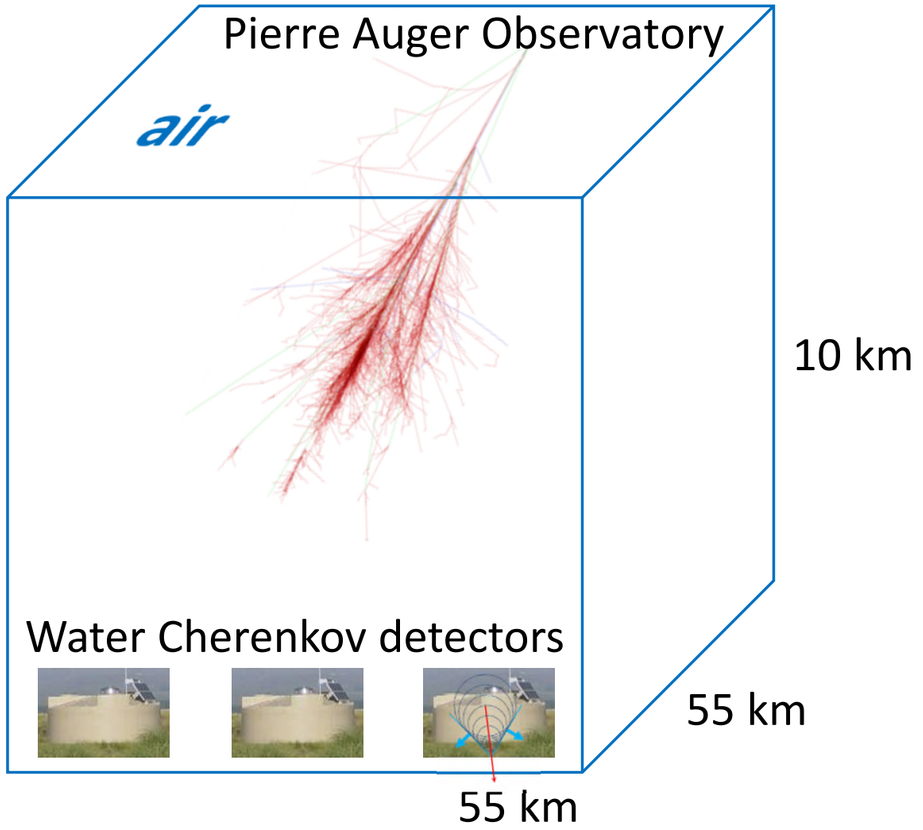
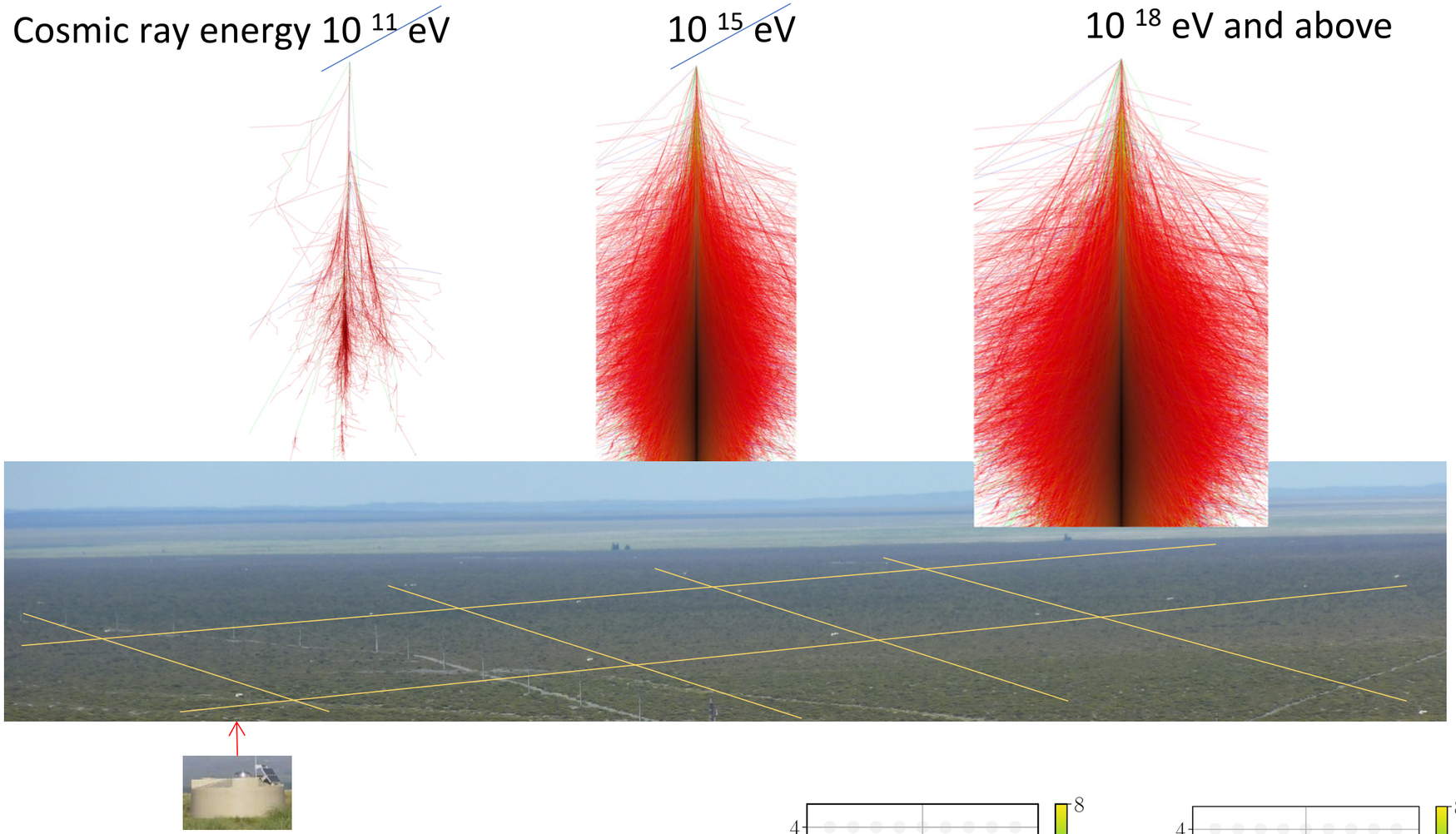
World‘s largest Calorimeter for Cosmic Nuclei

