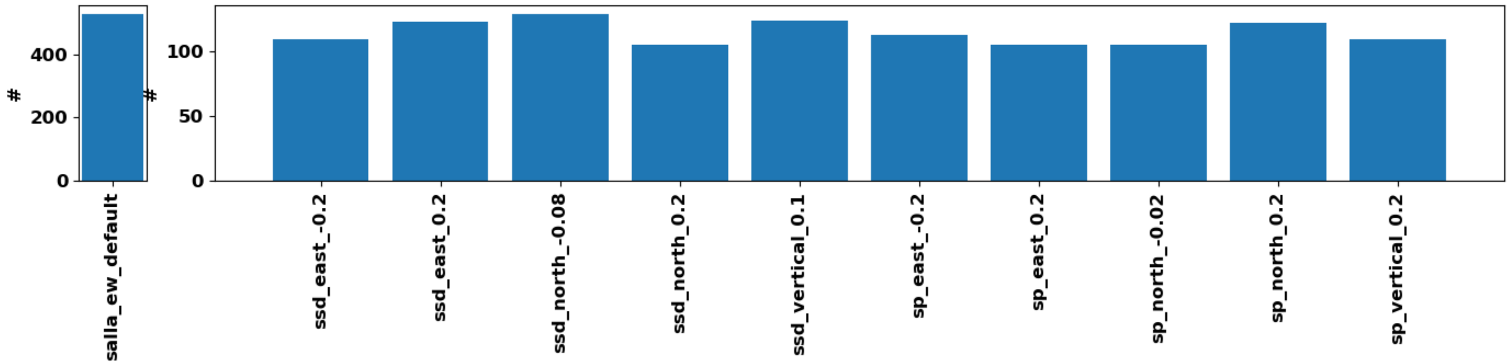
More Results – Modified geometry



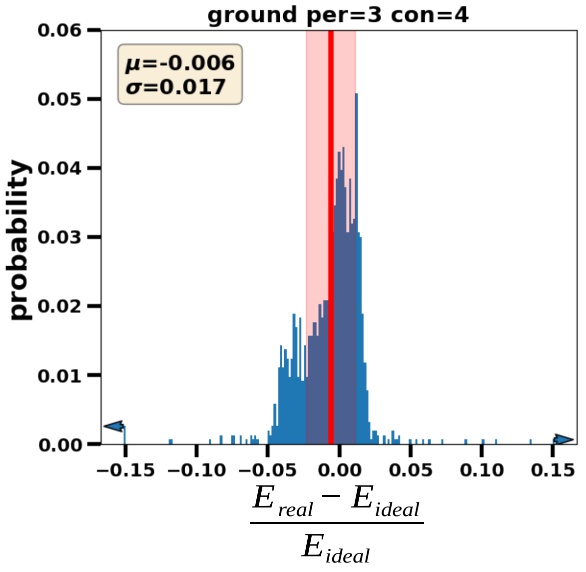
Shifted components

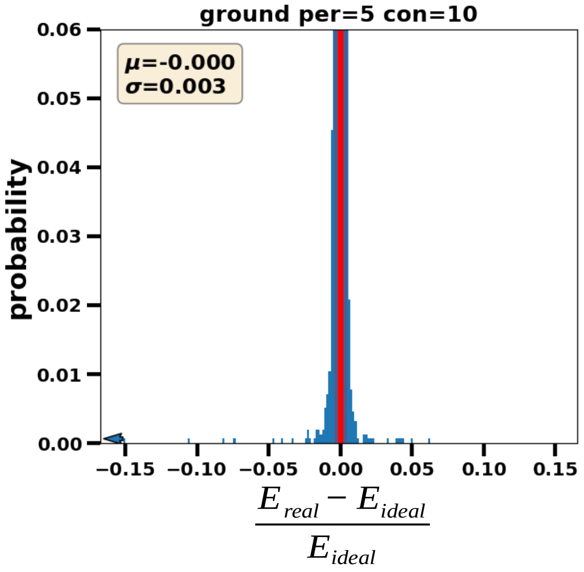


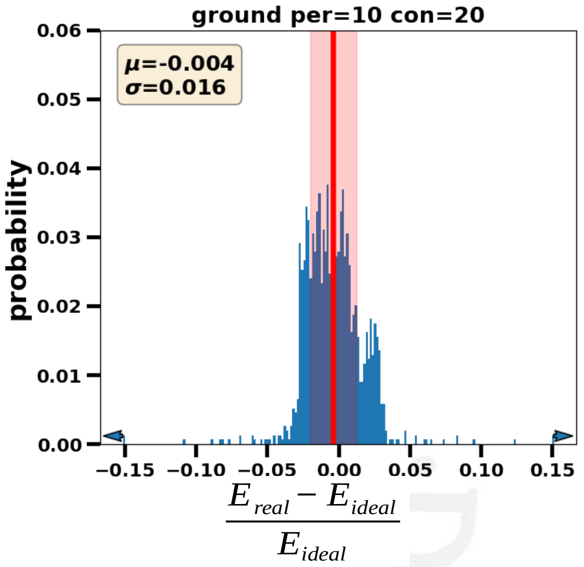


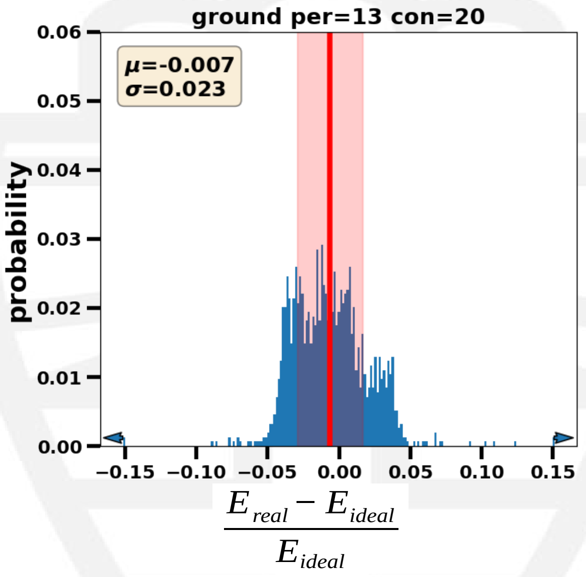


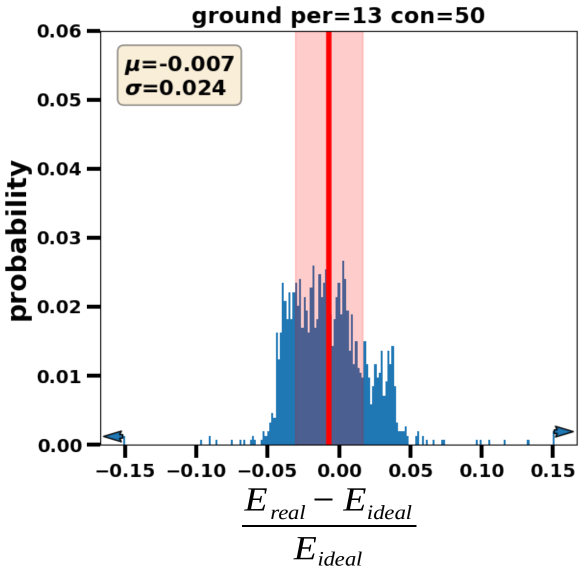
Modified grounds

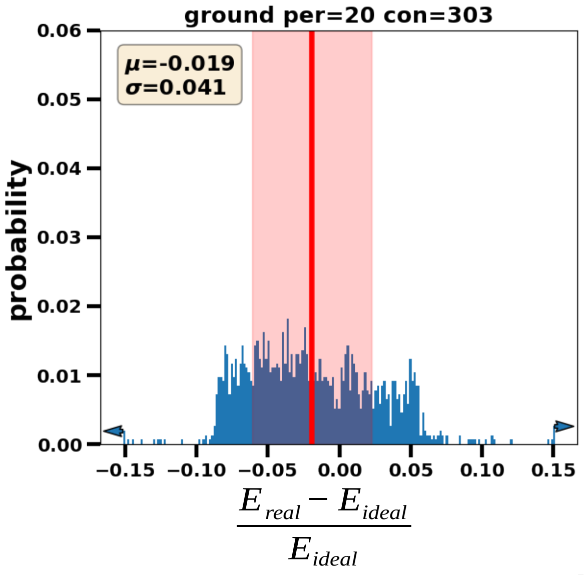


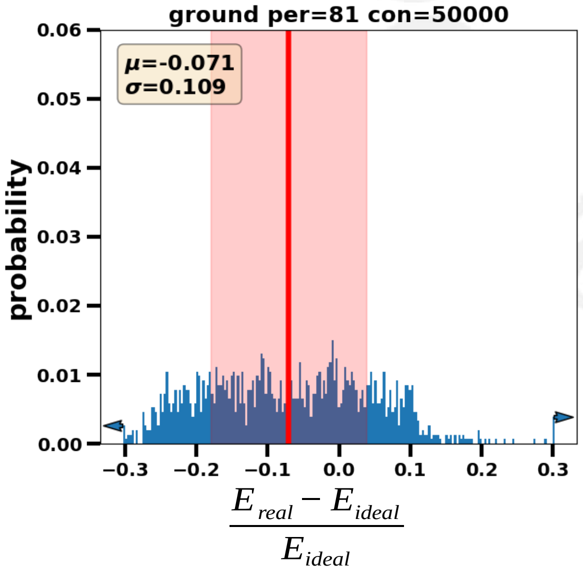












*Default model:
per=5.5 con=14
** con is in EC unit,
to convert to S/m divide by 10000

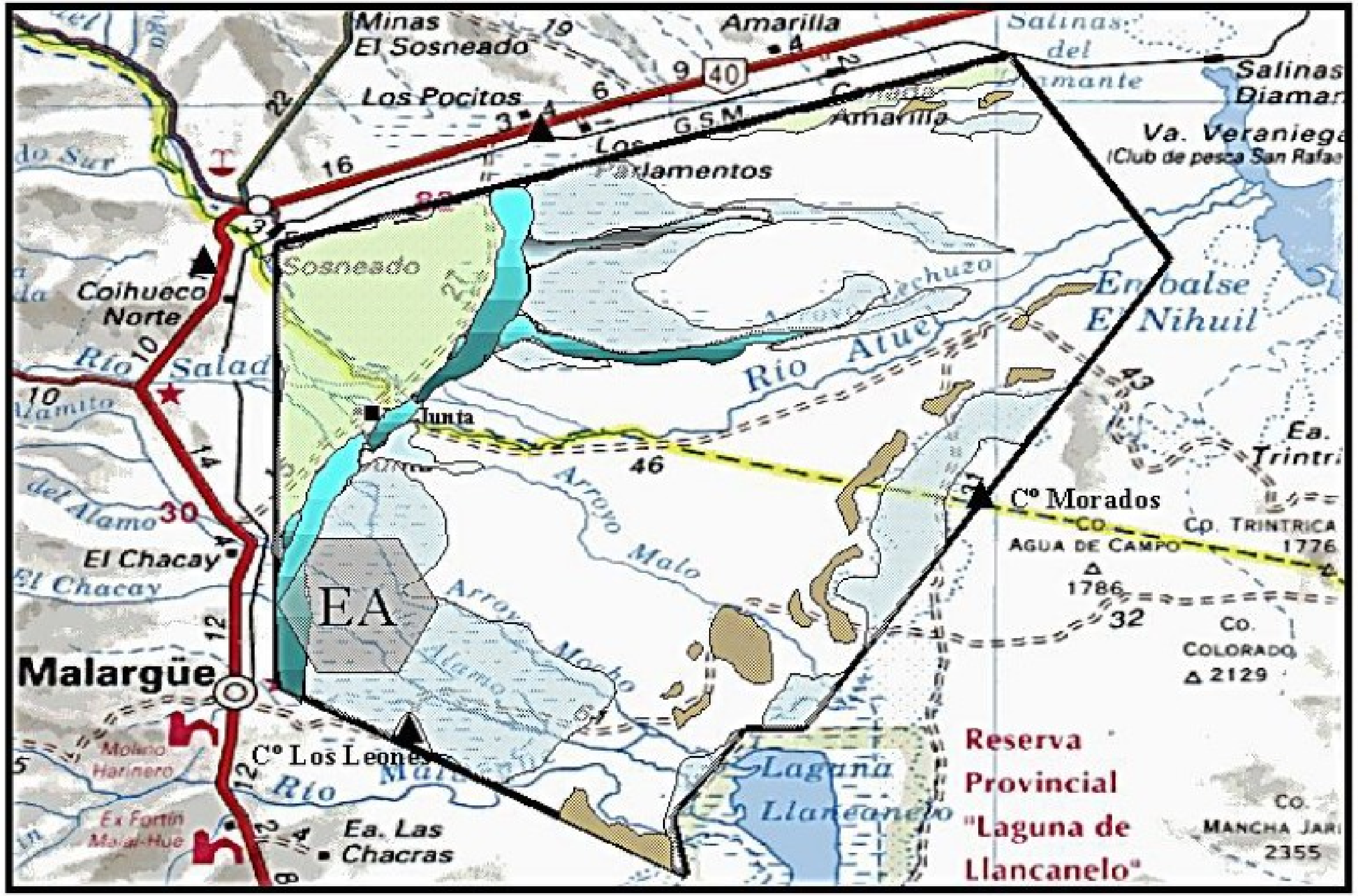
Results of other cases

	all modified models	all modified geometries (48% default model)	all modified geometries (12% default model)	only modified ground	tilted antenna (linearly decaying probability)	tilted antenna (uniform probability)	rotated antenna (linearly decaying probability)	rotated antenna (uniform probability)	tilted station (linearly decaying probability)	tilted station (uniform probability)	shifted components (uniform probability)
