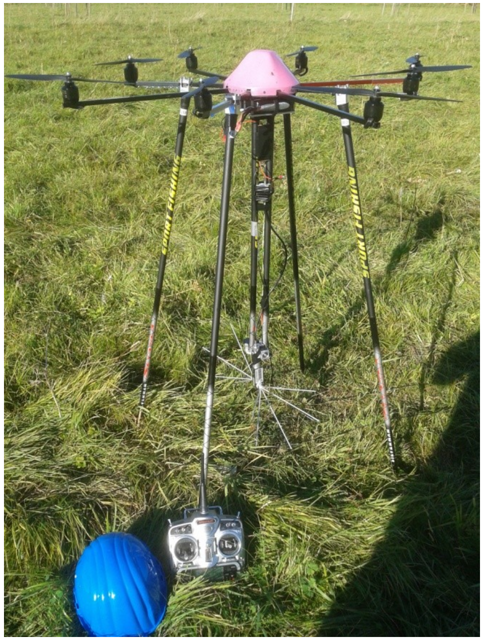

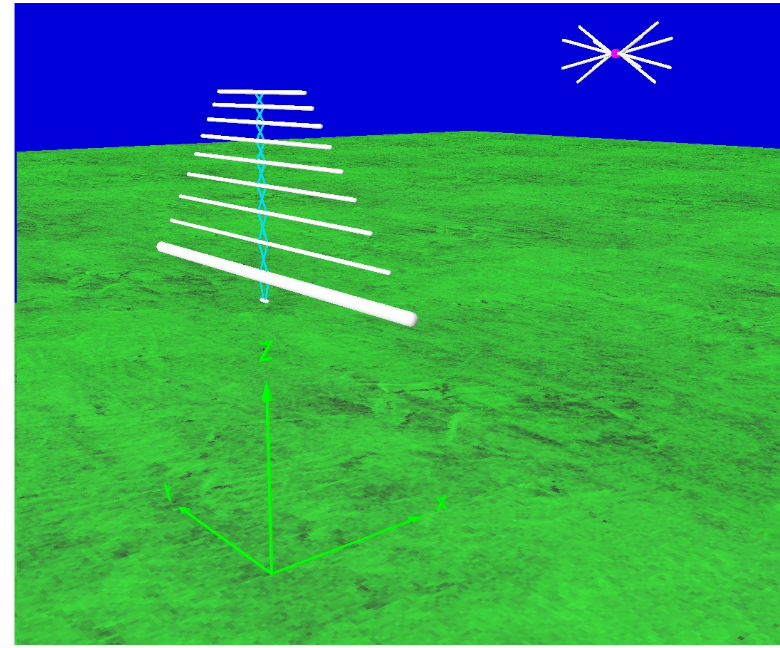

In-situ absolute calibration of electric-field amplitude measurements with the radio detector stations of the Pierre Auger Observatory

Florian Briechle
for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

HELMHOLTZ | ASSOCIATION
Alliance for Astroparticle Physics

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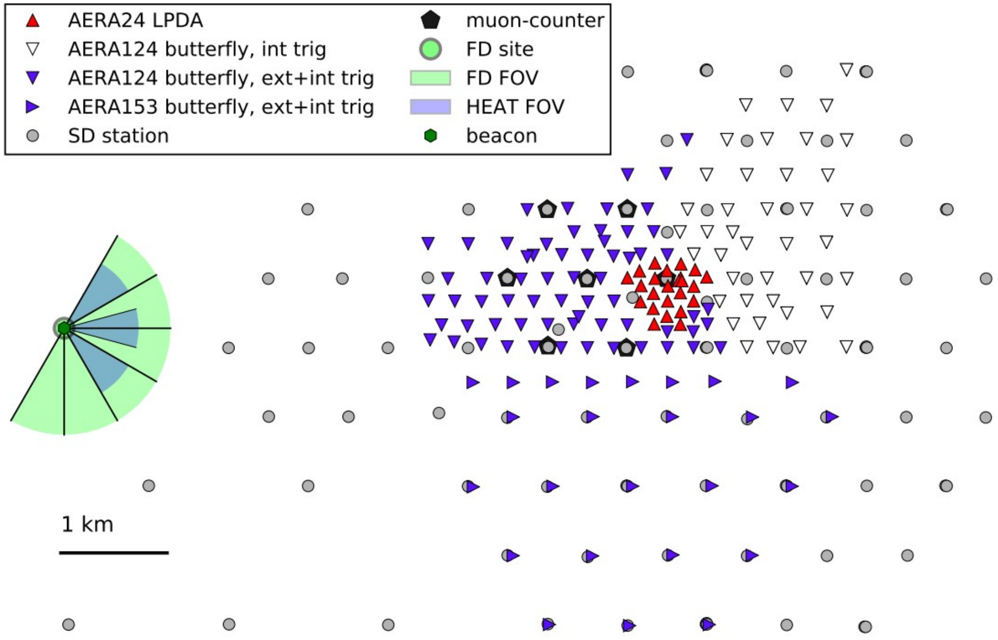
DFG