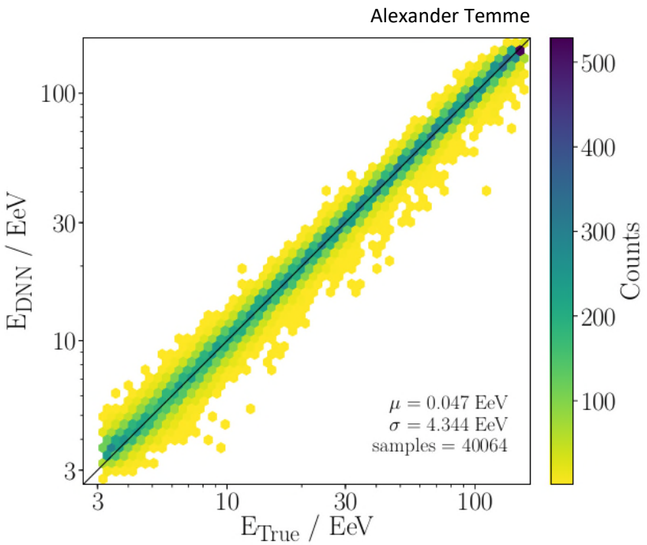


Neural Network reconstruction tasks

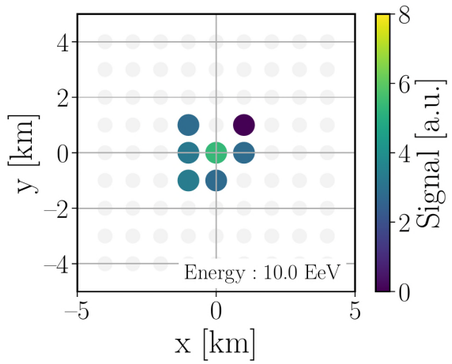
1. **Arrival direction** (accelerator site?)
2. **Energy** (much more than at CERN!)
3. **Height of maximum shower development** (which nucleus?)

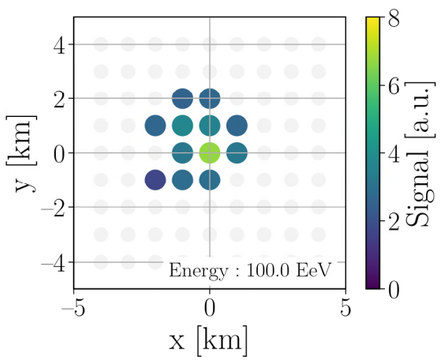
Cosmic Ray Energy





(a) Energy reconstruction



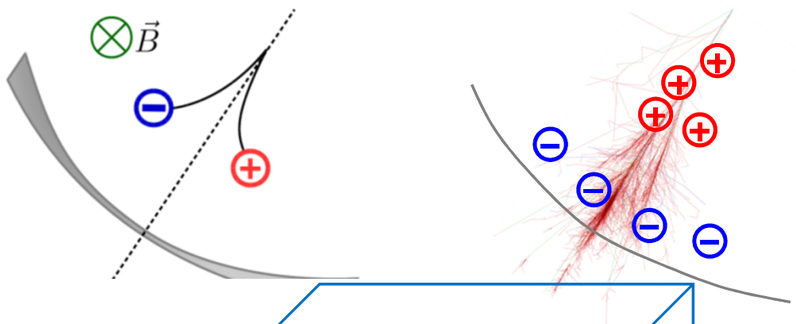


Pierre Auger Collab., PRD 93 (2016) 122005, PRL 116 (2016) 241101, JINST 12 (2017) T10005, arXiv:1706.01451

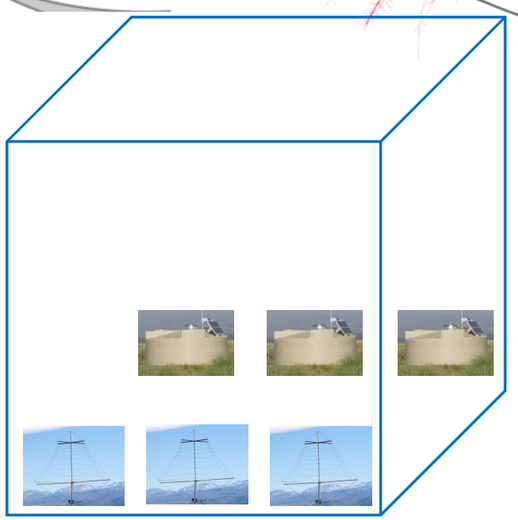
Absolute Cosmic Ray Energy from Radio Emission

Geomagnetic emission

Charge excess



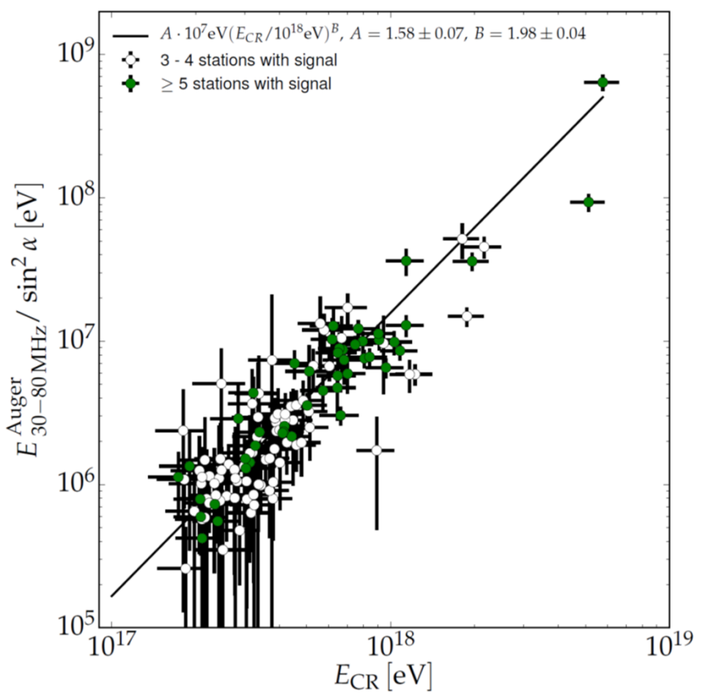
30-80 MHz



Classical electrodynamics:
cosmic ray energy →
energy emitted by shower particles as radio waves

uncertainty in antenna calibration dominates
→ cosmic ray energy calibration ~10%

Energy in
radio signal



Cosmic ray energy from
water Cherenkov tanks

The basic idea

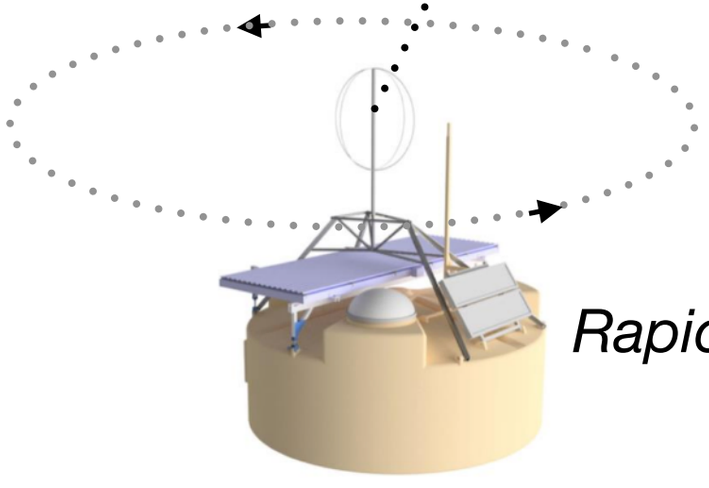
Goal:

End-to-end calibration of the whole system (complemented by galactic calibration for the full calibration)

- Measuring the **SALLA directional antenna response** with drone-mounted transmitter antenna:
  —> Validates our understanding of the NEC simulated antenna models

DJI Matrice 600 Pro ('M600')

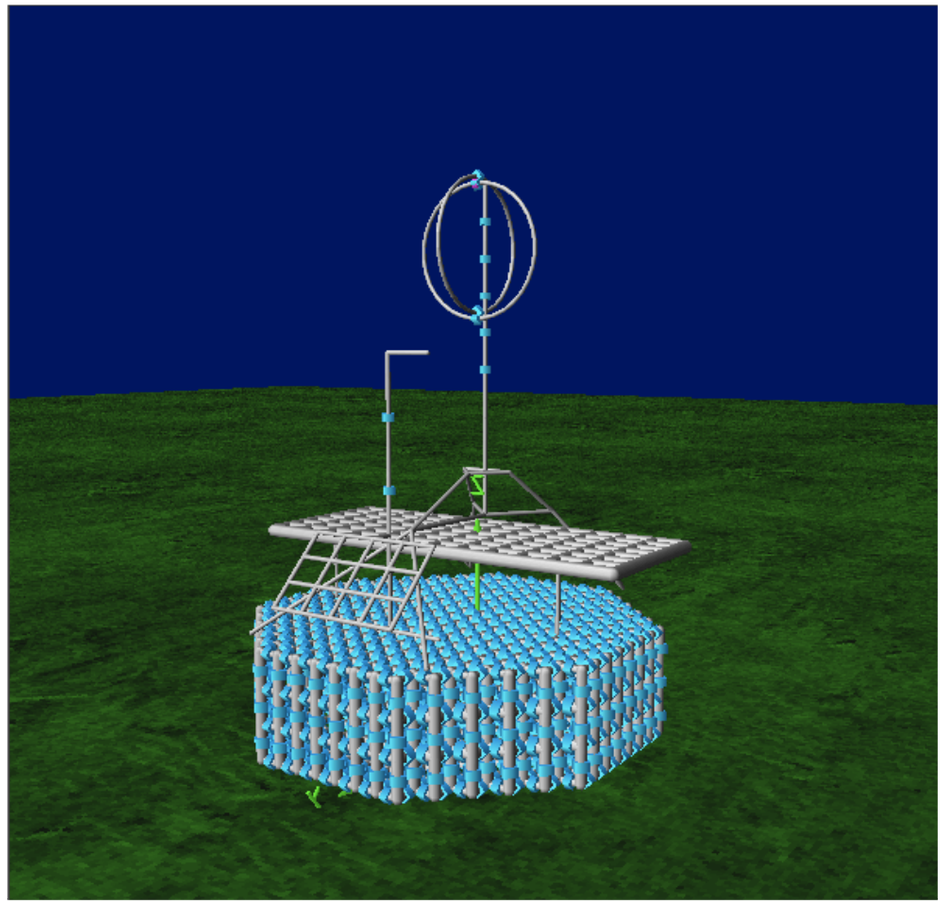
Hexacopter, not an octocopter :)



Rapid triggering DAQ (~1Hz)