Median	-0.0047	-0.0003	-0.0011	-0.0092	-0.0016	-0.0039	-0.0007	-0.0017	-0.0008	-0.0015	-0.0003
Mean	-0.0085	-0.0002	-0.0006	-0.0163	-0.0007	-0.002	-0.0008	-0.0007	0.0002	-0.0015	-0.0002
Standard deviation (STD)	0.0641	0.0374	0.0552	0.0836	0.0537	0.0674	0.0381	0.0497	0.0562	0.0343	0.0284
Truncated Mean (1^{st}-99^{th} percentile)	-0.0096	-0.0009	-0.0015	-0.0176	-0.0017	-0.0035	-0.0014	-0.0019	-0.001	-0.0016	-0.0004
Truncated STD (1^{st}- 99^{th} percentile)	0.0318	0.0109	0.0146	0.0436	0.0183	0.025	0.0137	0.0185	0.0127	0.0168	0.0029
Mean (within +/- 0.15)	-0.0085	-0.0008	-0.0015	-0.0149	-0.0016	-0.0035	-0.0013	-0.0019	-0.001	-0.0014	-0.0005
Standard deviation (within +/- 0.15)	0.0323	0.015	0.0186	0.0413	0.0221	0.0281	0.0177	0.0225	0.017	0.0204	0.0088

- The geometry can result mostly in <2% deviation, ground in ~4%
- Very conservatively, the error caused by the antenna modeling should not be bigger than 5%.

