PIERRE AUGER OBSERVATORY

Physics Institute III | RWTH AACHEN UNIVERSITY

Drone-Based Calibration of AugerPrime Radio Antennas at the Pierre Auger Observatory

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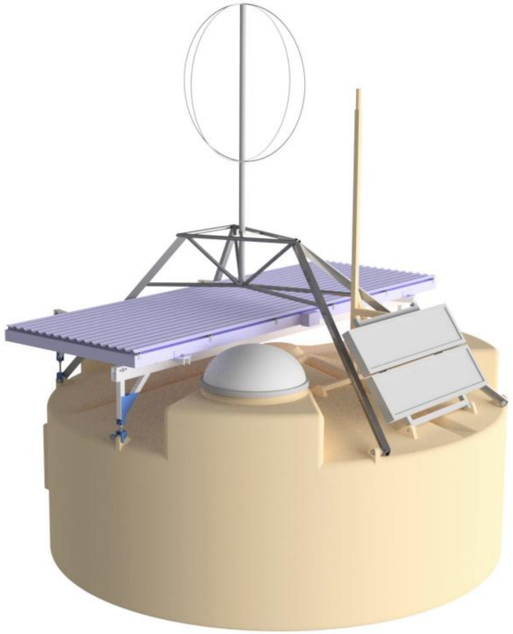
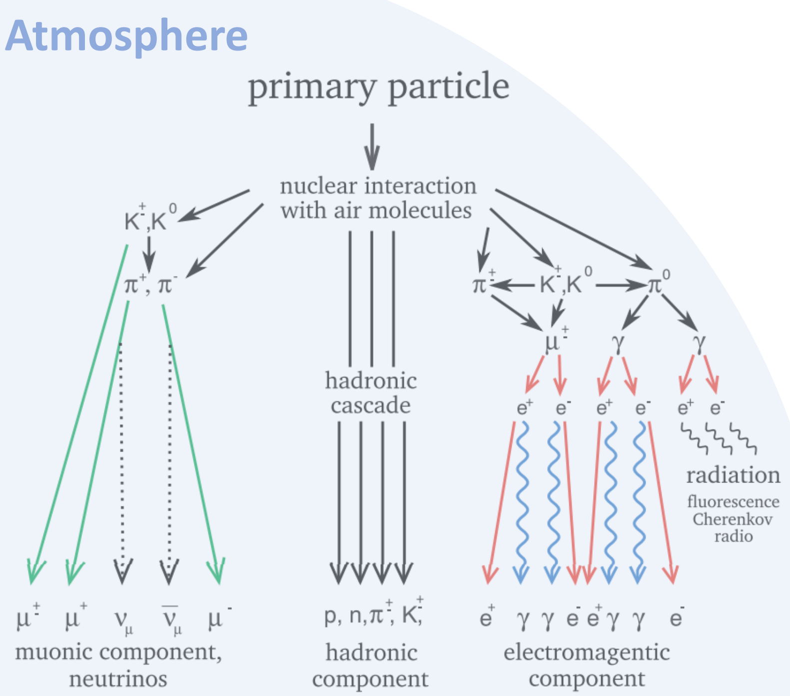
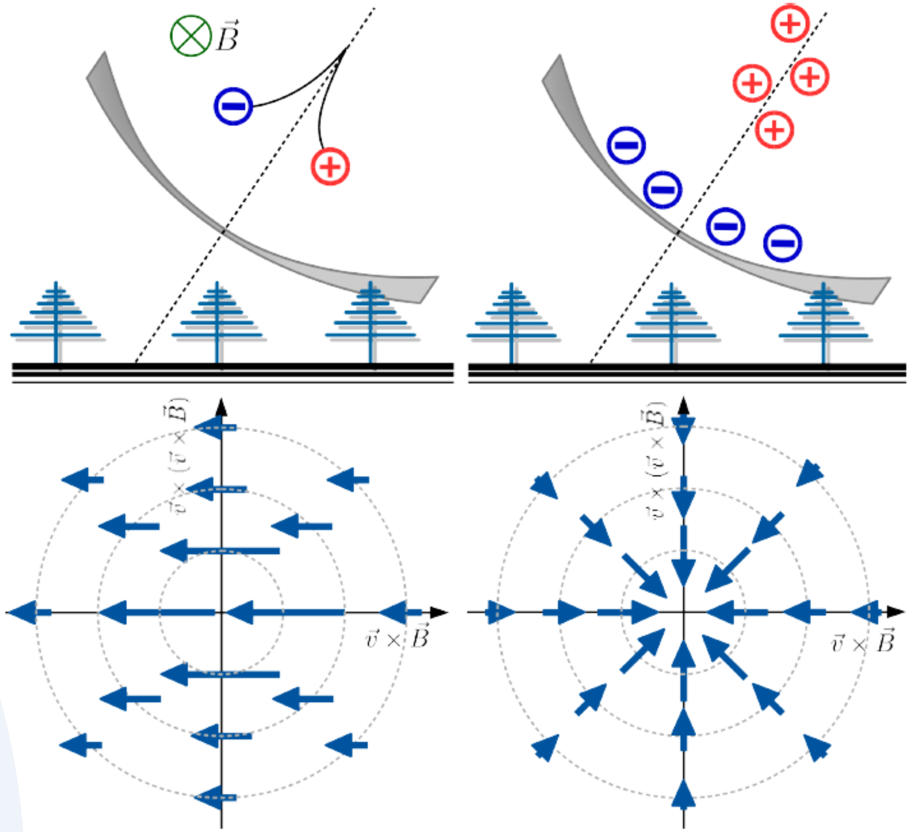


GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Radio Emission of Air Showers

Ultra-High-Energy Cosmic Ray





Geomagnetic Effect (left):

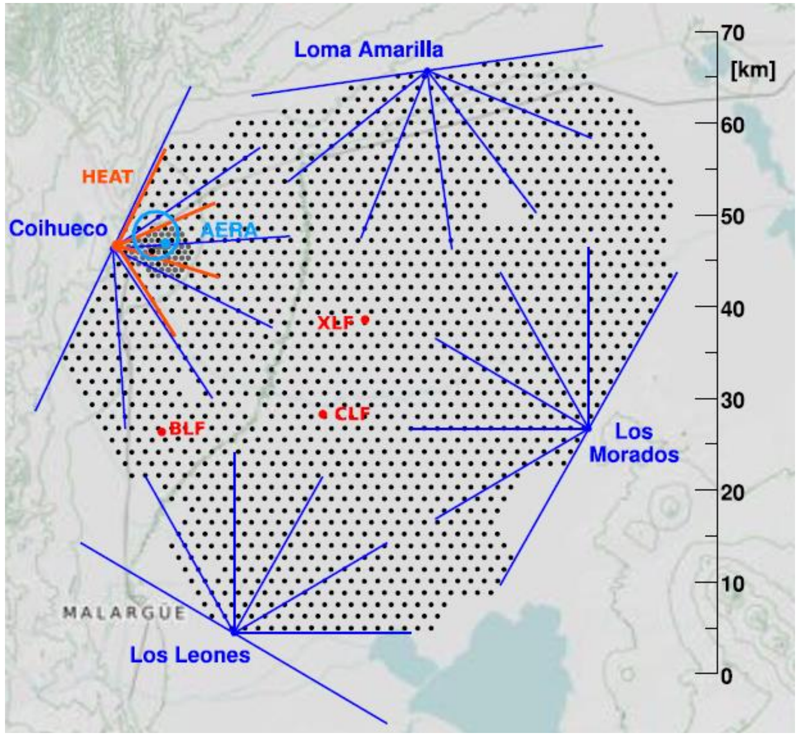
- **Deflection of e^+ & e^- in Earth's magnetic field**
- Creates time-varying current
- **Main contribution**

Askaryan Effect (right):

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

Pierre Auger Observatory

Pierre Auger Observatory:
- 1660 Water-Cherenkov Detector Stations
- 4 Fluorescence Detector sites



Science Goals:

Pierre Auger Observatory:

- Study cosmic rays of highest energies ,

  $E > 10^{17}$ eV (UHECR)

➢ **Origin** of UHECR

➢ **Acceleration** mechanism

AugerPrime Upgrade:

- Improve **mass sensitivity**

AugerPrime Radio Detector

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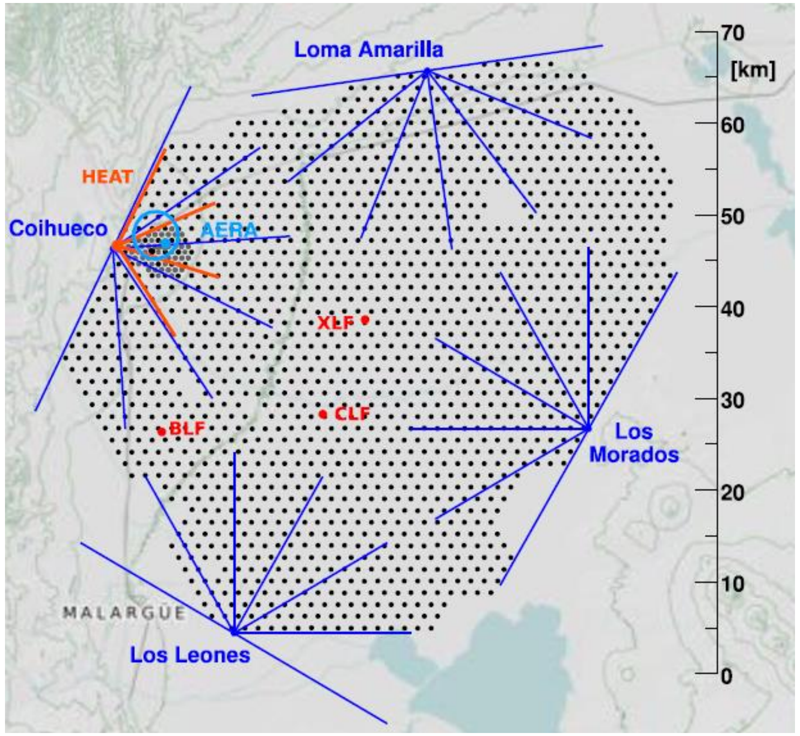
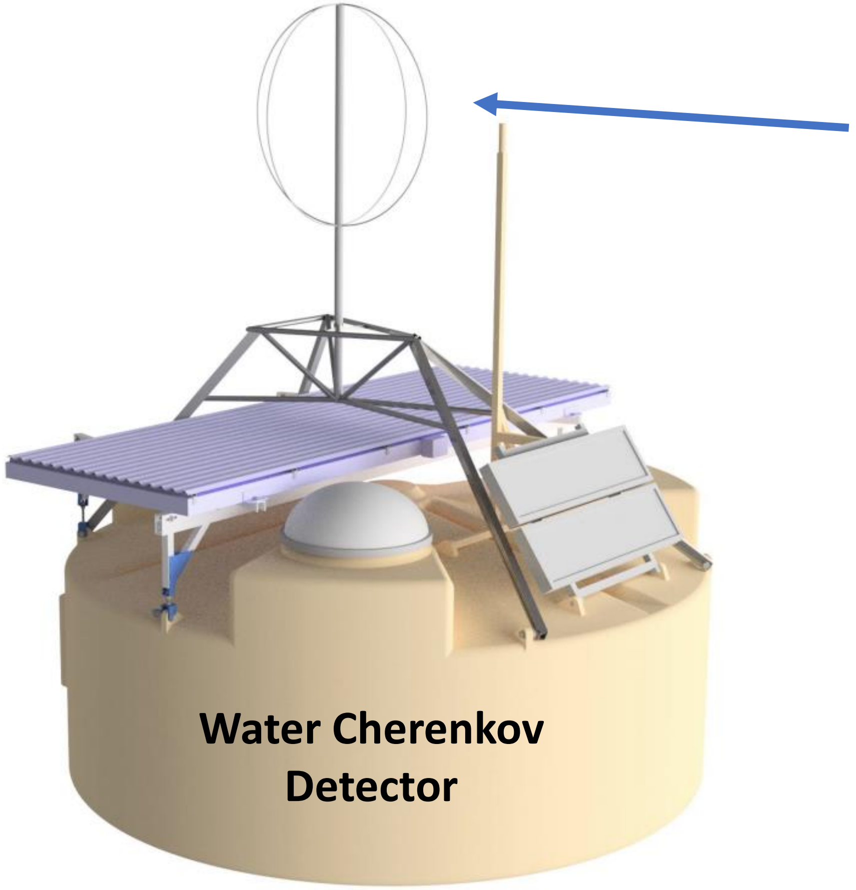