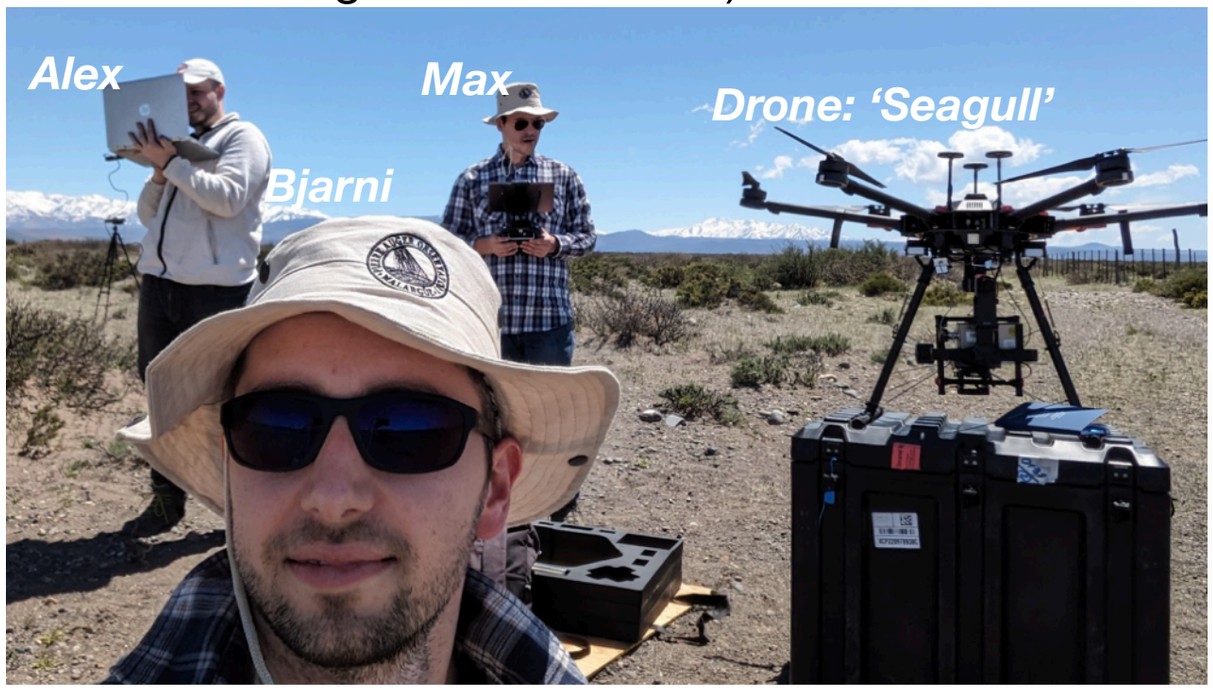
Validates —>

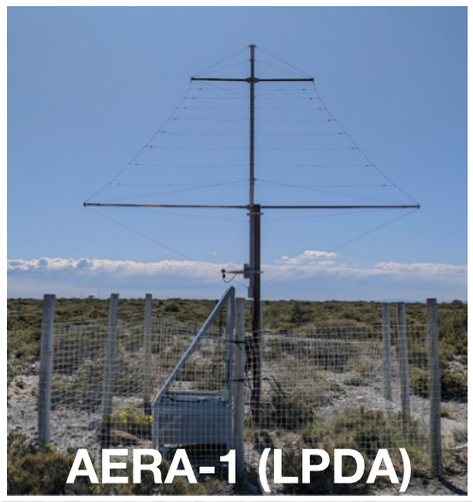
NEC antenna simulation

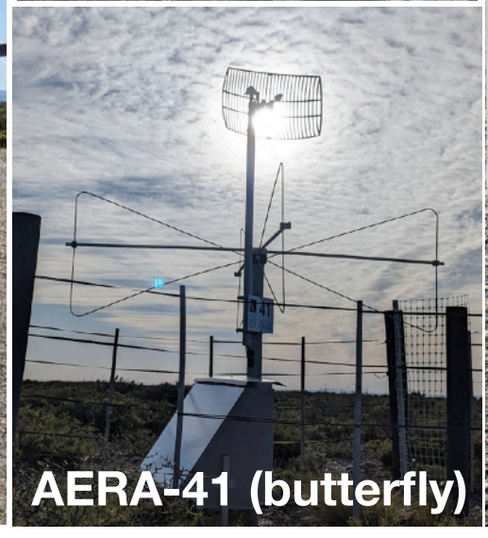


Measurement Campaign (ongoing)

- 3.5 weeks: Oct 26 - Nov 18
- Maximilian Straub (Aachen), Alex Reuzki (Aachen), Bjarni Pont (Nijmegen)
- In previous days:
  - Finished RD measurements antenna pattern
  - Additional flights to understand our systematic uncertainties
  - Finished AERA Butterfly antenna.
  - First measurements of AERA LPDA antenna
- Right now:
  - Finishing AERA LPDA antenna
- Remaining 1 half-day this week:
  - (Flights over Icecube / GRAND @ Auger if time allows)