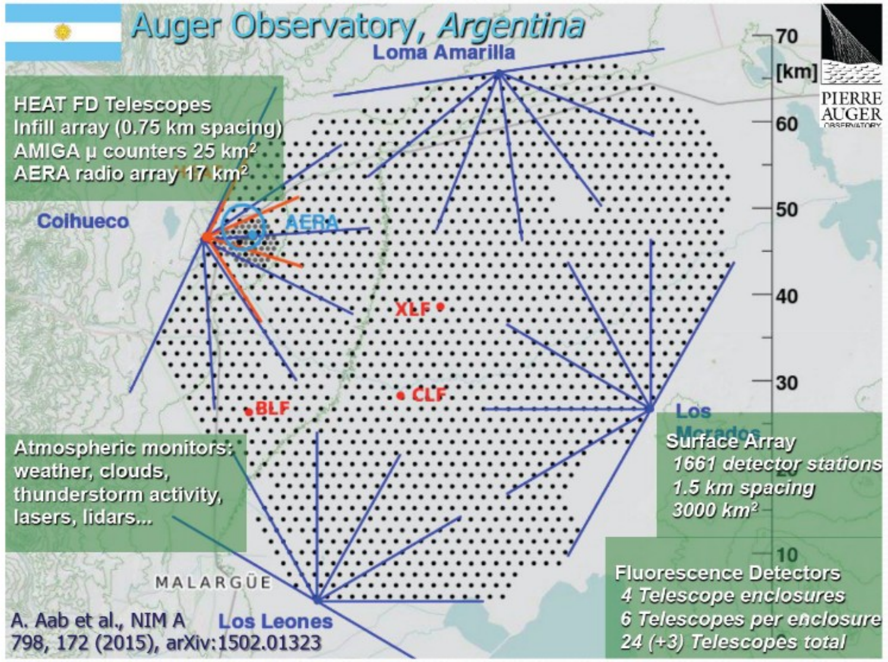
Sketch of the site soils distributions

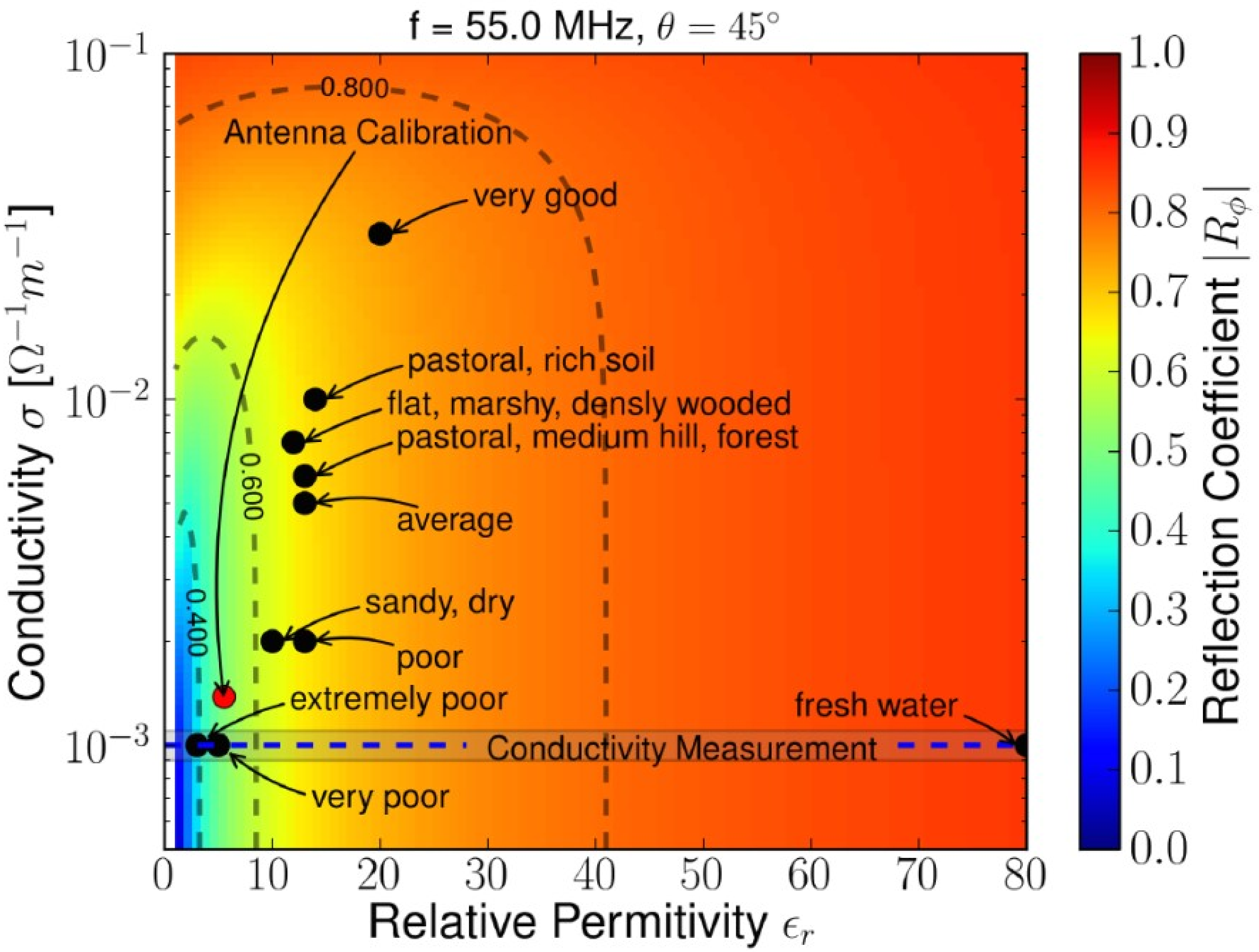
Regarding transit conditions



By Juan Carlos Meza

Fine grained sand.		Dunes (frequently not linked one another) resting on silty soils, scarce vegetation.
Silty with clay		Boggy lands with small lagoons in winter, dense bushes "cortaderas".
		Dry and soft soils, scarcely bushed area (mainly without thorns), difficult to pass after rain/snow.
		Wet and salty soils, not passable after heavy rains and hydrological rich years.
Mainly gravel and sand.		Alluvial cones and alluvial terrace, passable all year (bushes with dangerous thorns).





lower left region of Fig. 7.6, corresponding to the extremely dry and sandy ground at AERA. Soil measurements performed at the AERA site indicate a relatively low conductivity of $\sigma = (1 \pm 0.1) \cdot 10^{-3}$ $[\Omega^{-1}m^{-1}]$ [157]. We chose for antenna simulations associated with the AERA site values of $\sigma = (1.38) \cdot 10^{-3}$ $[\Omega^{-1}m^{-1}]$ and $\epsilon_r = 5.5$.

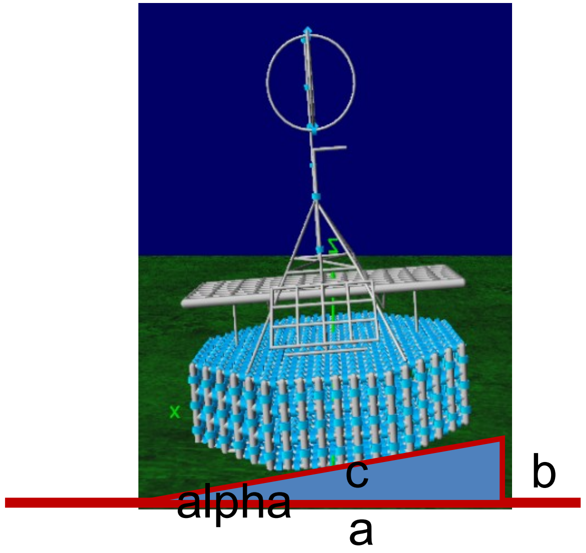
Ground properties also change with weather