The Auger Engineering Radio Array

- 153 radio stations on 17 km²
- Two different station types
  - Log-periodic dipole antenna (LPDA)
  - Butterfly
- Two polarizations
- Sensitive in the range of 30 – 80 MHz
- Precise energy measurements of cosmic rays only possible with high accuracy calibration



LPDA

Butterfly

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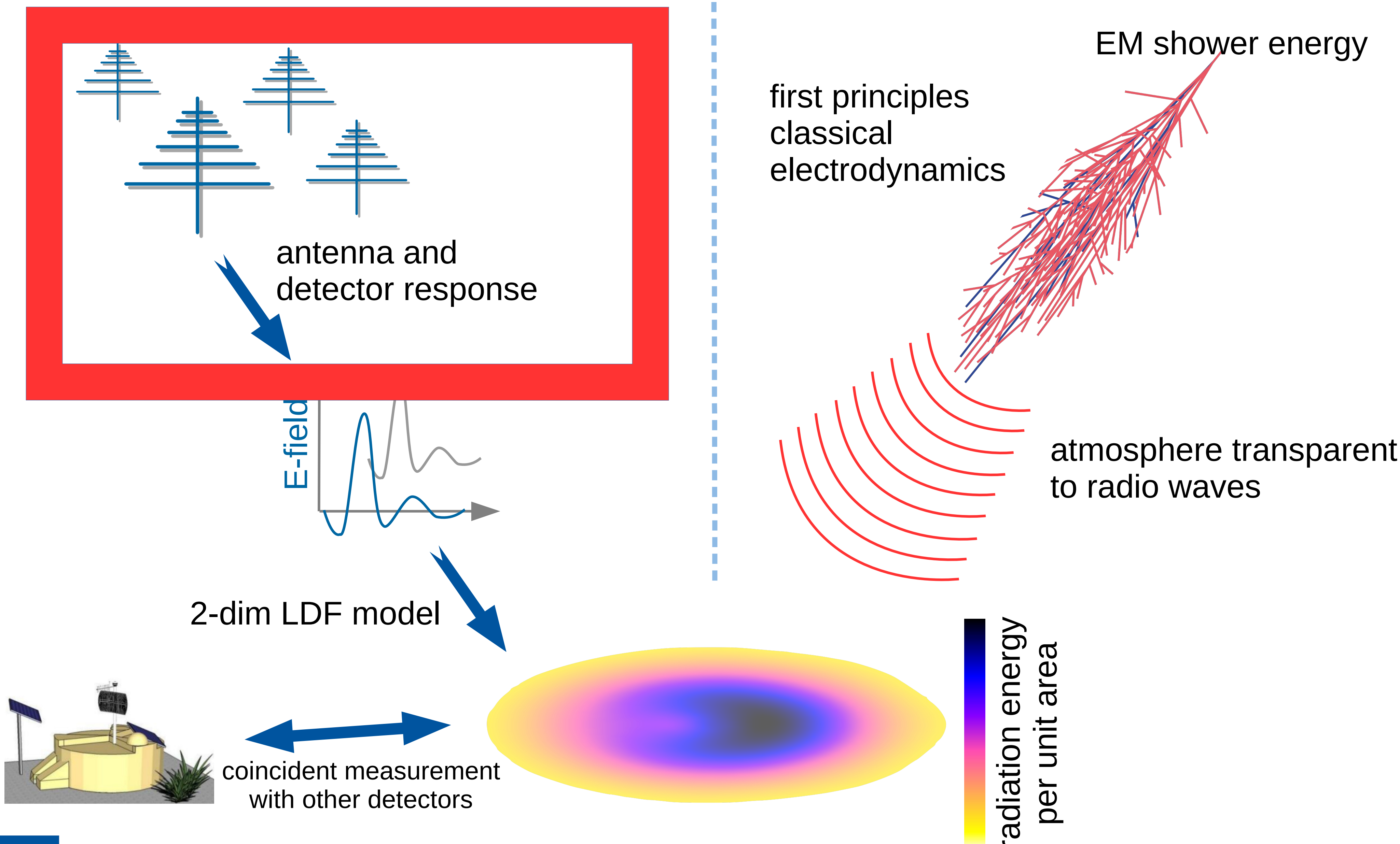
Independent Determination of Cosmic-Ray Energy Scale