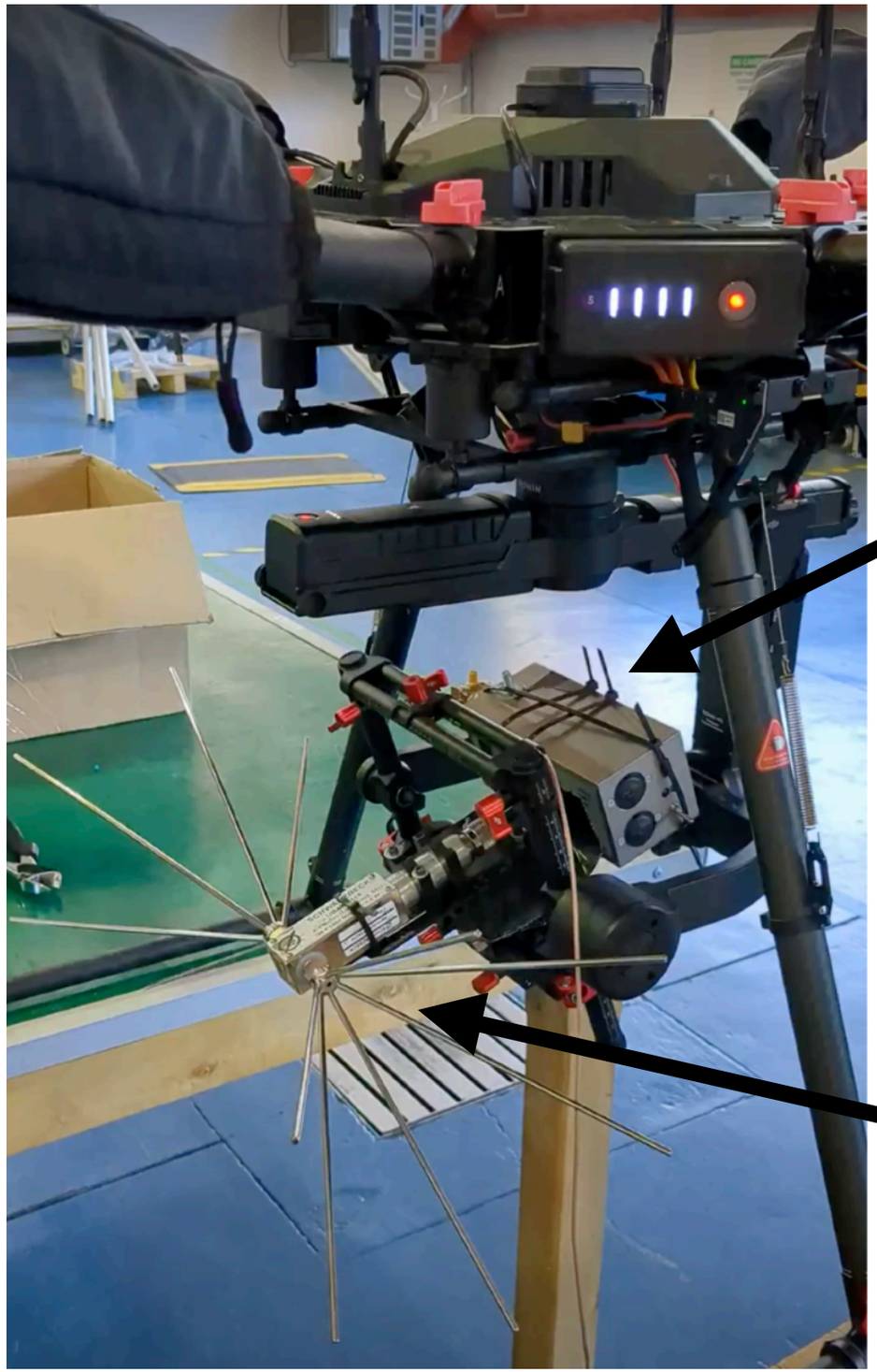




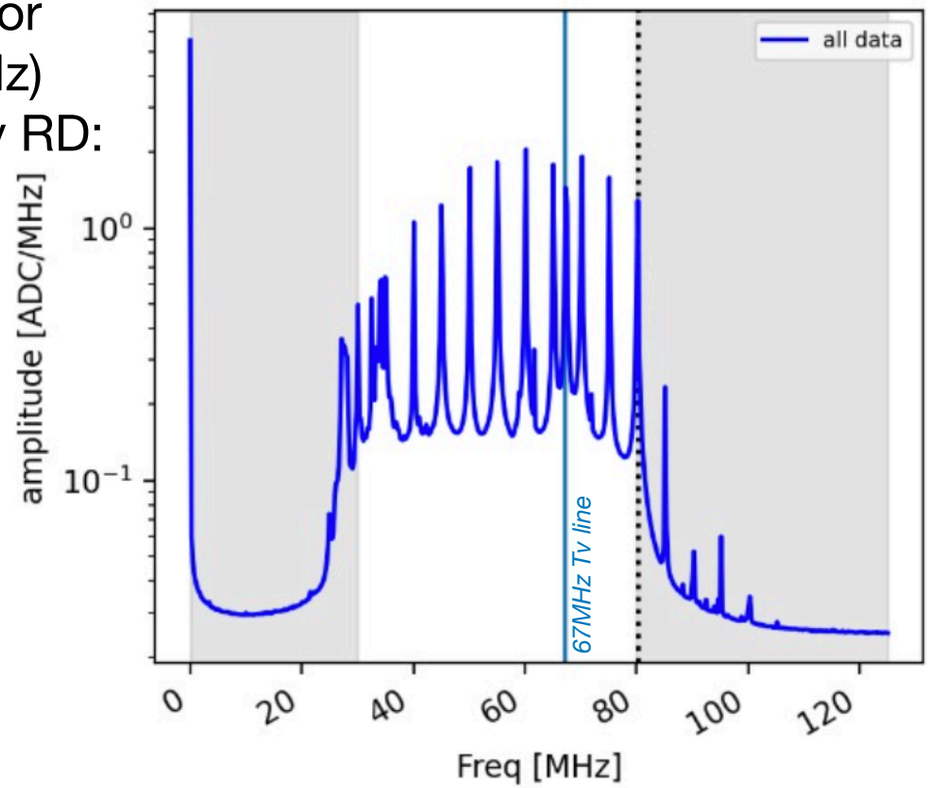


Our calibrator source

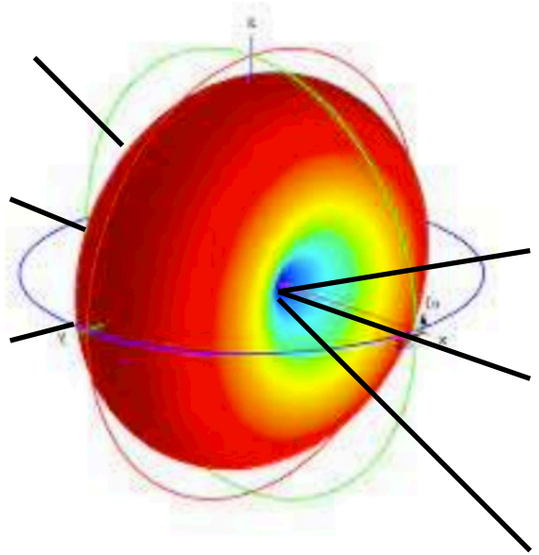
Antenna and signal generator mounted on a gimbal under the drone

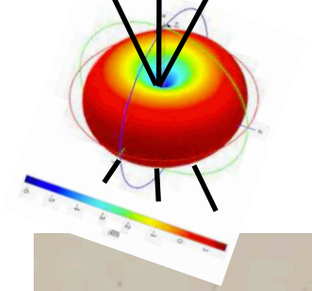


Comb generator
(peak per 5MHz)
Signal as seen by RD:

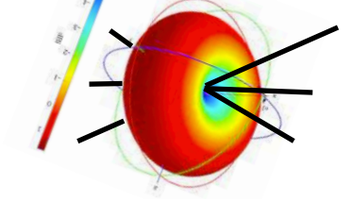


Biconical antenna.
—> points towards RD
for a constant reference
signal

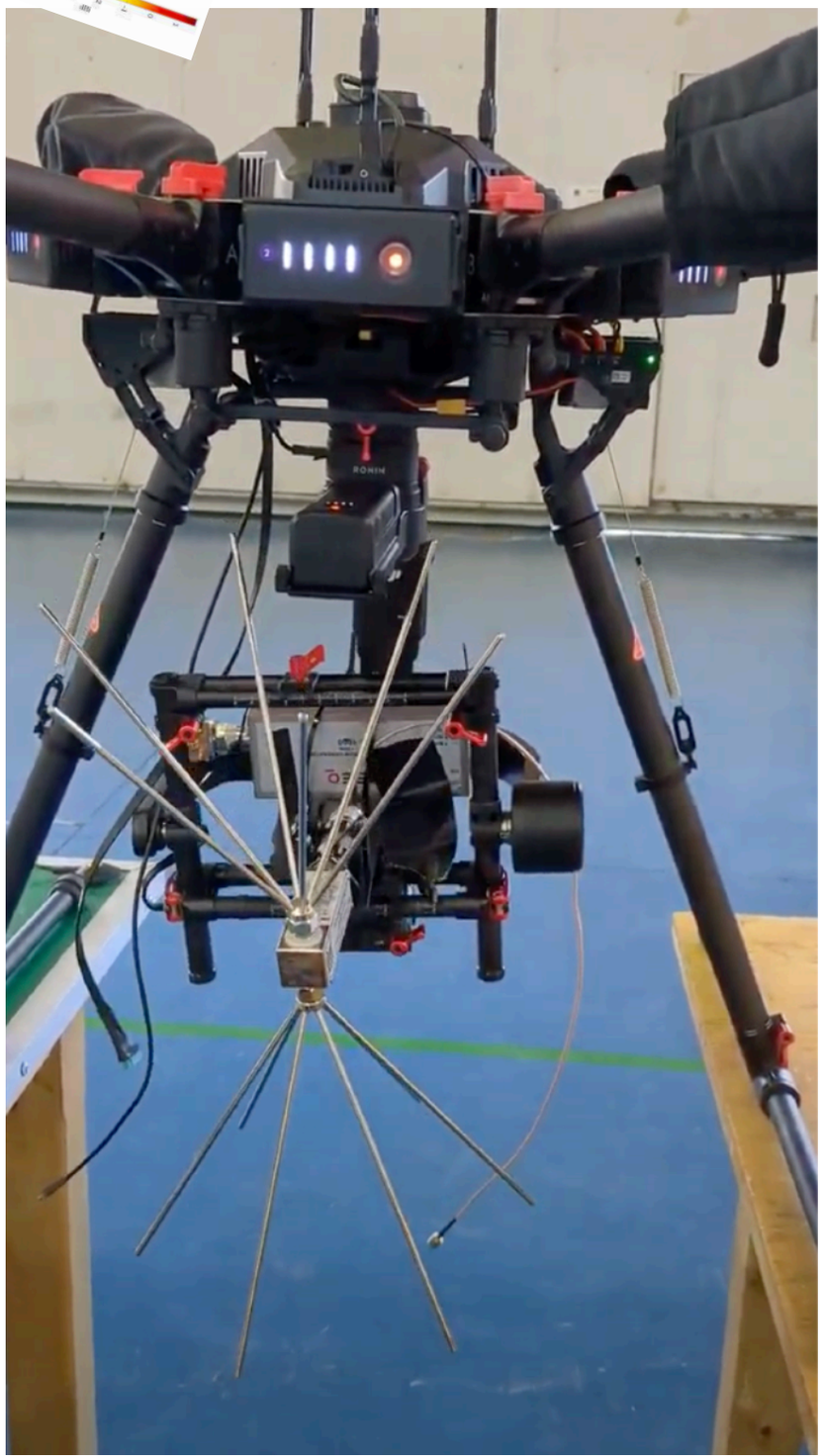


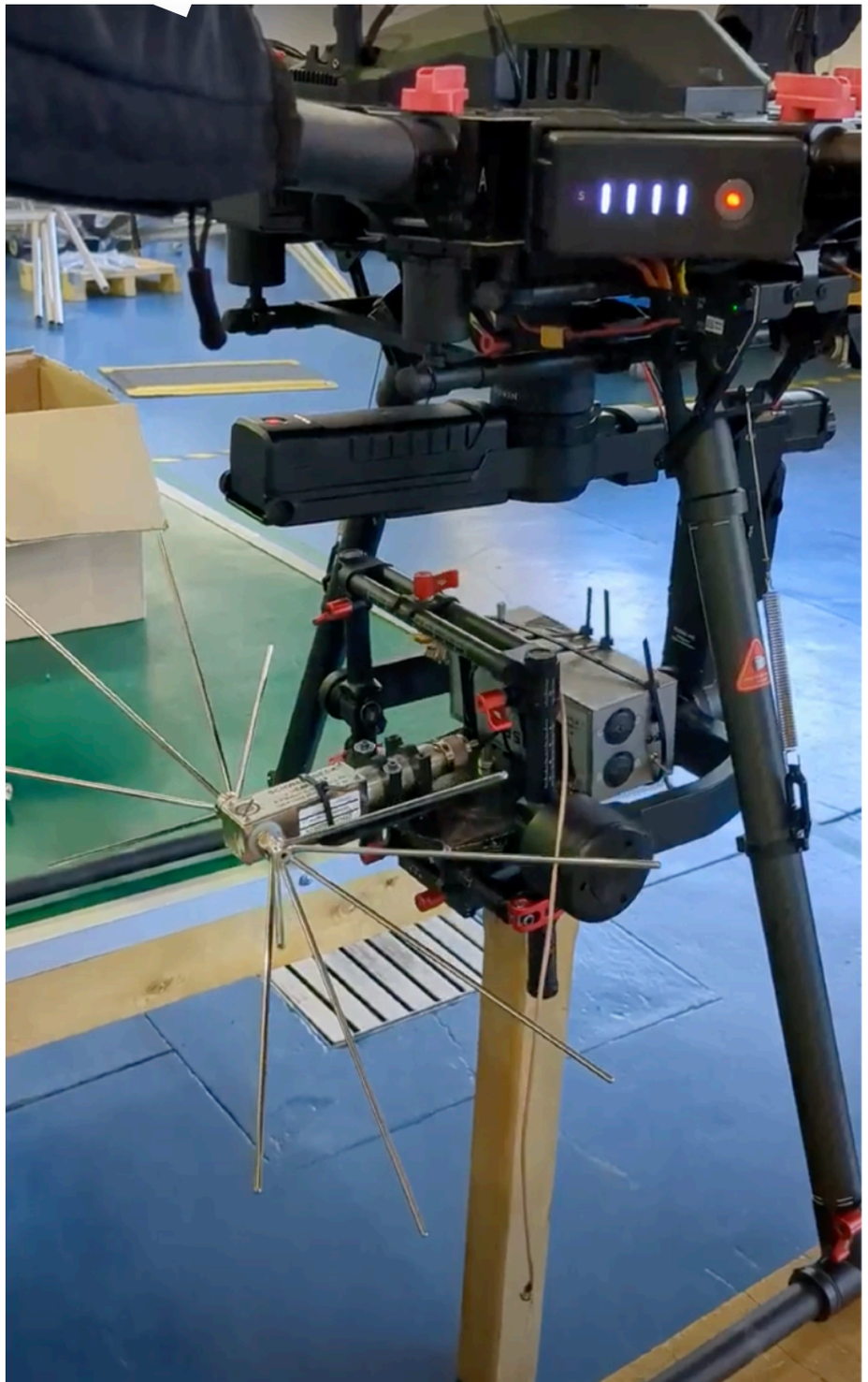


Theta polarization



Phi polarization

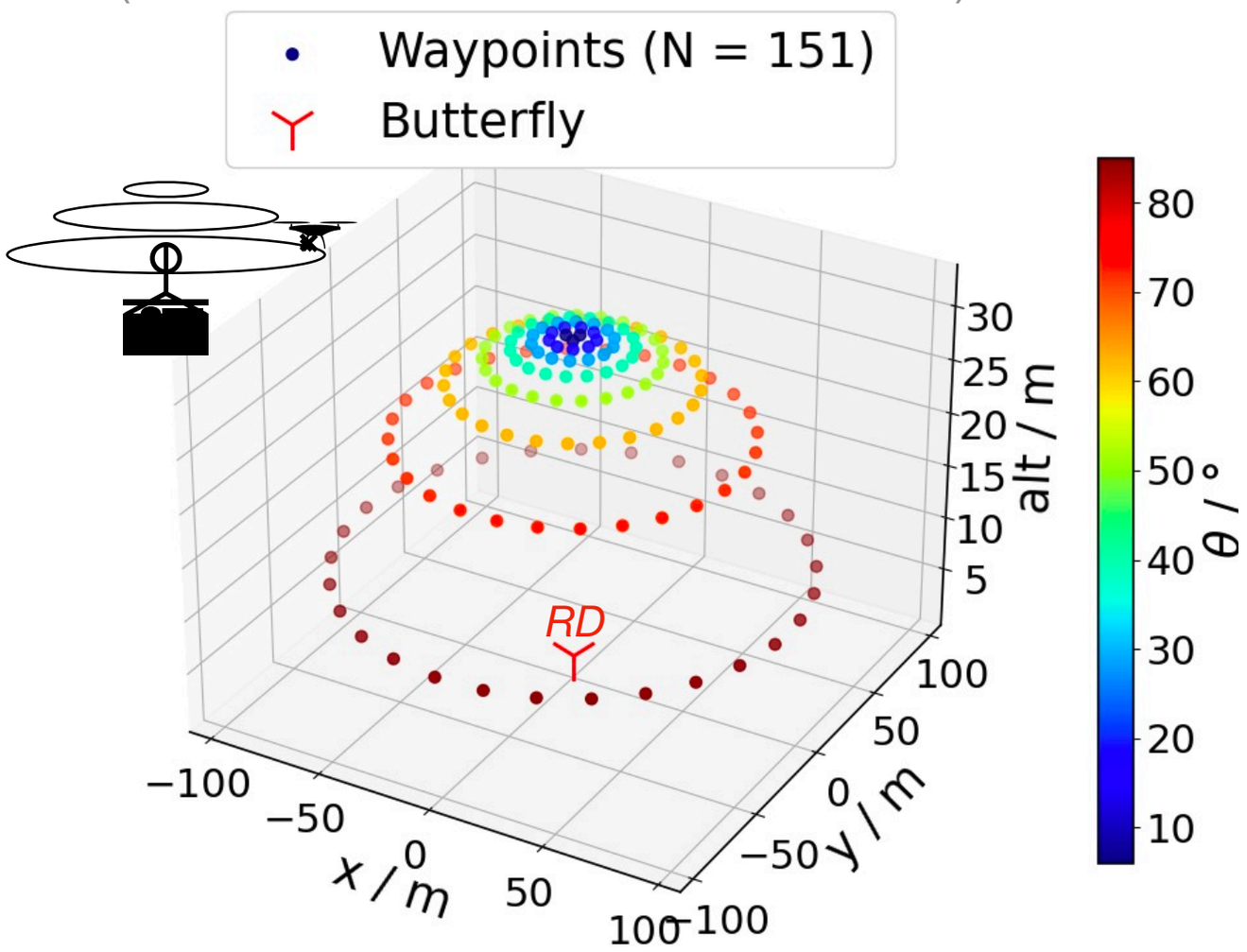




Flight plan & flight logs

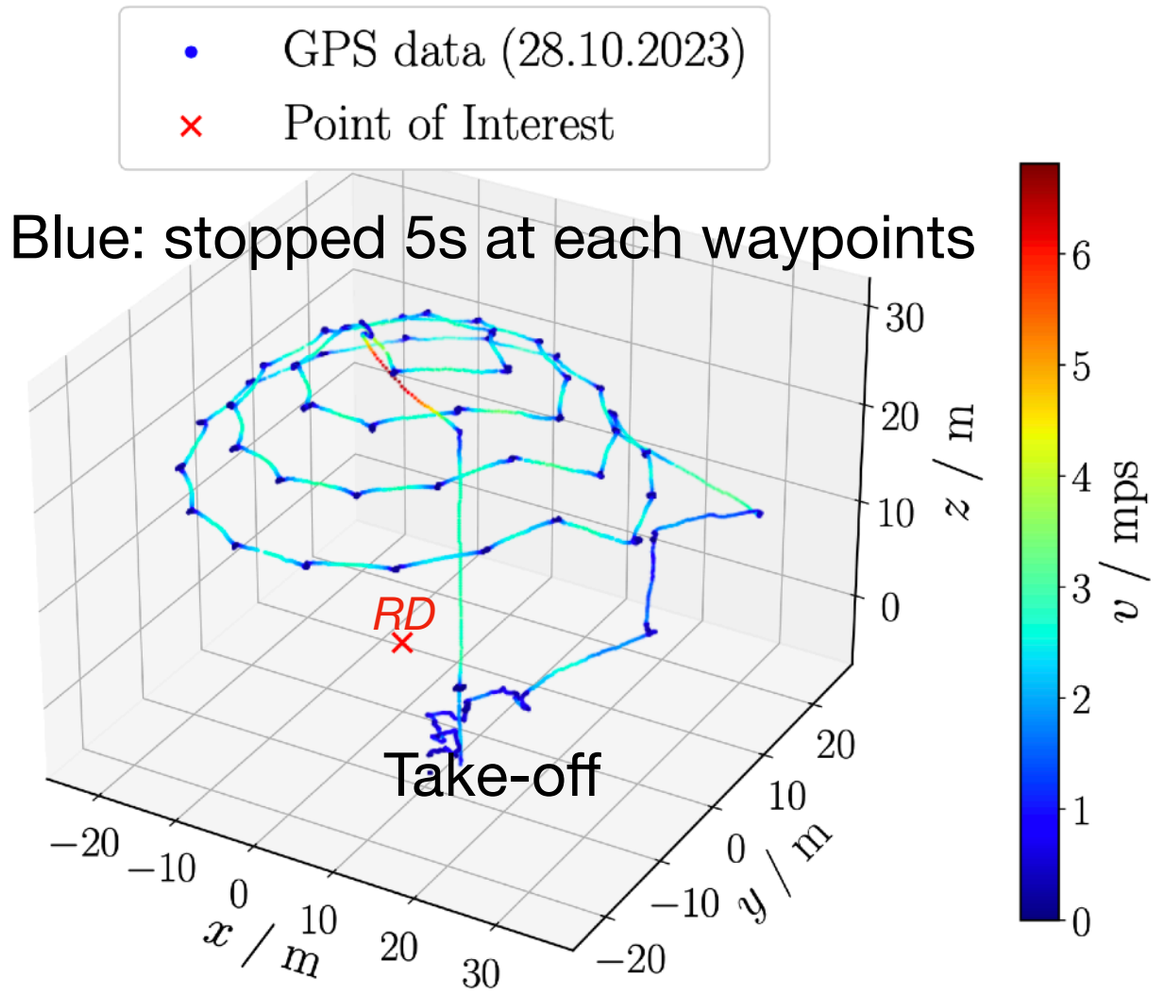
The typical ‘dome flight’

- has uniform sky coverage
- dome is flattened: r=30m at top, 150m at horizon
  (where antenna far-field conditions hold)