Material	Conductivity	Relative permittivity ε_r
	S/m	F/m
Air	0	1
Water	$10^{-4} - 10^{-2}$	81
Clay dry	$10^{-3} - 10^{-1}$	2-6
Clay saturated	$10^{-1} - 1$	15-40
Concrete dry	$10^{-3} - 10^{-2}$	4-10
Concrete wet	$10^{-2} - 10^{-1}$	10-20
Sand dry	$10^{-7} - 10^{-3}$	4-6
Sand saturated	$10^{-4} - 10^{-2}$	10-30
Sandy dry soil	$10^{-4} - 10^{-2}$	4-6
Sandy wet soil	$10^{-2} - 10^{-1}$	15-30
Loamy dry soil	$10^{-4} - 10^{-3}$	4-6
Loamy wet soil	$10^{-2} - 10^{-1}$	10-20
Clayey dry soil	$10^{-4} - 10^{-1}$	4-6
Clayey wet soil	$10^{-1} - 1$	10-15

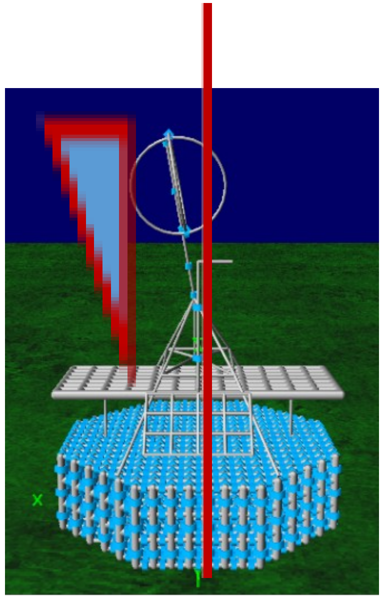
Degree - tilt relation

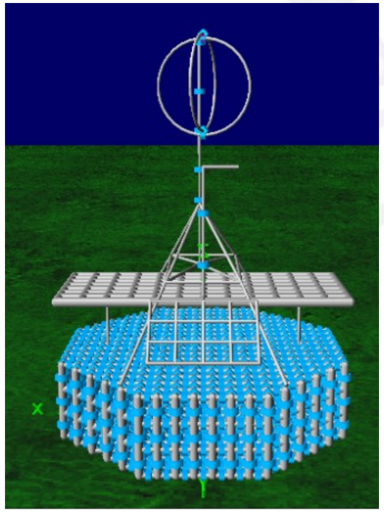
- If you tilt tank (3.5 meters long) by 5 degrees, the difference between the highest and the lowest point is 31 cm.
- If you tilt antenna (~2 meters high) by 5 degrees, the difference between the top point from the perpendicular is 17 cm.
- If you rotate antenna by 5 degrees, the difference between the furthest point pointing to the north and the north is 5 cm.

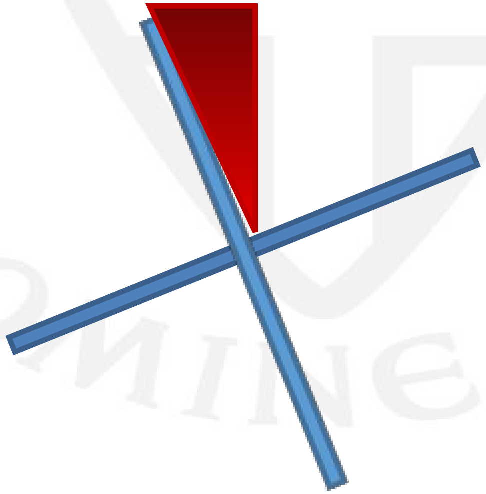
		Degrees of tilt					
		1	2.5	5	10	15	20
object size (meters)	0.6	0.01	0.03	0.05	0.10	0.16	0.21
	2	0.03	0.09	0.17	0.35	0.52	0.69
	3.5	0.06	0.15	0.31	0.61	0.91	1.22



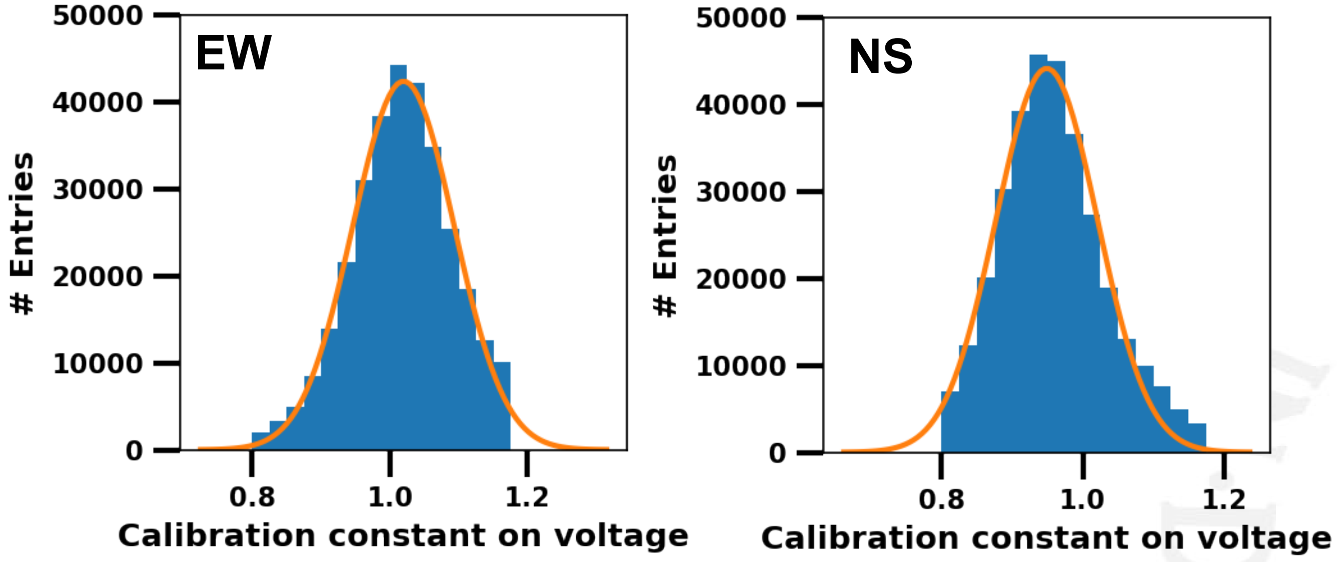
$b=\sin(\alpha)*c$







Absolute galactic calibration – method & results



channel	voltage calibration constant
EW	1.03±9.6%±2.0%
NS	0.96±9.7%±2.0%

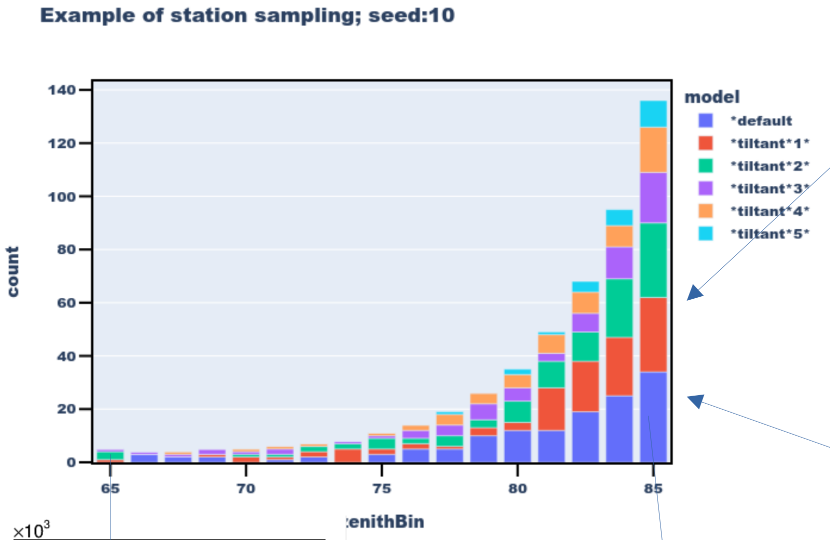
Table 1: Calibration constants. The first uncertainty is propagated from the simulated dataset. The second is the uncertainty propagated from the measured dataset.

