PIERRE AUGER OBSERVATORY

Physics Institute III | RWTH AACHEN UNIVERSITY

Drone-Based Calibration of AugerPrime Radio Antennas

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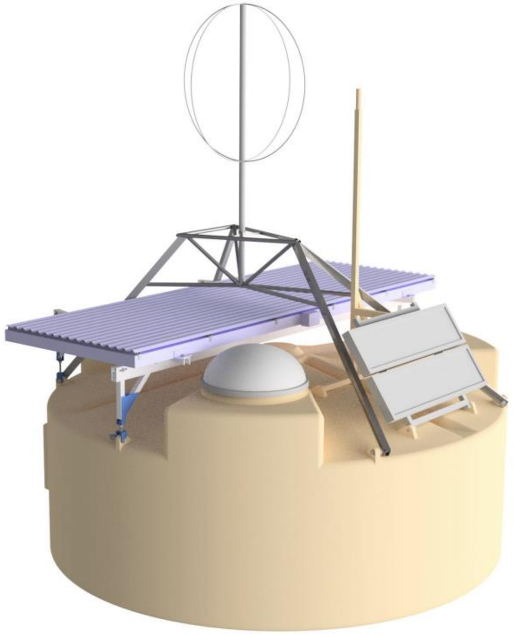


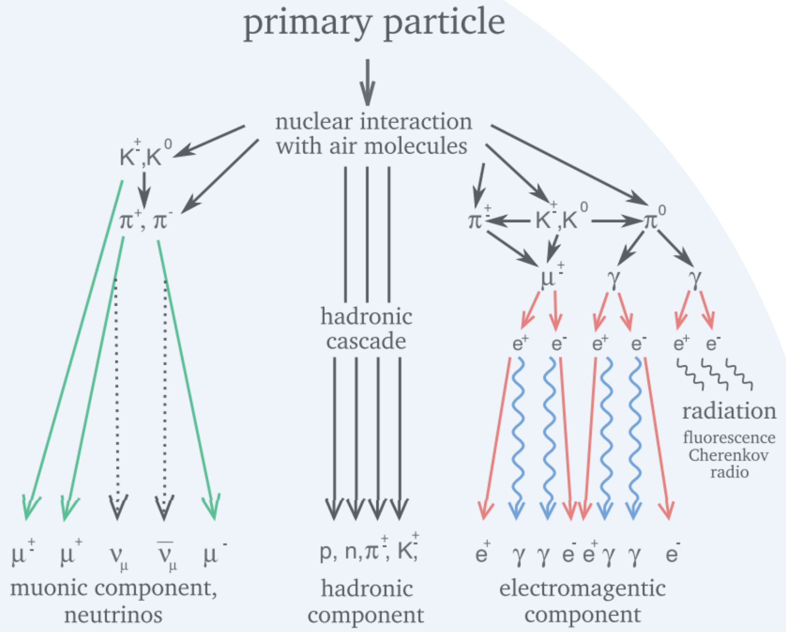
GEFÖRDERT VOM

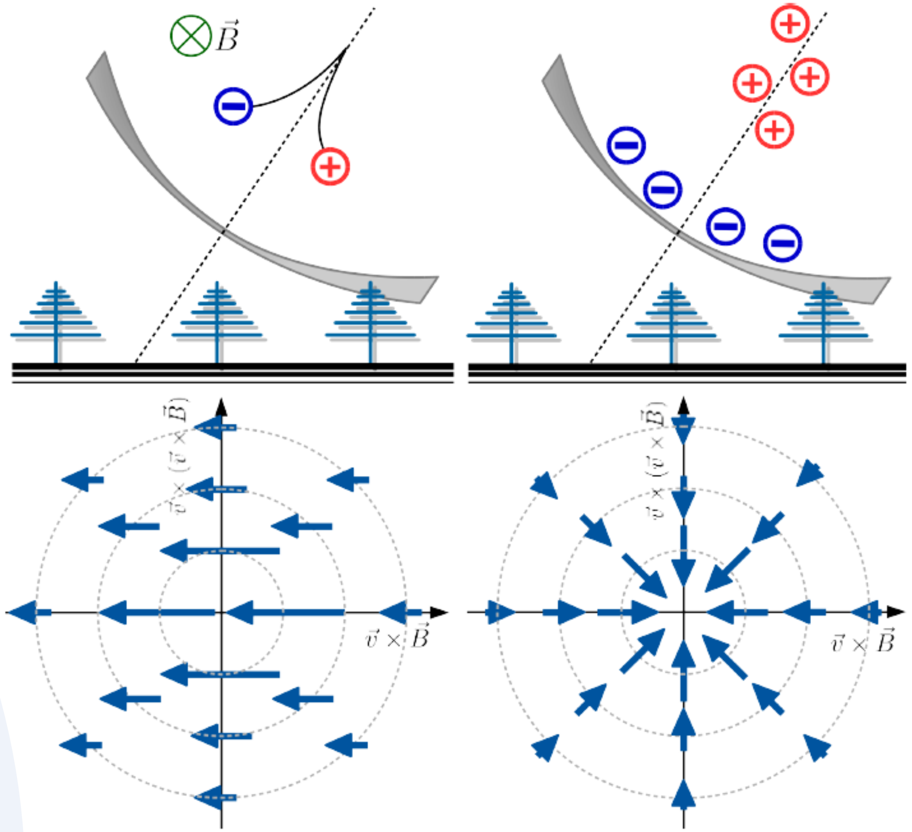
Bundesministerium für Bildung und Forschung

Radio Emission of Air Showers

Ultra-High-Energy Cosmic Ray

Atmosphere





Geomagnetic Effect (left):

- **Deflection of e^+ & e^- in Earth's magnetic field**
- Creates time-varying current
- **Main contribution**

Askaryan Effect (right):

- Shower particles ionizing air molecules
- **Electrons follow shower, nuclei stay behind**
- **Positrons annihilate**
- Charge-excess
- **Small contribution**