Flight log of a single flight 17min flight

(flight of 1 battery)



<u>At each planned waypoint:</u>

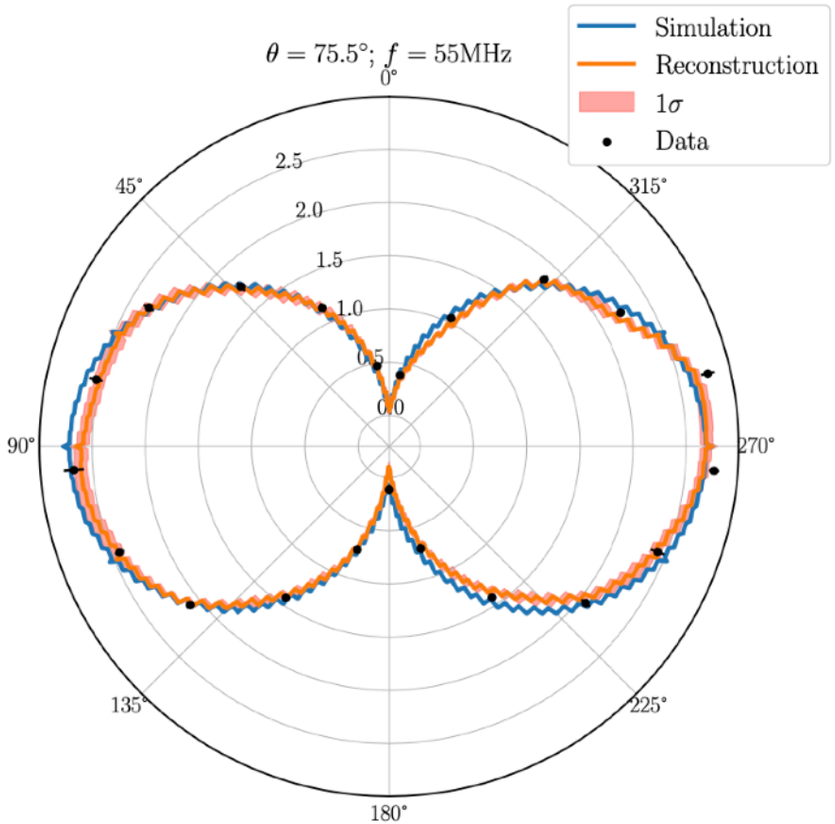
- Trigger differential GPS logging for 1cm location accuracy.
- Wait 5 seconds at each waypoint for signal averaging (to lower noise)

- Flight logs have full drone telemetry
  (Linked to differential GPS for 1cm accuracy)
- ~3 flights required for full dome
  (x2 for both vertical and horizontal polarization directions) = two mornings of measuring.