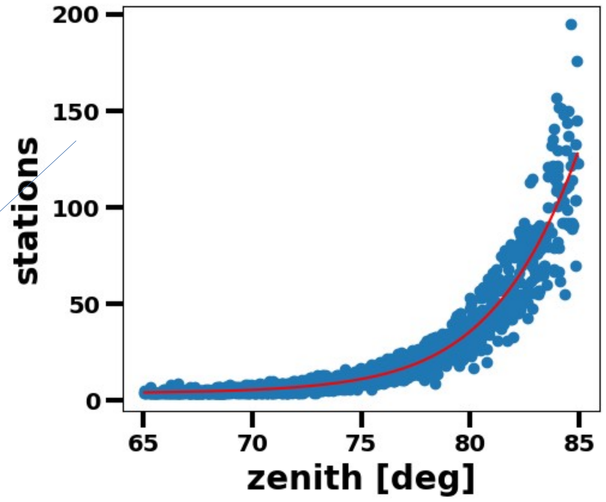
factor	min	max	mean
choice of the sky map	4.0	5.1	4.5
choice of calibration method	1.6	5.0	3.6
*	(8.4)	(11.2)	(10.0)
antenna model	0.3	1.4	0.9
antenna - different ground	0.2	1.8	1.0
antenna - shifted components	0.1	0.7	0.4
antenna - missing components	0.2	1.9	0.6

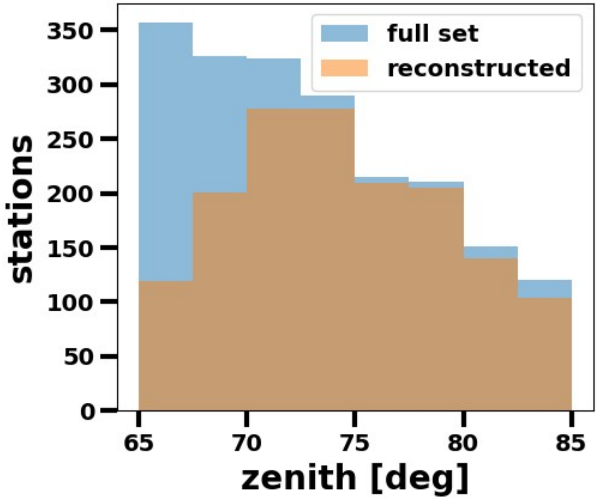
Table 2: Effect of the different factors (in percents) on the calibration constant. *When the LFSS map is fixed, the methods yield higher inconsistency compared to when the other maps are used.

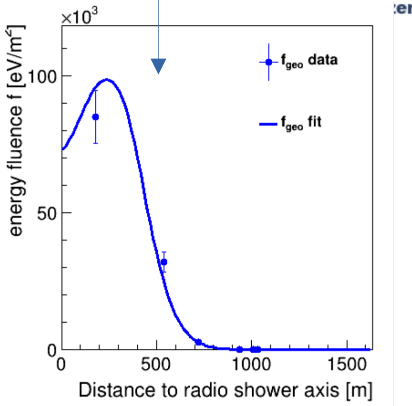
Zenith correlation (tilted antenna)

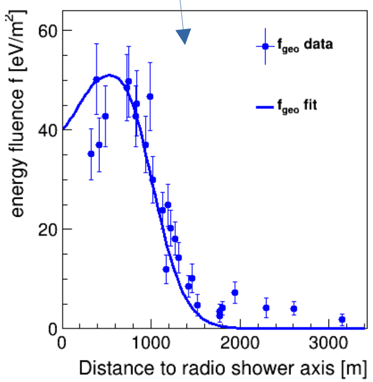
Central theorem suggestion:
Large zenith –> larger foot print –> more stations –>
large sample -> better approximation of the true value
Example:

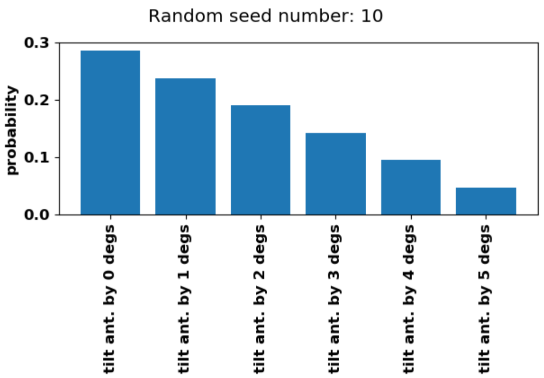


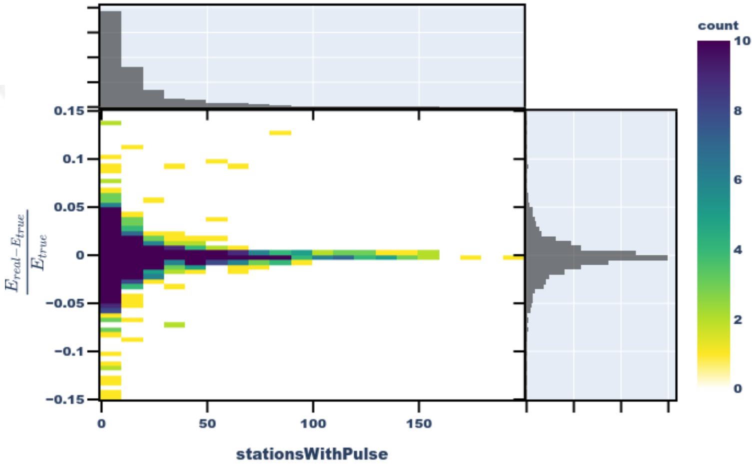








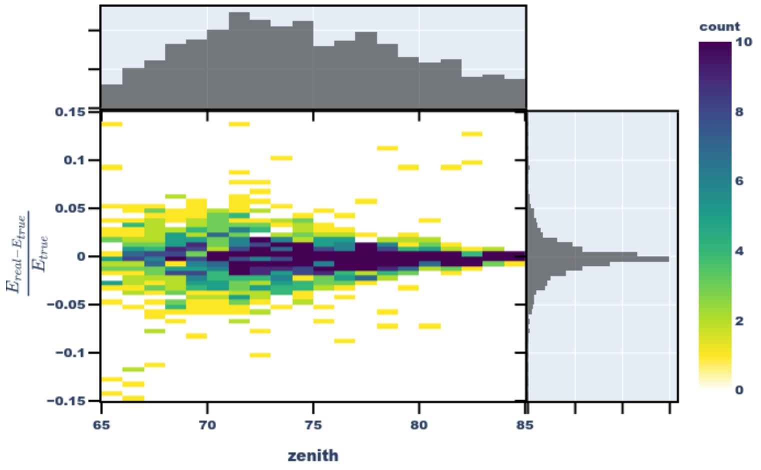


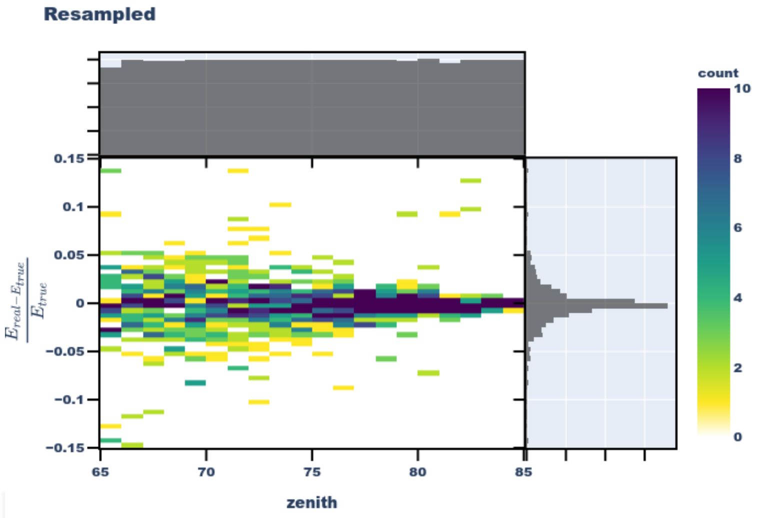


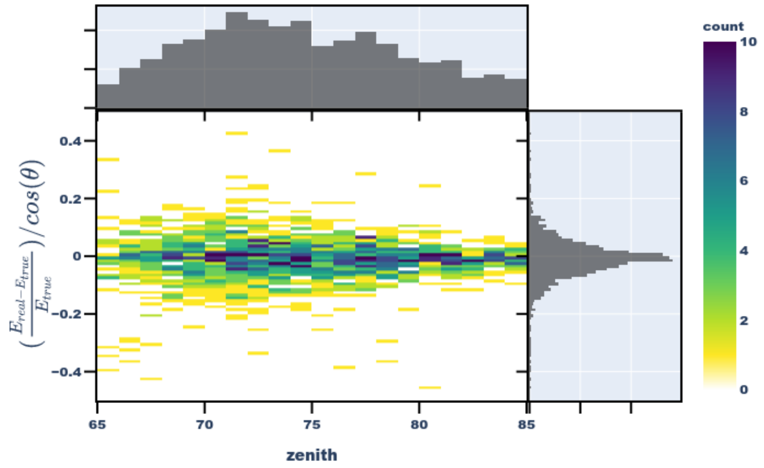
Zenith correlation (tilted antenna)

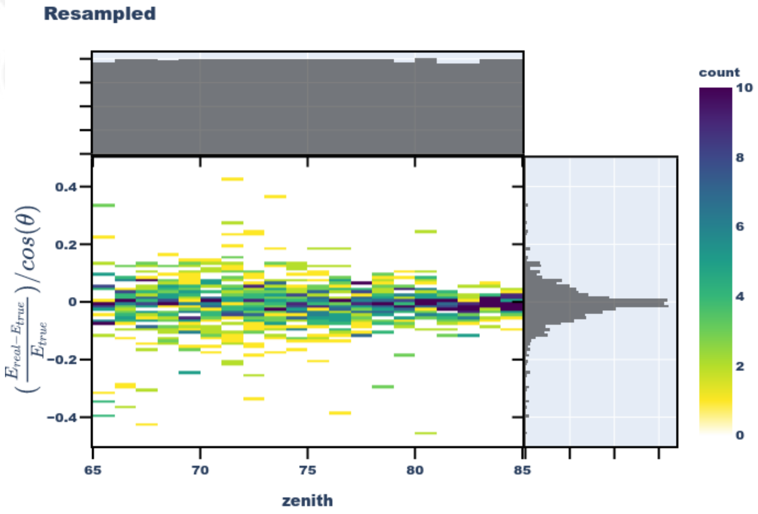
1) re-sample to have same # of samples in each zenith bin

2) divide by cos(theta)



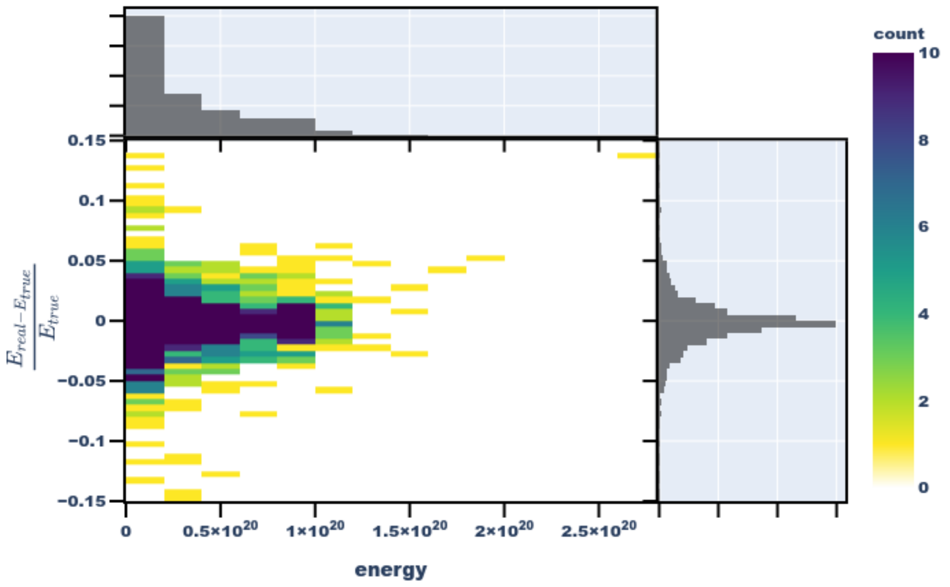


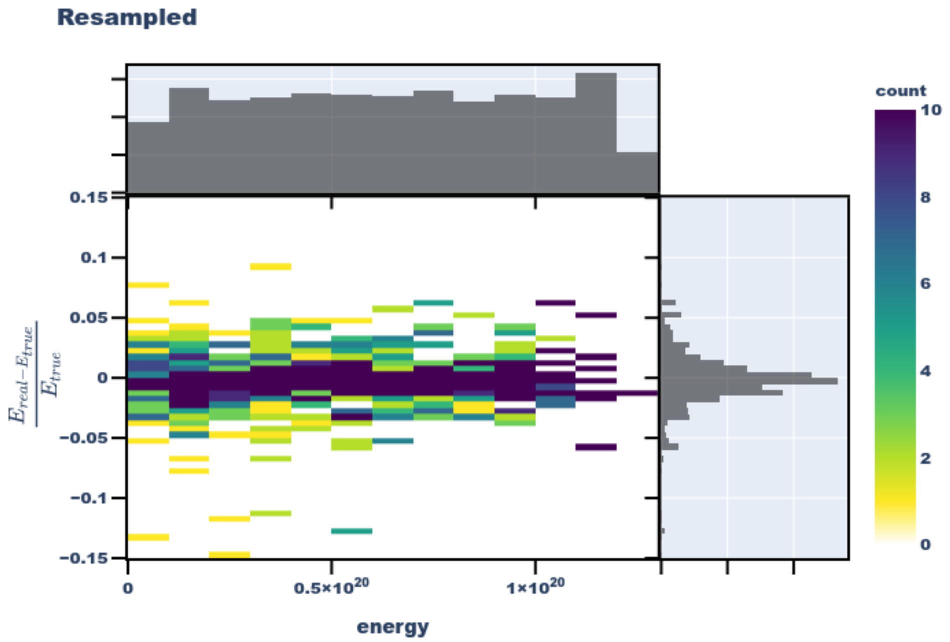




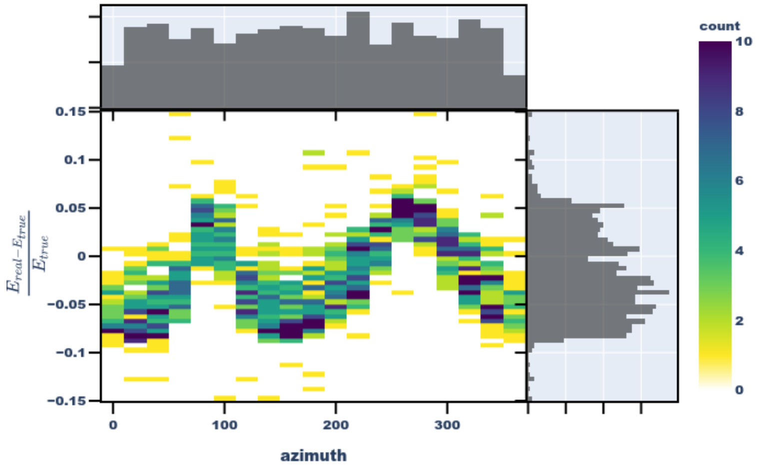
Energy correlation (tilted antenna)