AugerPrime Radio Detector

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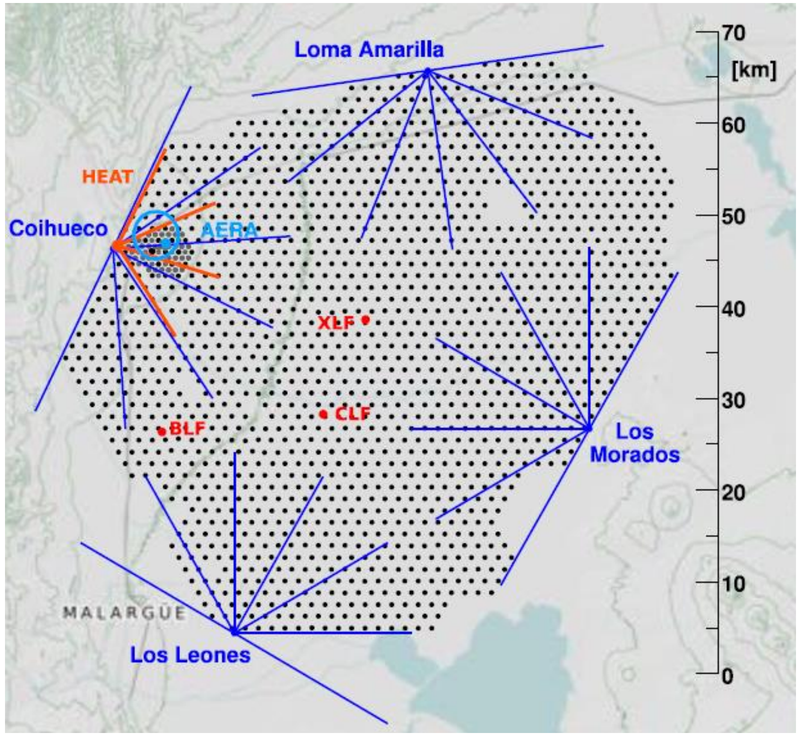
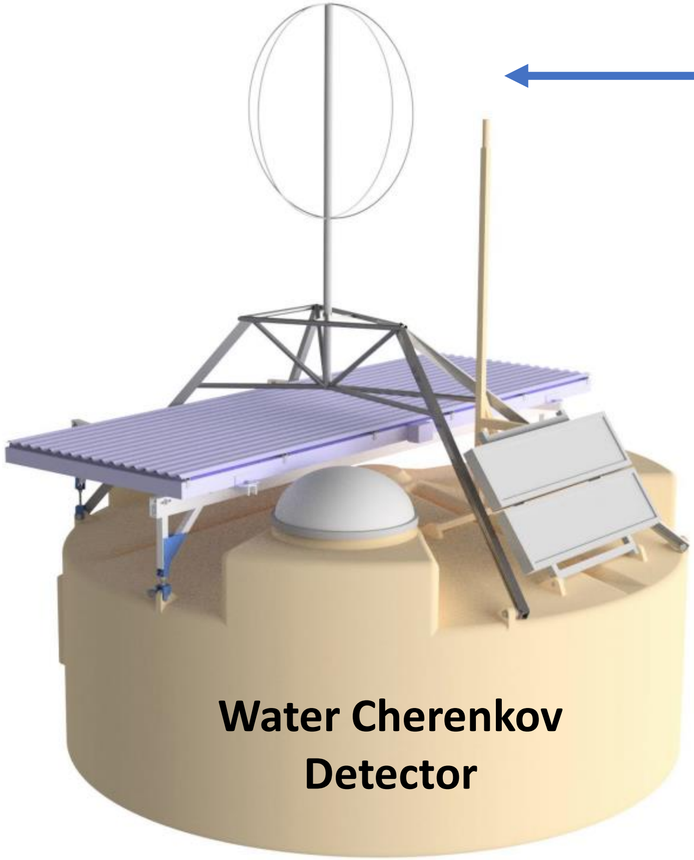
Pierre Auger Observatory:





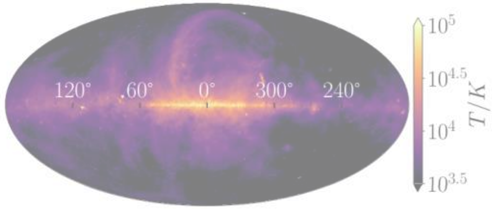
Radio Detector (RD):

- Deployed on **1660** stations
- Short aperiodic loaded loop antenna **(SALLA)**
- **Dual-polarized**
- **30 – 80 MHz** range
- **250 MHz** sampling rate

General Calibration Strategy

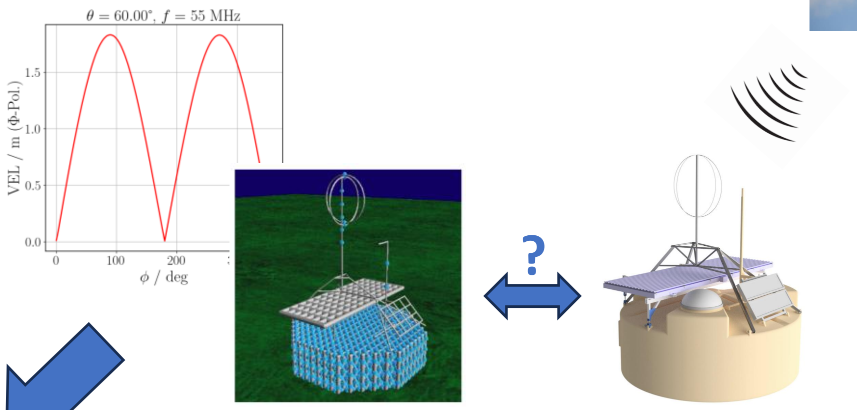
<u>Absolute Galactic Calibration:</u>

- Calibrate **absolute scale** as function of frequency
- Use galaxy as reference signal



<u>Relative Drone-Based Calibration:</u>

- Calibrate **direction-dependence** of antenna pattern for each frequency
- Cross-Check with Simulation