Antenna pattern reconstruction with IFT (Alex Reuzki)

- Using information field theory (IFT) reconstruction pipeline
  - It finds the ‘field’ (antenna pattern) given the measured data
  - It propagates all input uncertainties into the antenna pattern + uncertainties at any point (Bayesian method)

!!! Pipeline evaluation on sampling from simulated NEC pattern !!! Not the data yet :)



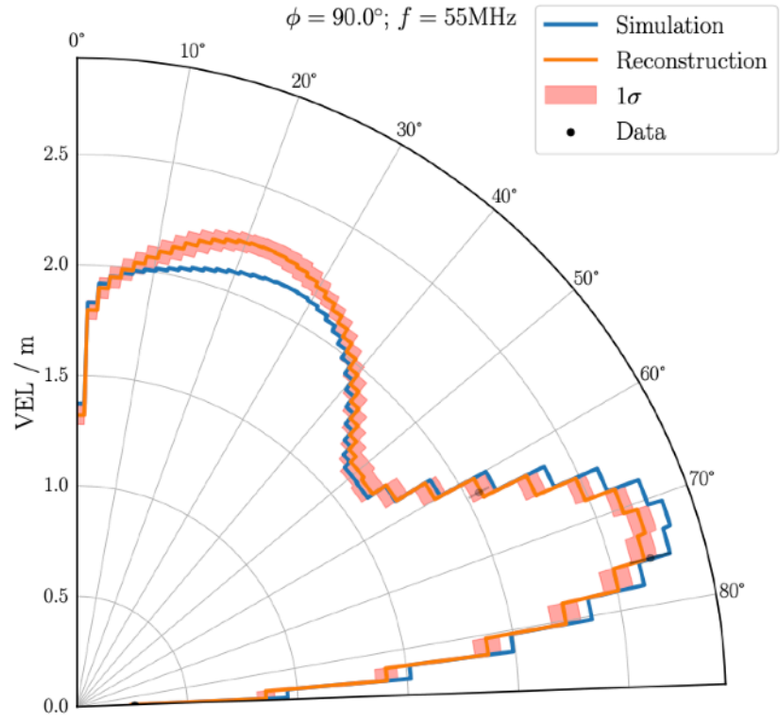


Figure 5.4: Slice for $\theta = 75.5°$ (left) and $\phi = 90°$ (right) at $f = 55$ MHz. The black dots represent the data points, whereas their transparency represents their distance to the sliced angle. The red line with the red band shows the ion and its 1σ band. The blue line is the simulation prior.

Drone-Based Calibration of Radio Antennas at the Pierre Auger Observatory with Information Field Theory

von

Alex Reuzki

Masterarbeit in Physik

vorgelegt der

Fakultät für Mathematik, Informatik und Naturwissenschaften

RWTH Aachen

angefertigt am

III. Physikalischen Institut A

vorgelegt im **Oktober 2023**

Modeling Signal Propagation through the Atmosphere for Air Shower Radio Emissions

ErUM-IFT Kickoff 23.11.2023

Maximilian Straub | straub@physik.rwth-aachen.de

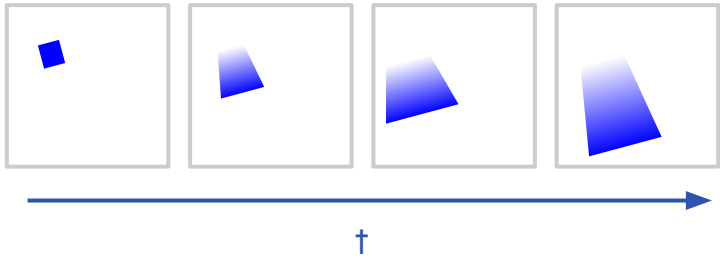
The Goal

- Measured radio emissions of extensive air showers with antenna array

- Analytic description of measurement process → incorporate all knowledge
- Generative model can be more black box-y
  - Needs to cover phase space of possible solutions
  - Needs to output data in usable format
- Reconstruct 4D sky/time image from measured traces (“inverse interferometry”)
  - Correlating signals between neighboring antennas
  - Spatio-temporal information encoded in antenna-antenna variations

Method

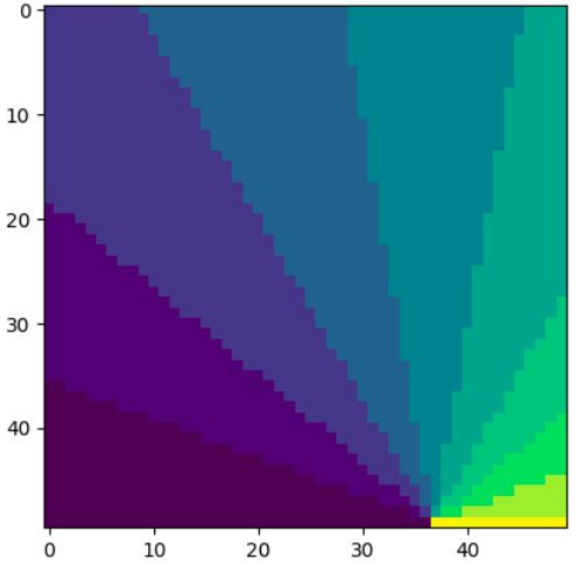
- For each antenna:
  - Construct Measurement-function
  - Propagate each sky voxel towards antenna
- Effects include:
  - Distance-dependent amplitude drop-off of signal
  - Distance-dependent time-shift
  - Angle-dependent antenna response (amplitude + phase)
  - Refractive index of atmosphere
- Voxels can emit signal (Generative model, to-do)
- all signals are propagated to the antenna and summed



Propagate every pixel at every time to every antenna

Binning Values

- Precompute angle-dependent values in angular bins
- Ditto for position dependent values
  - Compute line of sight integral over atmospheric density
  - Look up antenna response for given direction
- “3D end-cap” for 4D volume of interest
- Apply these element-wise to entries



Outlook

- Investigate generative models for emissions
  - E.g. parametrizations, DNNs, model agnostic point clouds…
  - Start with simple model and increase complexity over time
- Abstract representation vs 4D point source cloud?
- Increase physical accuracy of measurement process
- Adaptive, position dependent resolution?
- Proper noise modeling of radio traces