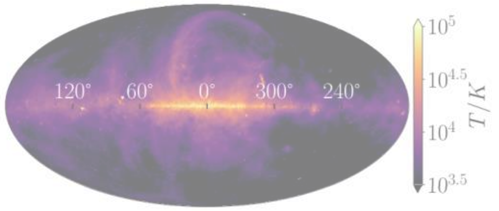


Radio Detector (RD):
- Deployed on **1660** stations
- Short aperiodic loaded loop antenna **(SALLA)**
- **Dual-polarized**
- **30 – 80 MHz** range
- **250 MHz** sampling rate

General Calibration Strategy

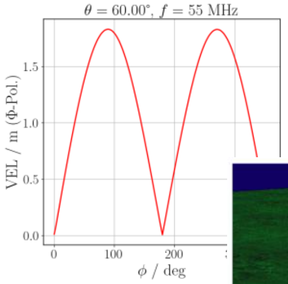
Absolute Galactic Calibration:

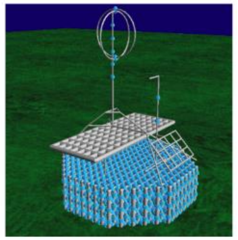
- Calibrate **absolute scale** as function of frequency
- Galaxy emits radio in relevant frequency band
- Use galaxy as reference signal



Relative Drone-Based Calibration:

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





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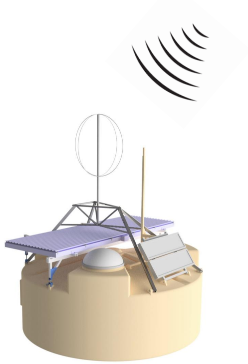


Full-system calibration

Drone Calibration Strategy

Gain Calibration

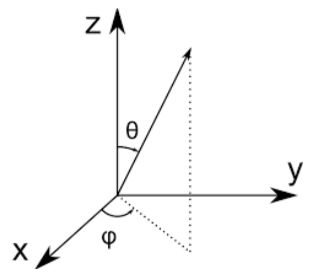
Read-out Voltage — **Incoming electric field**

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

Vector Effective Length (VEL)

VEL for transmission measurements:

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



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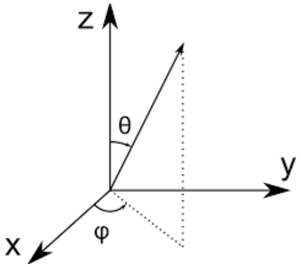
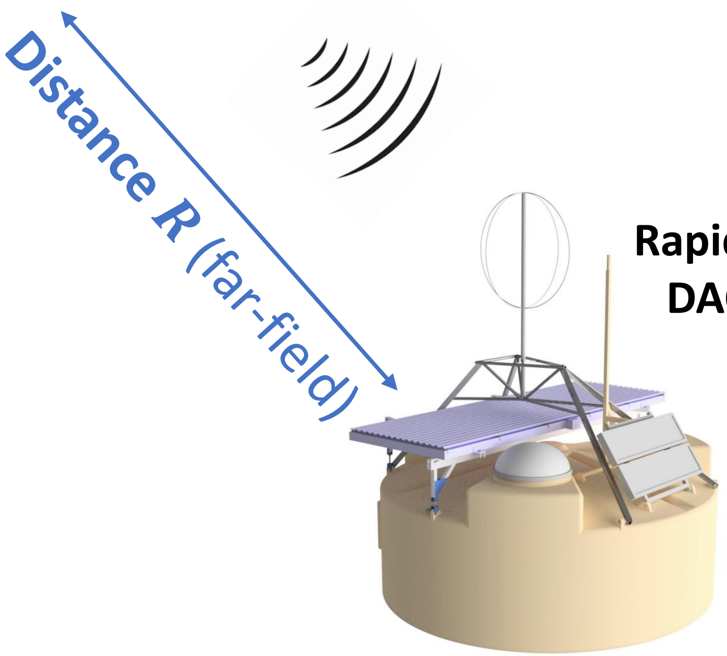