Full-system calibration

Drone Calibration Strategy

Gain Calibration

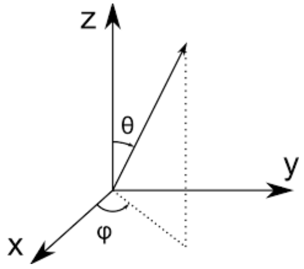
Read-out Voltage **Incoming electric field**

$$\mathcal{U}(\Phi,\Theta,f) = \left|\vec{H}_k(\Phi,\Theta,f)\right| \cdot \left|\vec{\mathcal{E}}_k(f)\right|$$

Vector Effective Length (VEL)

VEL for transmission measurements:

$$|H(\Phi,\Theta,f)| \propto R \cdot \sqrt{P(\Phi,\Theta,f)}$$



Drone Calibration Strategy

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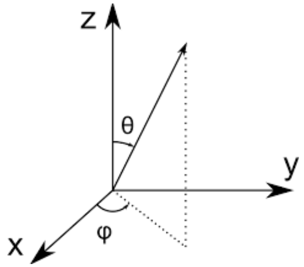
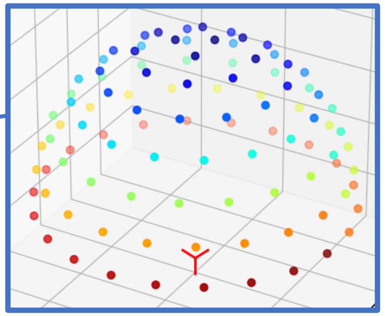


Position (Φ, Θ)

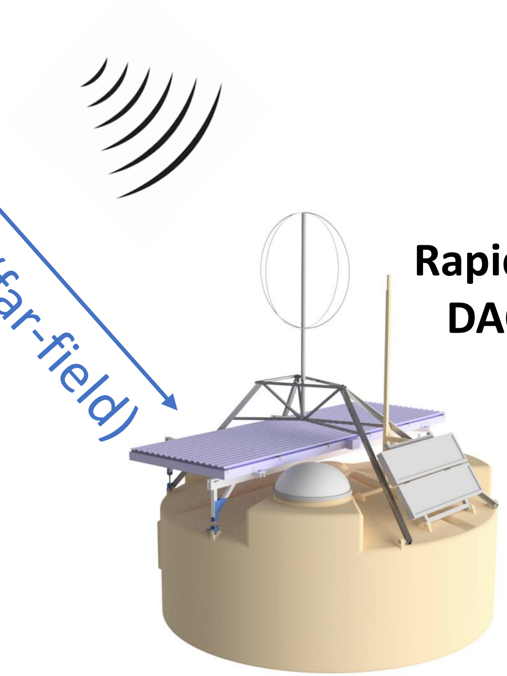
Automated flight

Via **Litchi** Flight Software



- Fly to **"Waypoints"**
- **Stop** for 6s
- **Automatically aim** at antenna

Distance R (far-field)



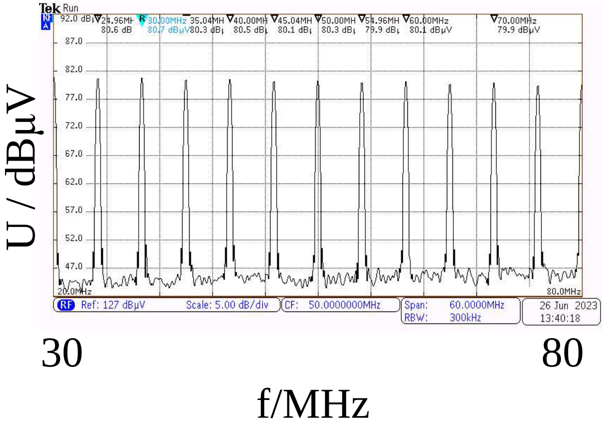
Rapid triggering DAQ (≈ 1 Hz)

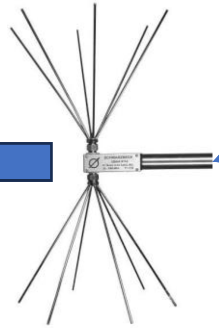
→ **Power P**

Calibration Setup

Spectrum Generator

Amplifier





DJI M600 Pro

- Built-in GPS
- Gimbal for transmission antenna
- Swap polarization between horizontal & vertical

Correction Signals

Differential GPS Base Station

- $\mathcal{O}$(cm) accuracy in station reference frame

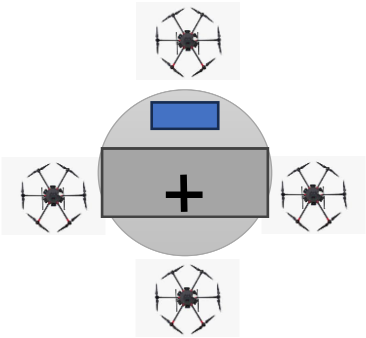
Differential GPS

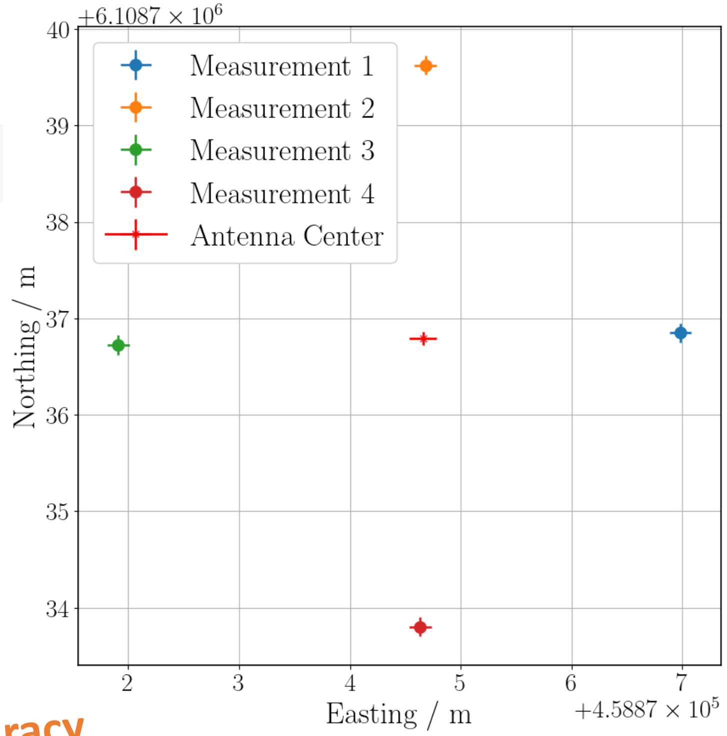
"Take Picture"