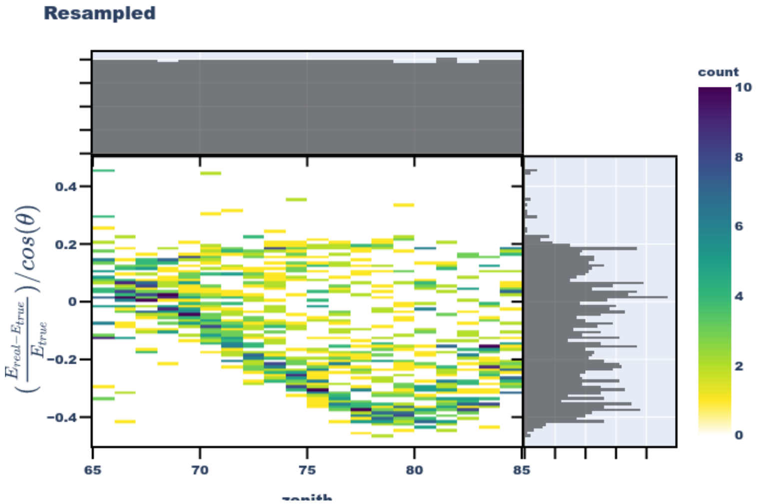
- No strong energy correlation after resampling

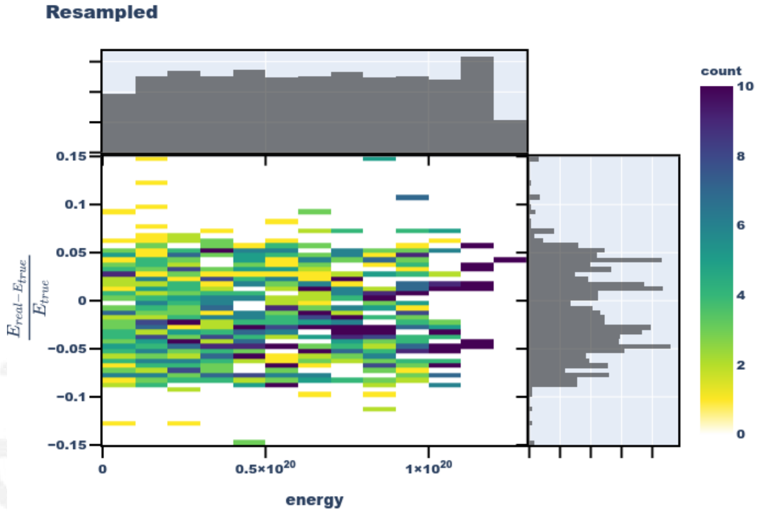


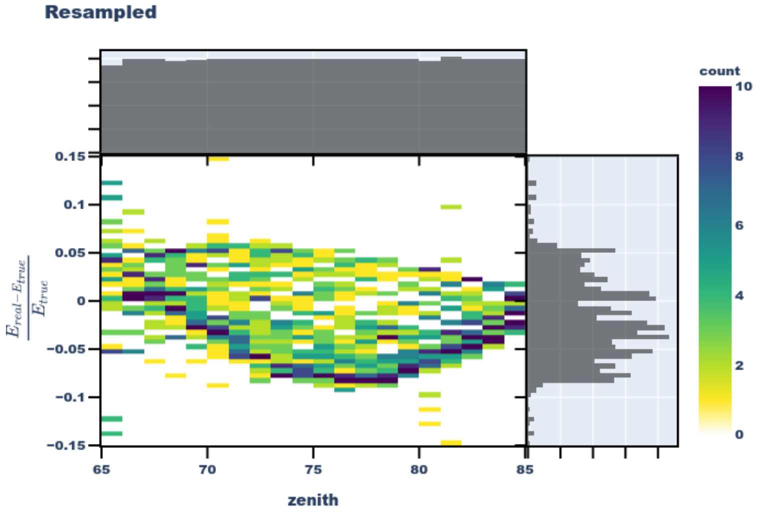


Correlations for different ground (p=20 c=303)





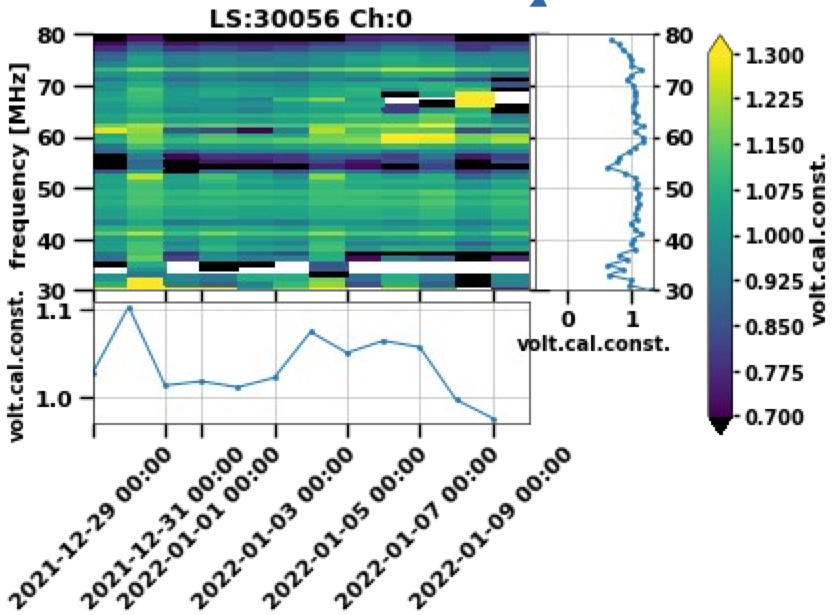


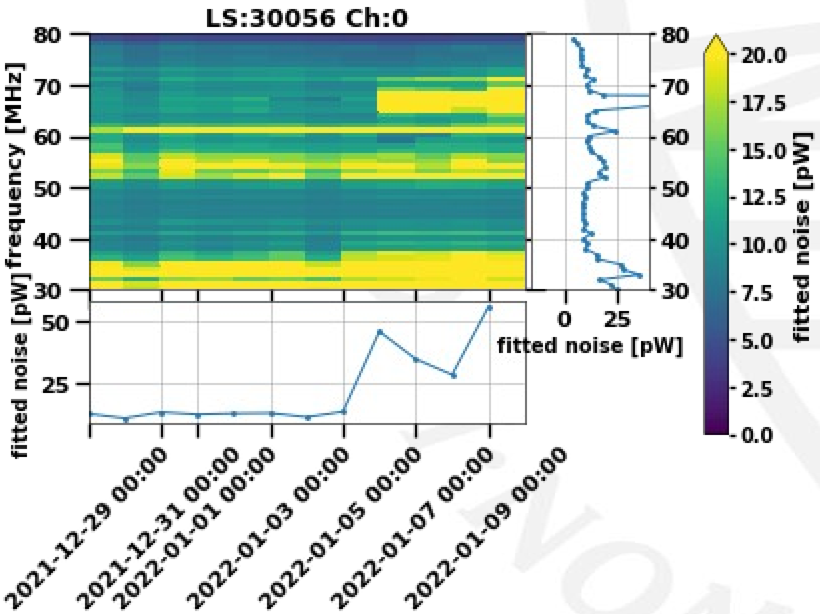


Calibration – fitting each band separately

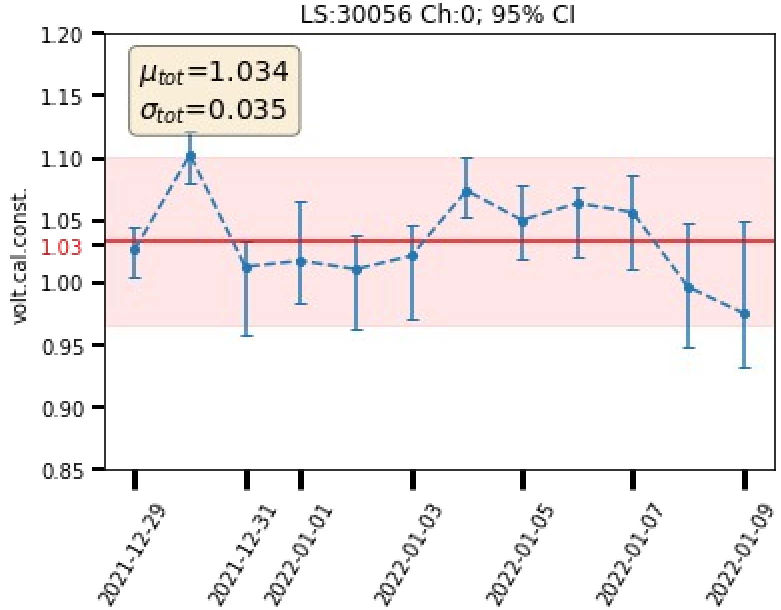
Fitting formula:

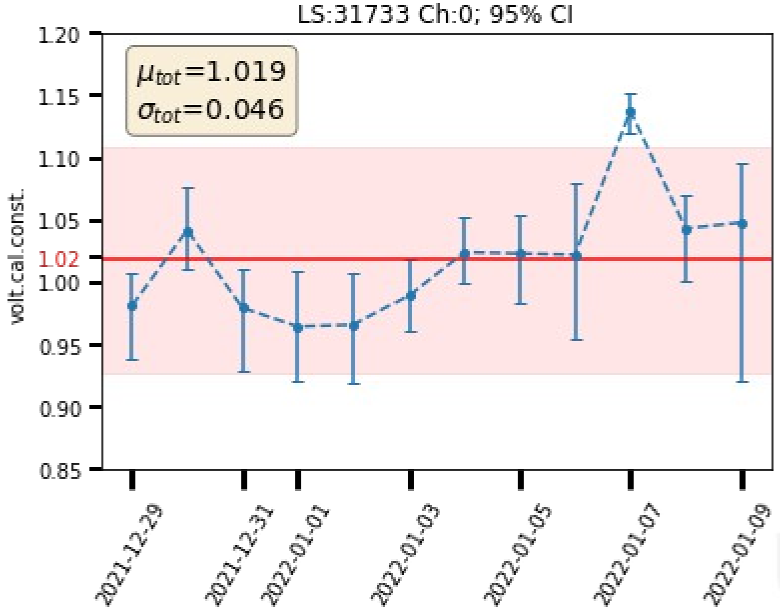
Measured (f,t) = simulated (f) * **calibration constant (f,t)** + **noise (f,t)**

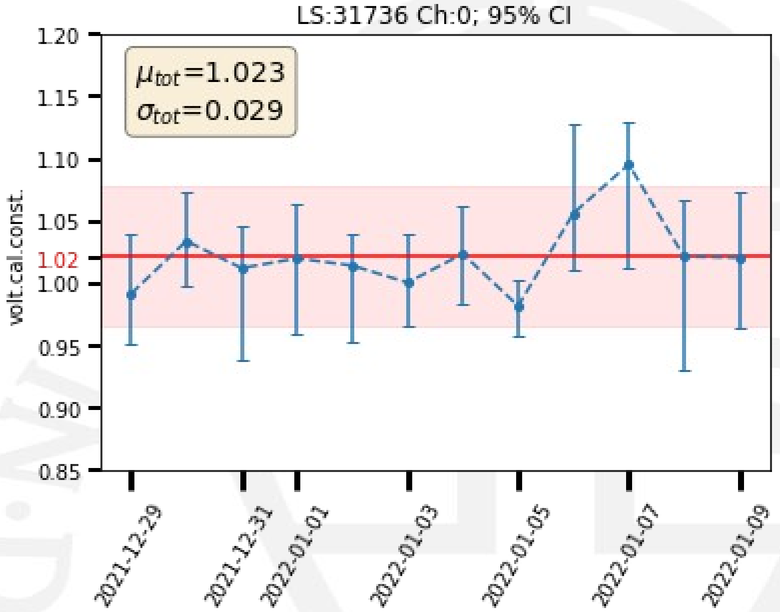


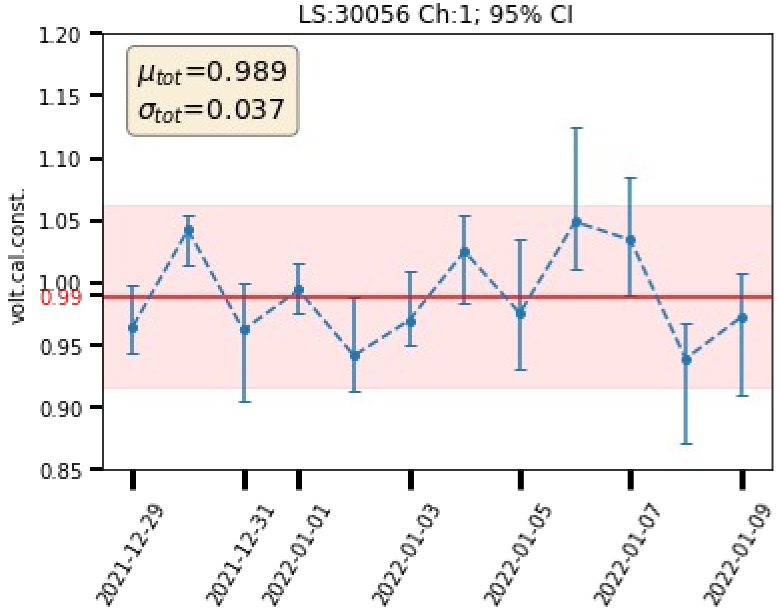


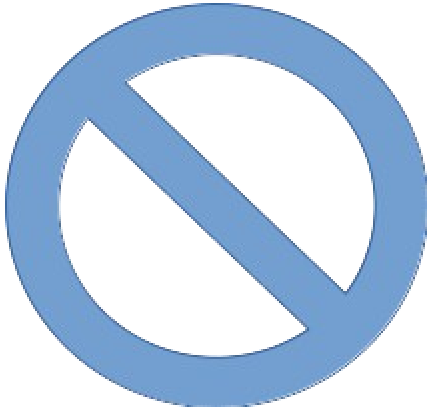
Median of the frequency dependent calibration constants

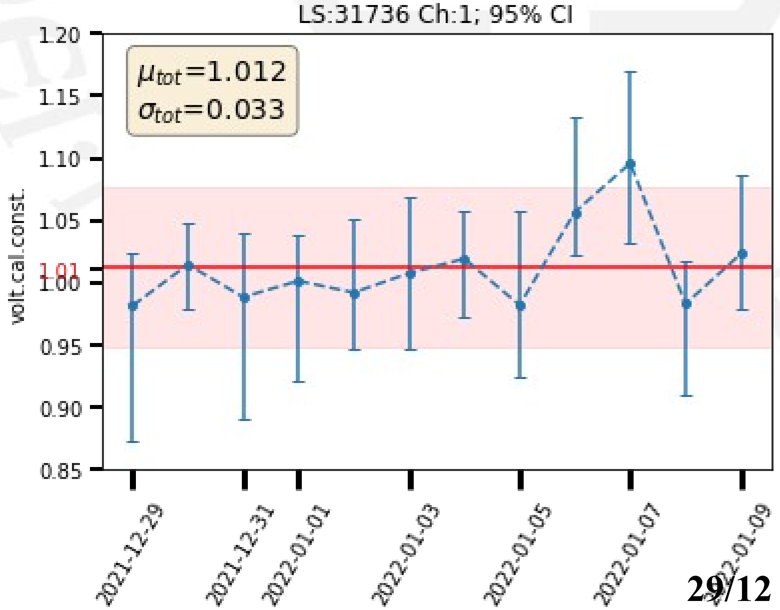












Median of the frequency dependent calibration constants