Position (Φ, Θ)



Rapid triggering DAQ (≈ 1 Hz)

Power P

Drone Calibration Strategy

Gain Calibration

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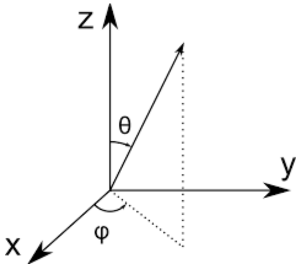
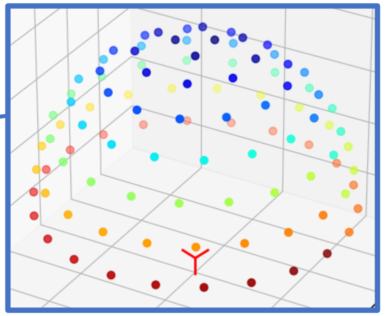


Position (Φ, Θ)

Automated flight

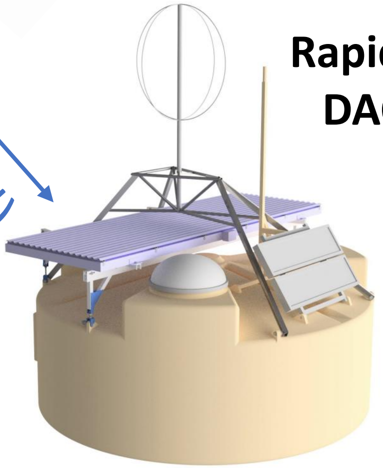
Via **Litchi** Flight Software



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

Distance *R* (far-field)

Rapid triggering DAQ (≈ 1 Hz)

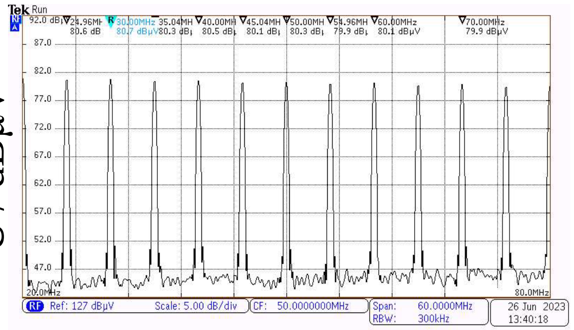


Power *P*

Calibration Setup

Spectrum Generator

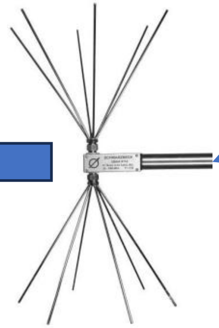
Amplifier



U / dBµV

30 80

f/MHz



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)

Drone

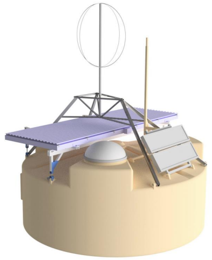
$\mathcal{O}$(cm) accuracy

High accuracy

- High accuracy in **base station reference frame**
- Logger triggered **at each waypoint**

Base Station

$\mathcal{O}$(cm) accuracy



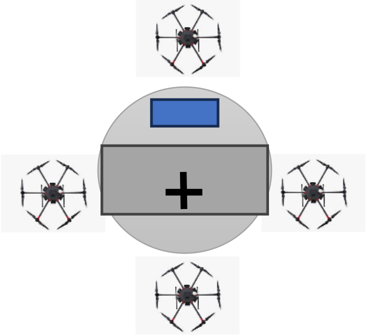
Differential GPS

"Take Picture"

Trigger

dGPS Data Logger (50x in 5s)

Top-Down View



Drone

$\mathcal{O}$(cm) accuracy

High accuracy

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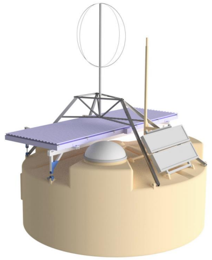
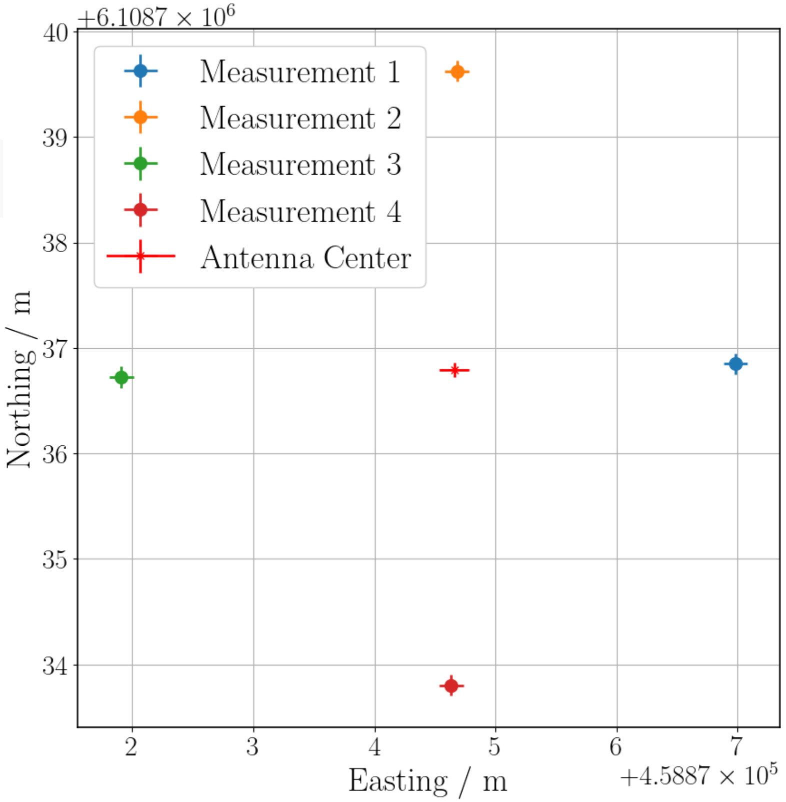
Base Station