Trigger → **dGPS Data Logger (50x in 5s)**

- High accuracy in **base station reference frame**
- Logger triggered **at each waypoint** (via **pre-programmed** flight)

Top-Down View





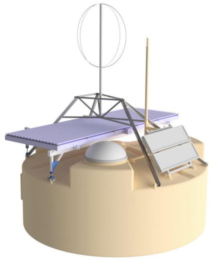
Drone

$\mathcal{O}$(cm) accuracy

High accuracy

Base Station

$\mathcal{O}$(cm) accuracy

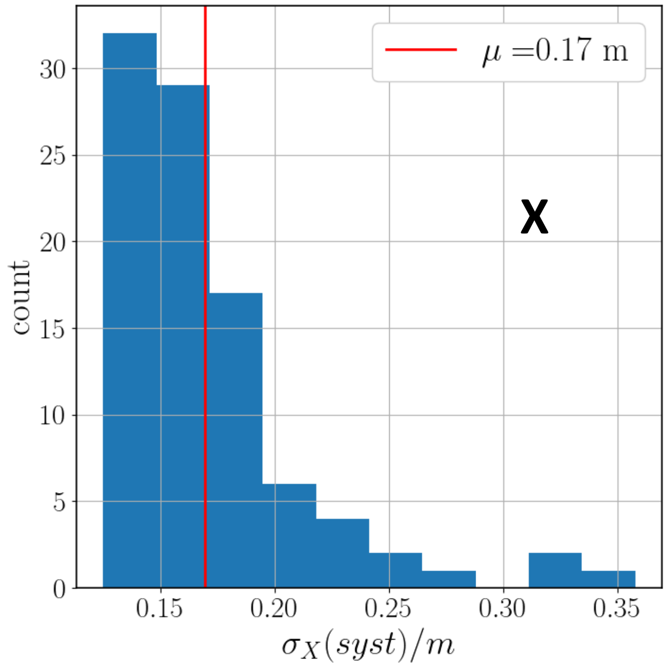


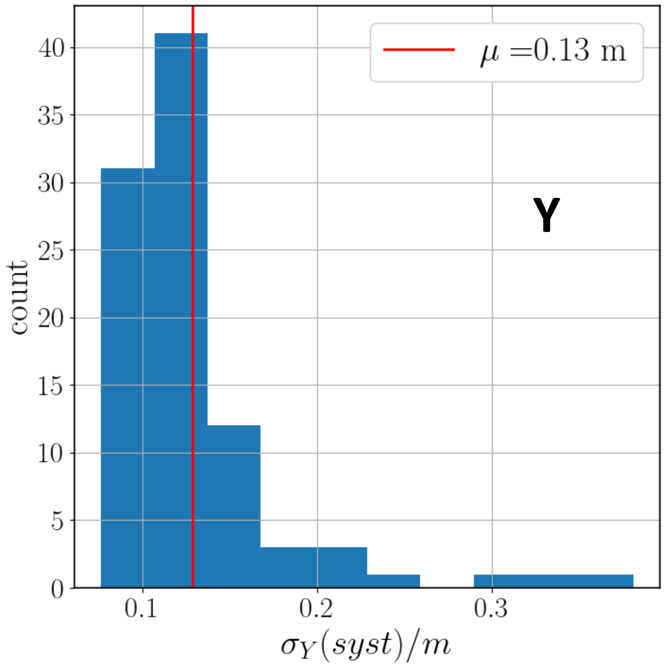
<u>Determine RD coordinates:</u>

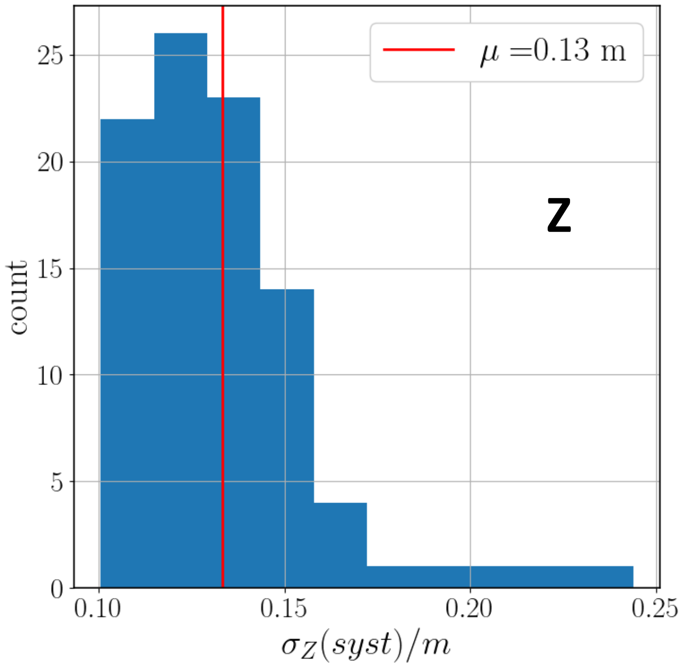
- Perform "Cross-Measurement"
- Place drone in a cross around RD
- Relate RD to dGPS base station

Position Uncertainty

- dGPS time uncertainty and RD position uncertainty increases total position uncertainty
- Uncertainty in **O(10cm)** → 0.3% at 30 m distance







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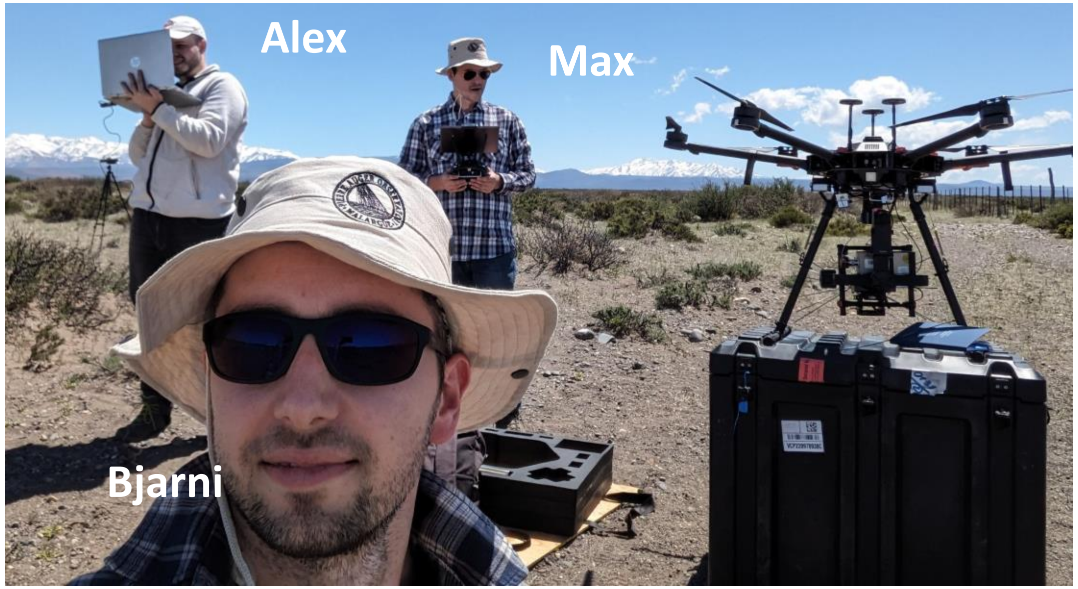
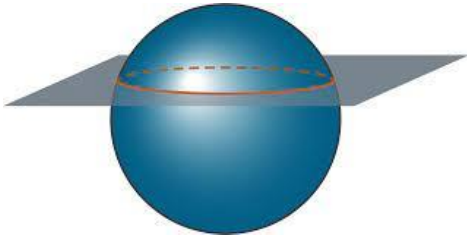
Measurement Campaign

- 3.5 weeks in Argentina: Oct 26 – Nov 18, 2023
- Performed flights: **64**
- Average flight duration: **≈ 13 min**
- Total flight time: **13 h 21 min**



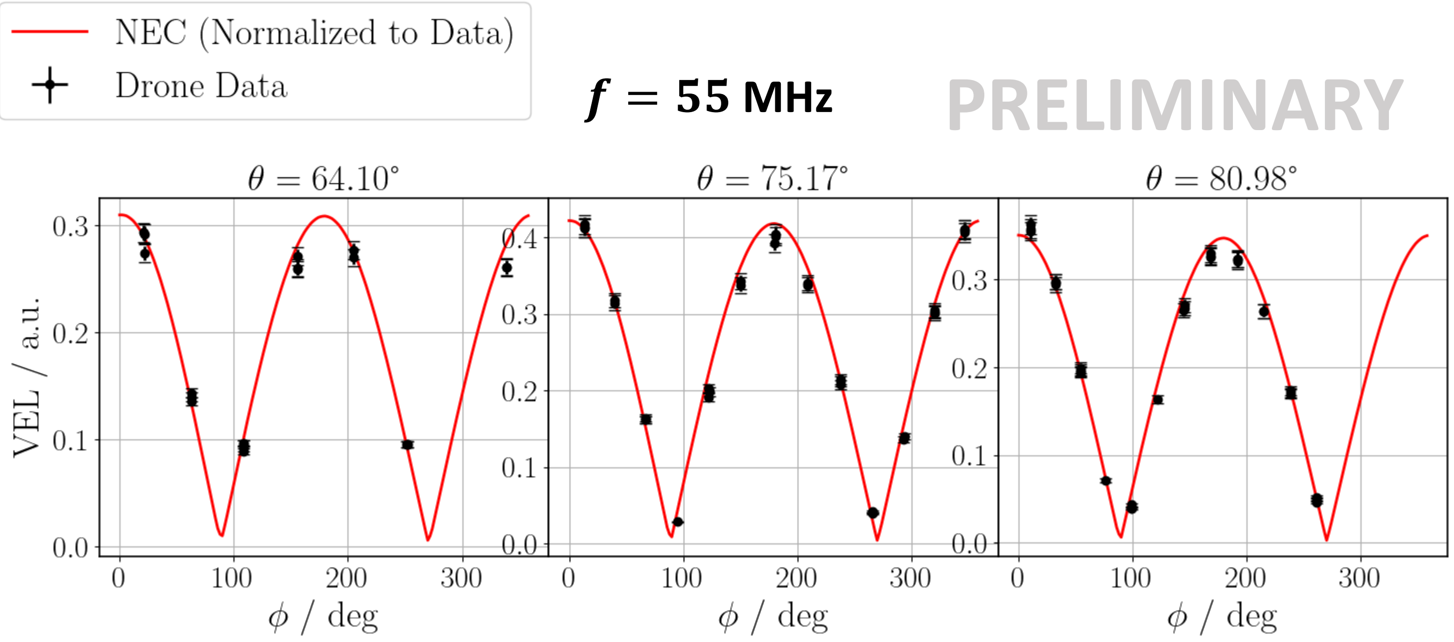
First Results – Example Flight

- ϕ-Polarization flight
- Slices at different zenith angles θ
- Simulation (red) normalized to data
  - ➢ In rough agreement at 7%



Uncertainties:

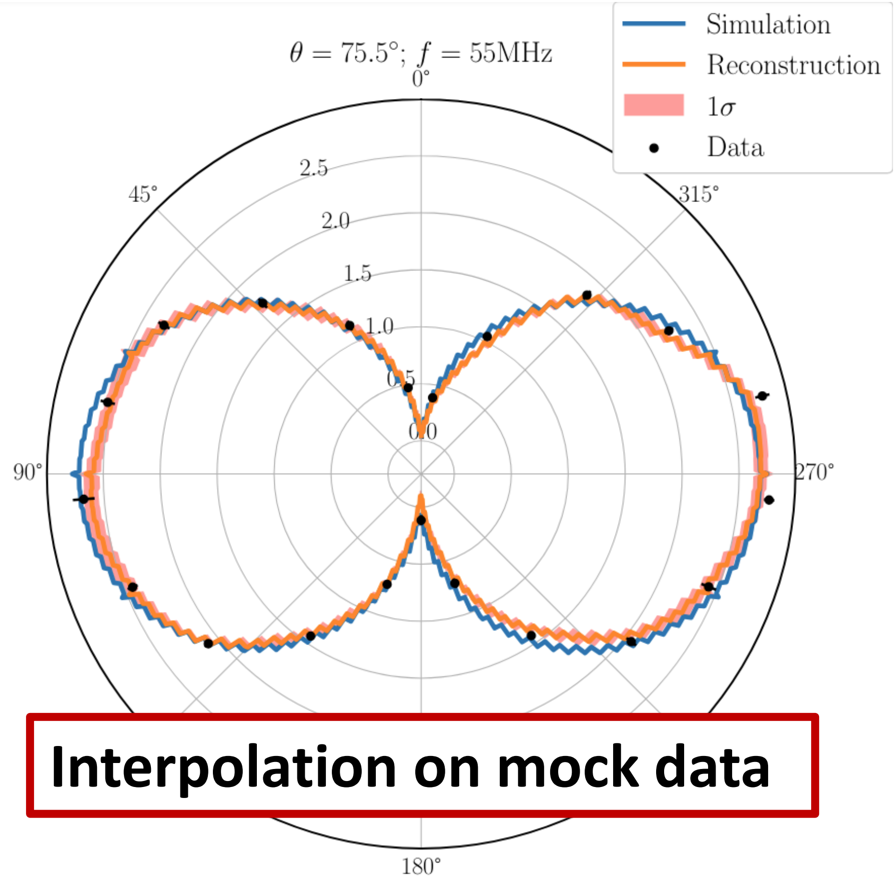
- Systematic: 3%
  - **Electronics**
  - Position Accuracy
  - Trace time-resolution
  - Misalignment Correction
- Statistical: < 1%
  - Background Noise
- Not included:
  - Drone-Influence Correction



Outlook: Interpolation

- Interpolation with **Information Field Theory (IFT)**
- Reconstruct **high dimensional signal field** given **sparse data**
- Bayesian statistics

➢ **Interpolate the VEL in frequency, θ and ϕ with bayesian uncertainties**



Interpolation on mock data

Summary

- Developed **Drone-Based** transmission setup with
  - High accuracy **differential GPS**
  - **Gimbal** for automatic aiming and stabilization
- Performed a **full calibration campaign** on site in Argentina
- **Outlook:** Repeat campaign in **Oct/Nov 2025** with knowledge we gained last year

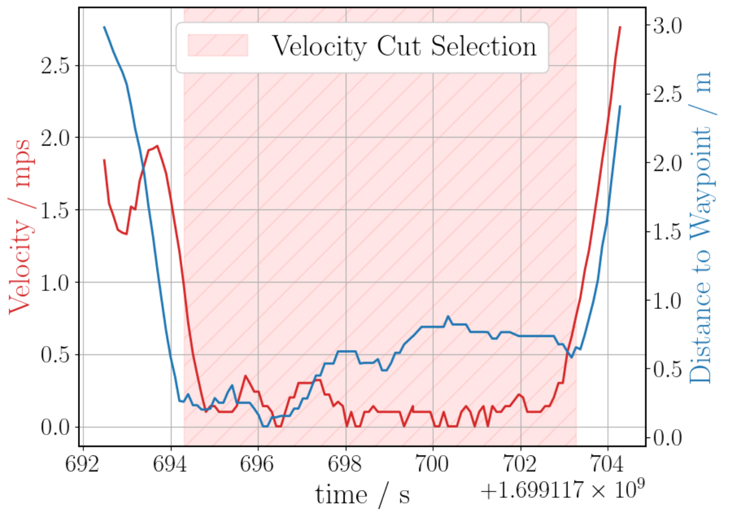
Backup

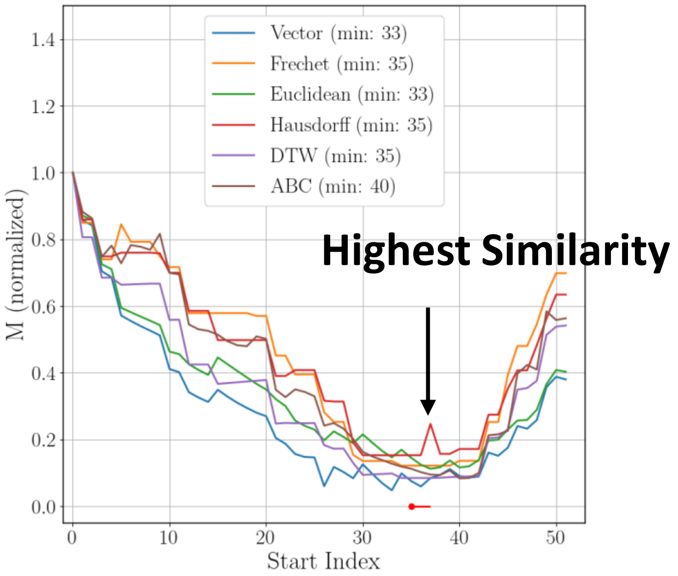
Data Selection

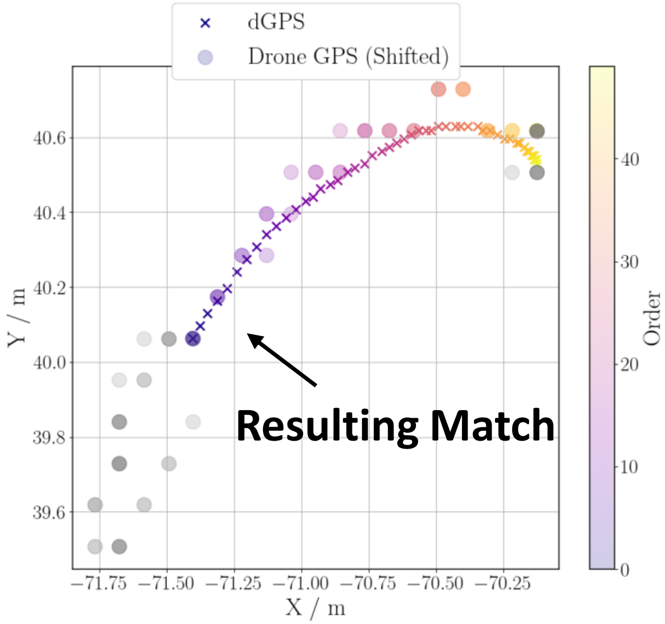
<u>Goal: Select data recorded while **drone stationary**</u>