$\mathcal{O}$(cm) accuracy



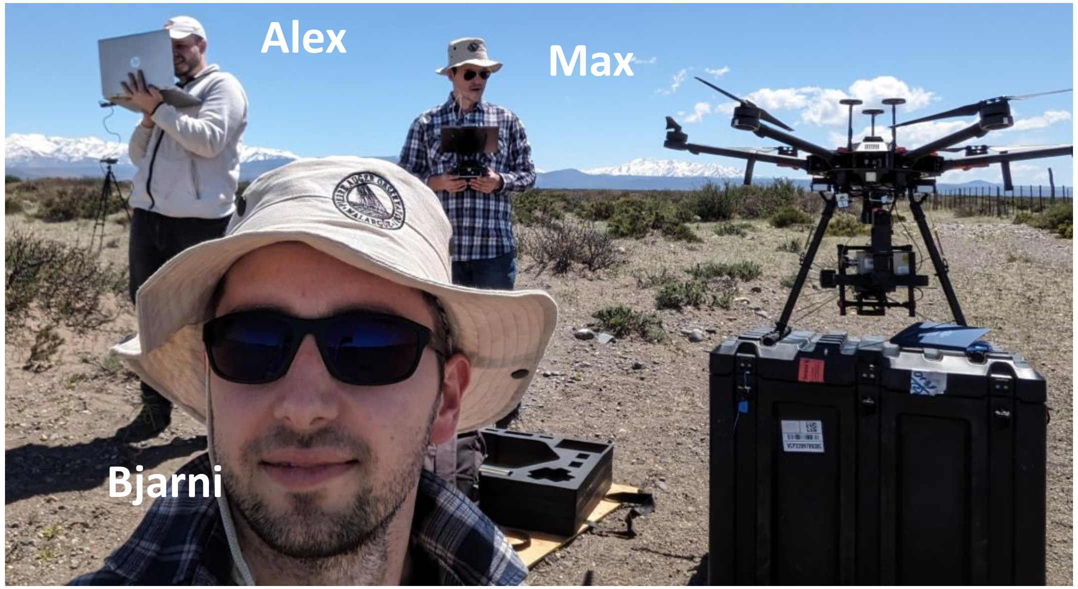


Determine RD coordinates:

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

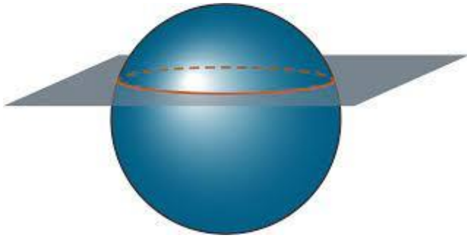
Measurement Campaign

- 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%

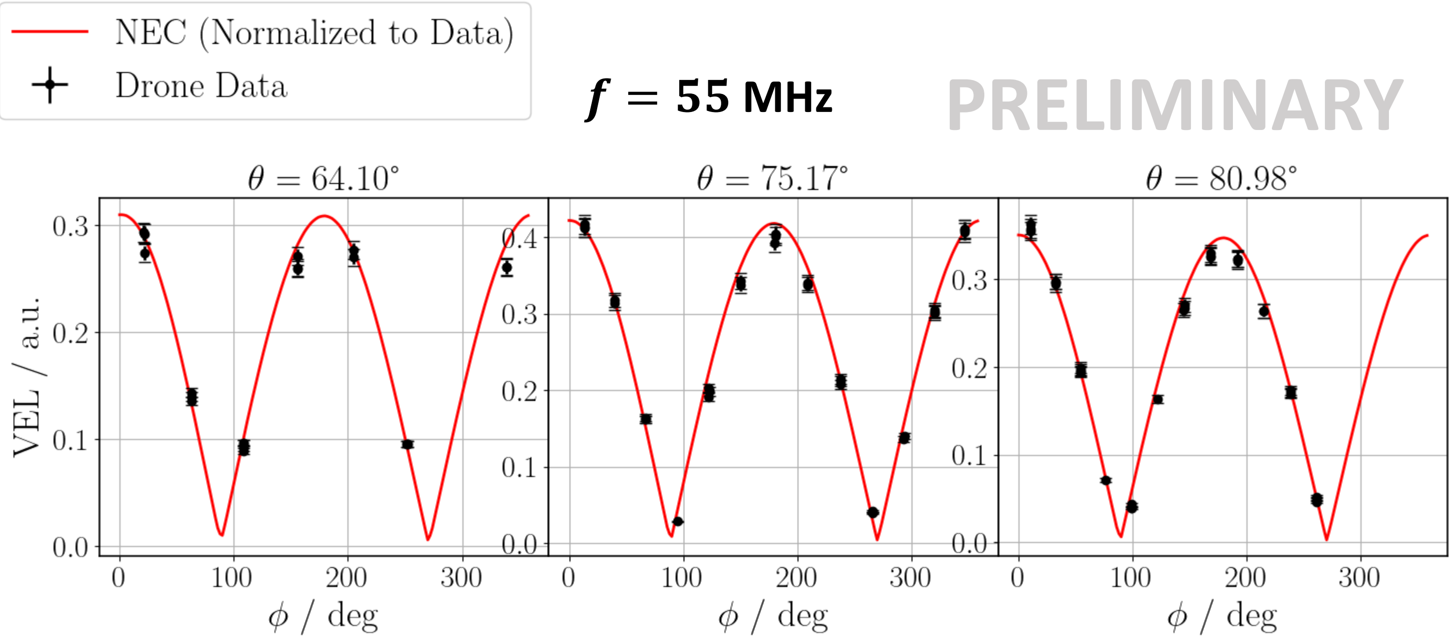


Uncertainties:

- Systematic: 3%
  - **Electronics**
  - Position Accuracy
- Statistical: $< 1\%$
  - Background Noise
- Not included:
  - Drone-Influence Correction

f = **55 MHz**

PRELIMINARY



Summary & Outlook

Summary:

- Developed **Drone-Based** transmission setup with
- Performed a **full calibration campaign** on site in Argentina

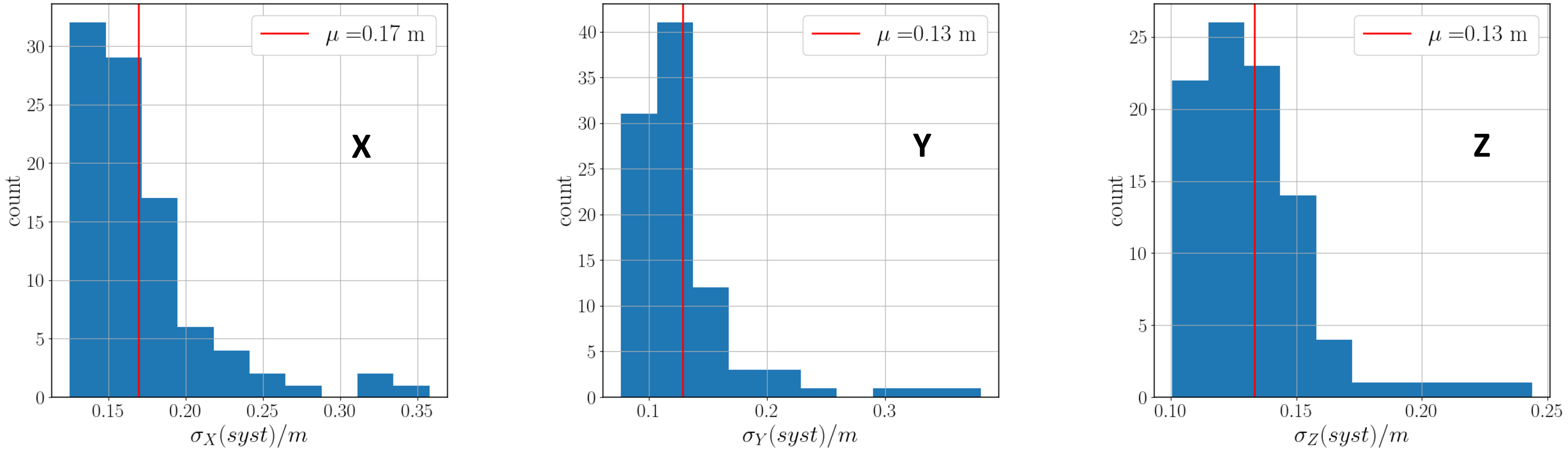
Outlook:

- Interpolation with Information Field Theory
- Repeat campaign in **Oct/Nov 2025** with knowledge we gained last year

Backup

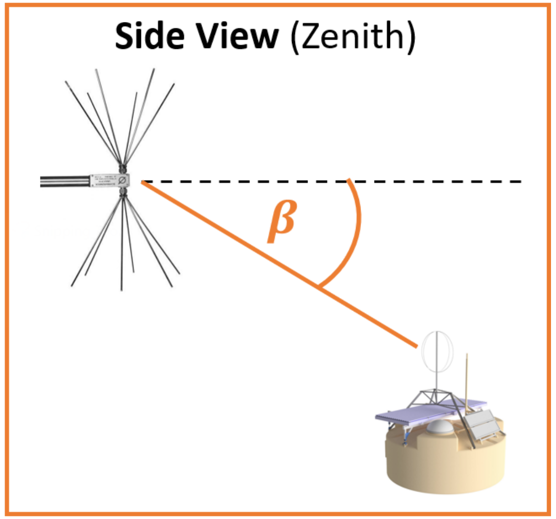
Position Uncertainty

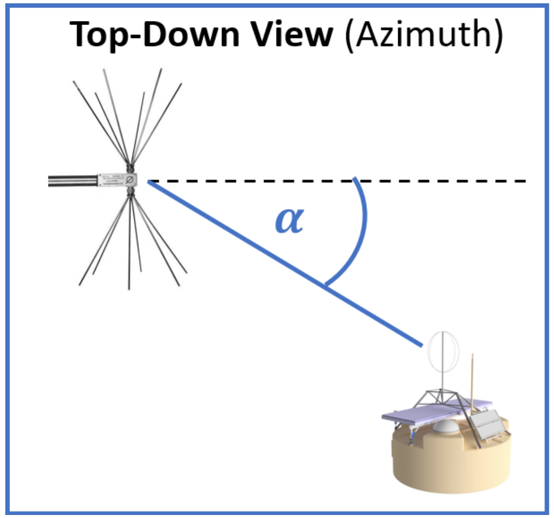
- dGPS time uncertainty and RD position uncertainty increases total position uncertainty
- Uncertainty in **O(10cm)** → 0.3% at 30 m distance



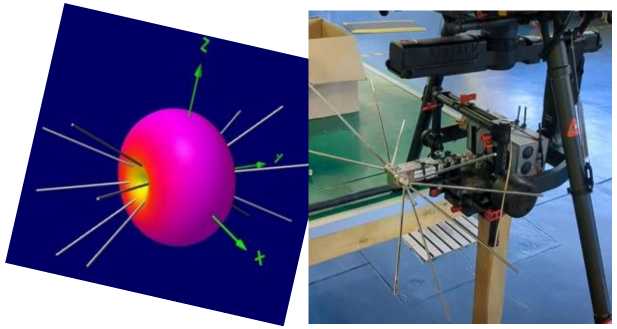
Misalignment Correction & Drone Influence

- 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**



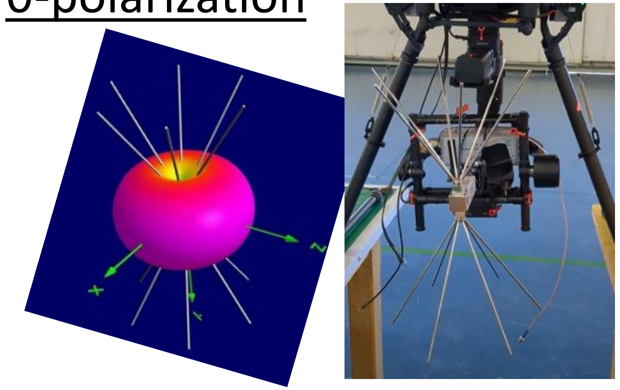


<u>ϕ-polarization</u>



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

<u>θ-polarization</u>



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

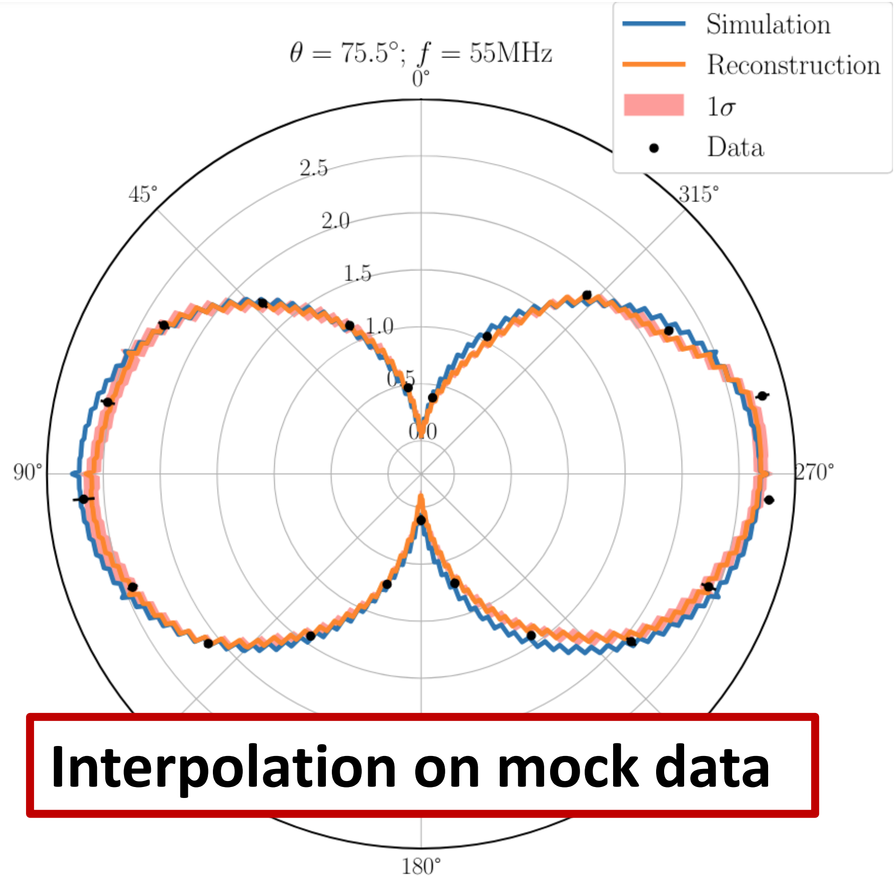
❖**Dipole behavior changes when adding a surrounding structure (drone+gimbal)!**