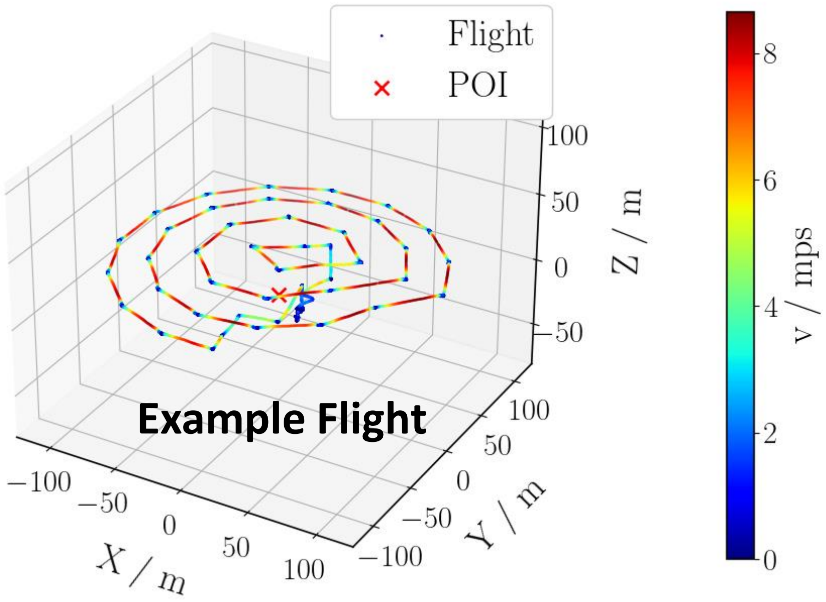
1. Rough **velocity & distance cut**
2. Find time of dGPS data inside rough cut using **similarity measures**
   - Compare dGPS trajectory with drone GPS trajectory
   - Distance Metrics used as similarity measure
   - Uncertainty on time propagates into position error

Velocity & Distance Cut



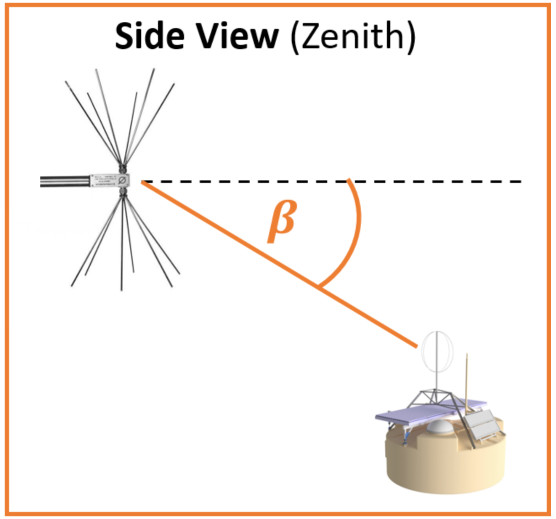


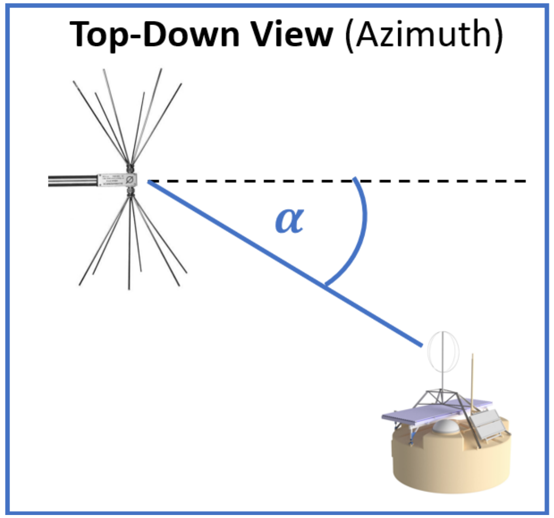




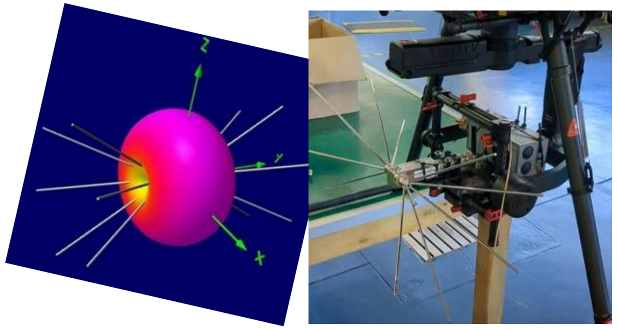
Misalignment Correction & Drone Influence

- Quantify misalignment using two angles
  - **α:** Misalignment in azimuth of emitter
  - **β:** Misalignment in zenith of emitter
- Emitter in **free-space** represents a **normal dipole**