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

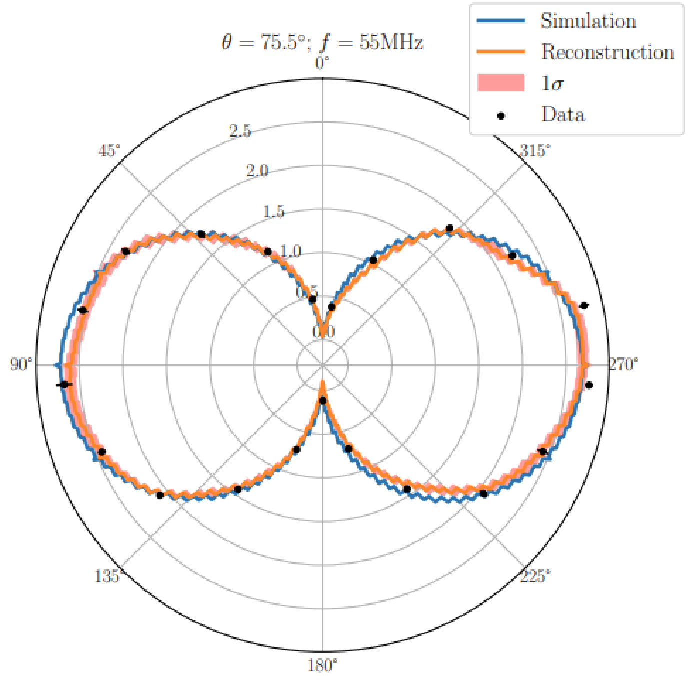
Outlook: Interpolation

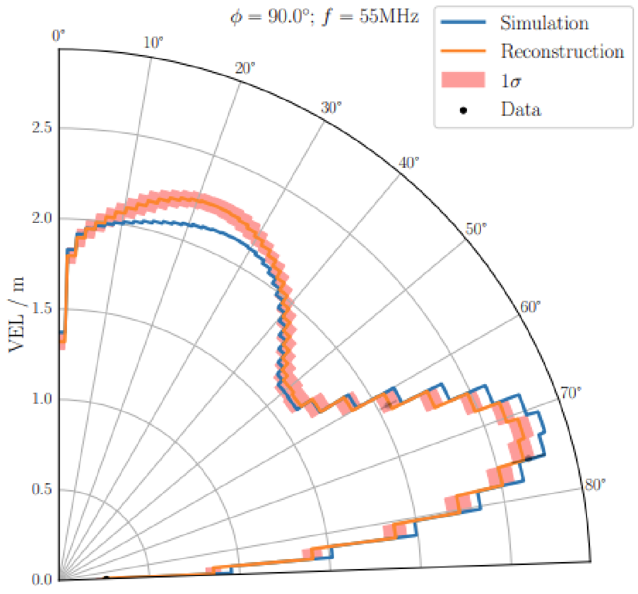
- Interpolation with **Information Field Theory (IFT)**
- Reconstruct **high dimensional signal field** given **sparse data**
- Bayesian statistics

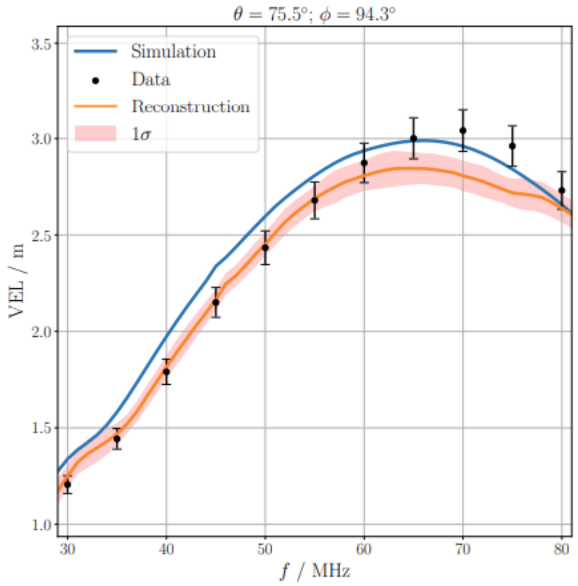
➢ **Interpolate the VEL in frequency, θ and ϕ with bayesian uncertainties**

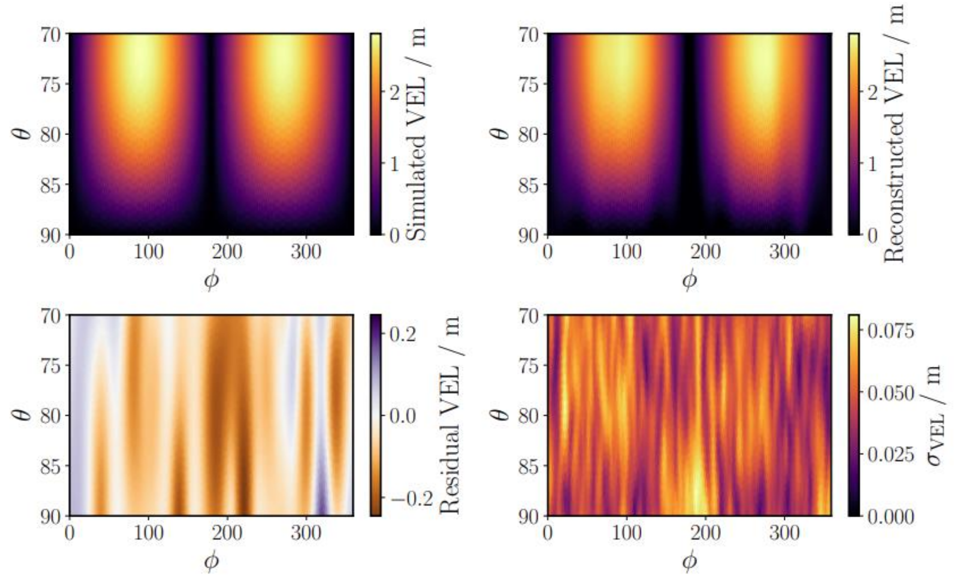


Mock Interpolation









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