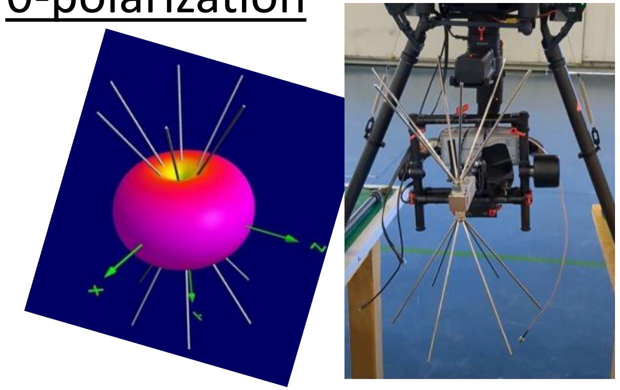


ϕ-polarization



- In azimuth (α): $\cos^2 \alpha$
- In zenith (β): constant

θ-polarization

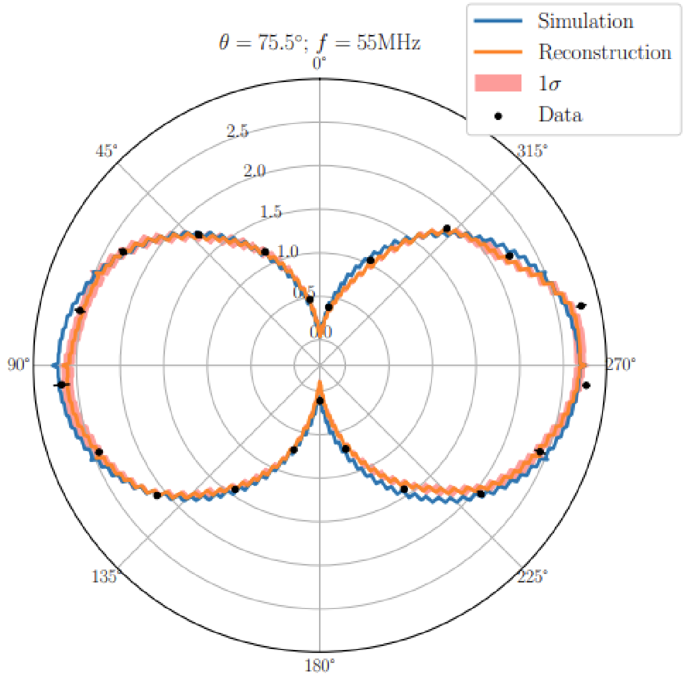


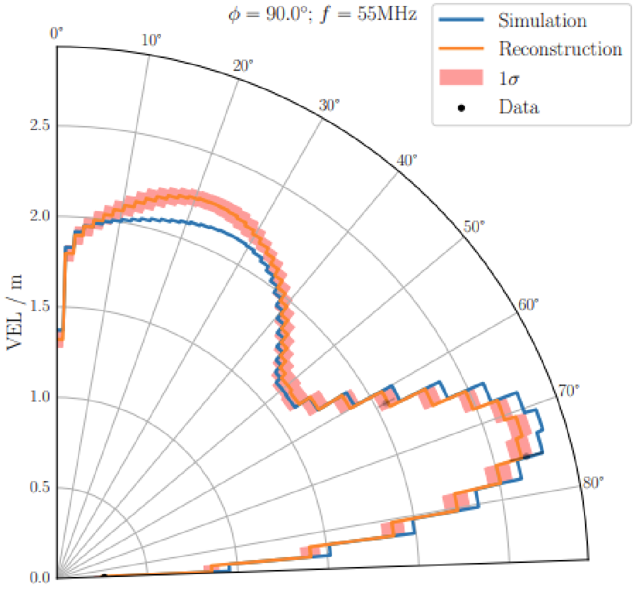
- In azimuth (α): constant
- In zenith (β): $\cos^2 \beta$

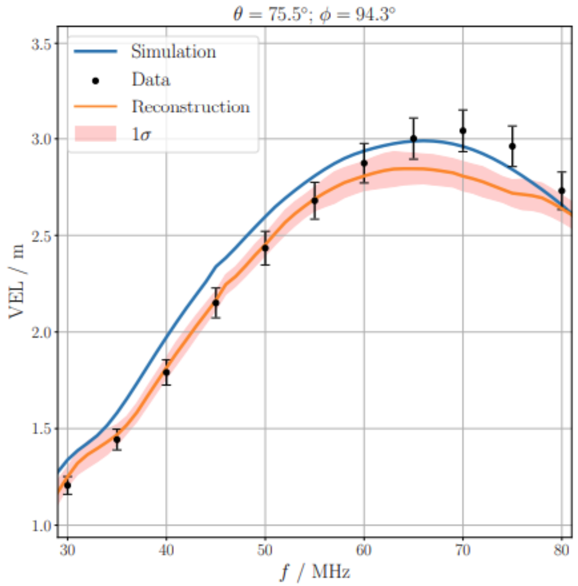
❖**Dipole behavior changes when adding a surrounding structure (drone+gimbal)!**

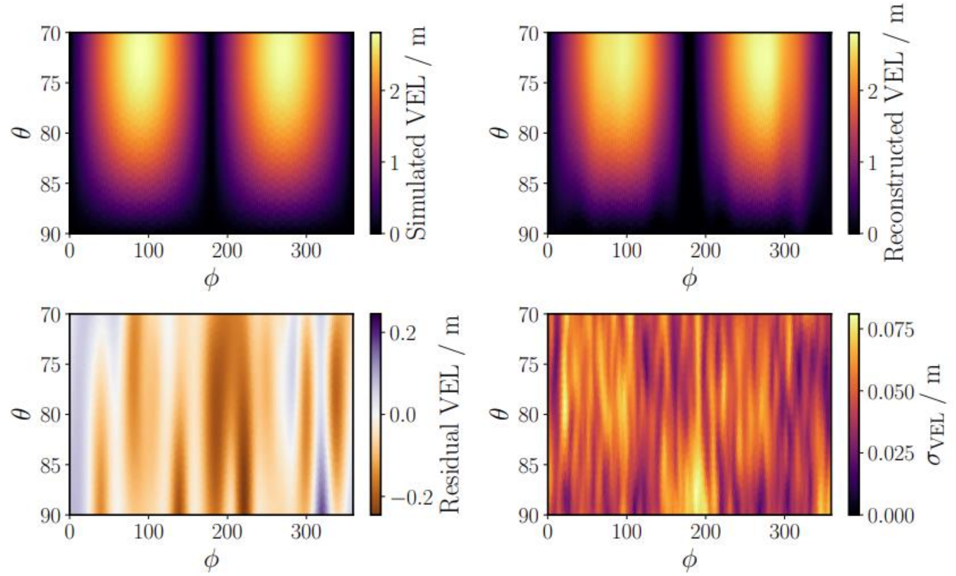
❖Correction not implemented yet, expected to be in the order of 1-10%

Mock Interpolation









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