Measurement

Theoretical calculation



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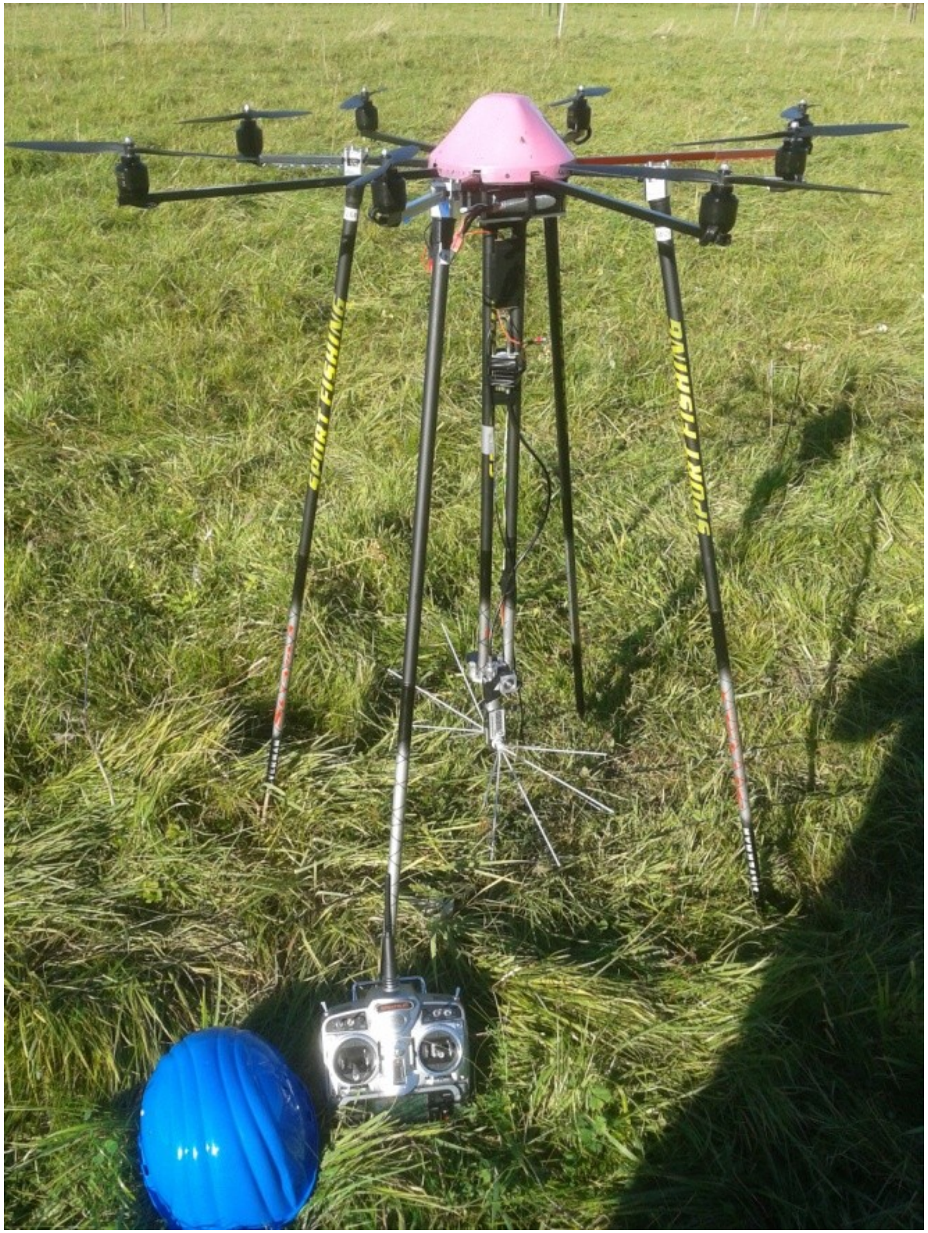
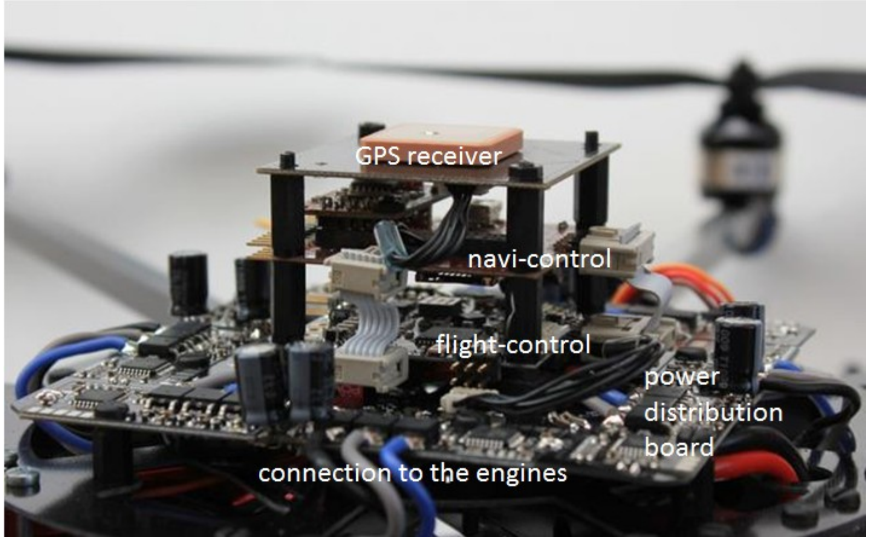
Octocopter





- power: 6600 mAh Lipo 13-16 V
- Payload: ~2000 g
- Mass: 2545 g (including 715g accumulator)
- flight time: 25 min/ 7 min (without/with payload)
- barometer → elevation
- gyroscope → inclination
- acceleration sensor → angular speed
- GPS → position

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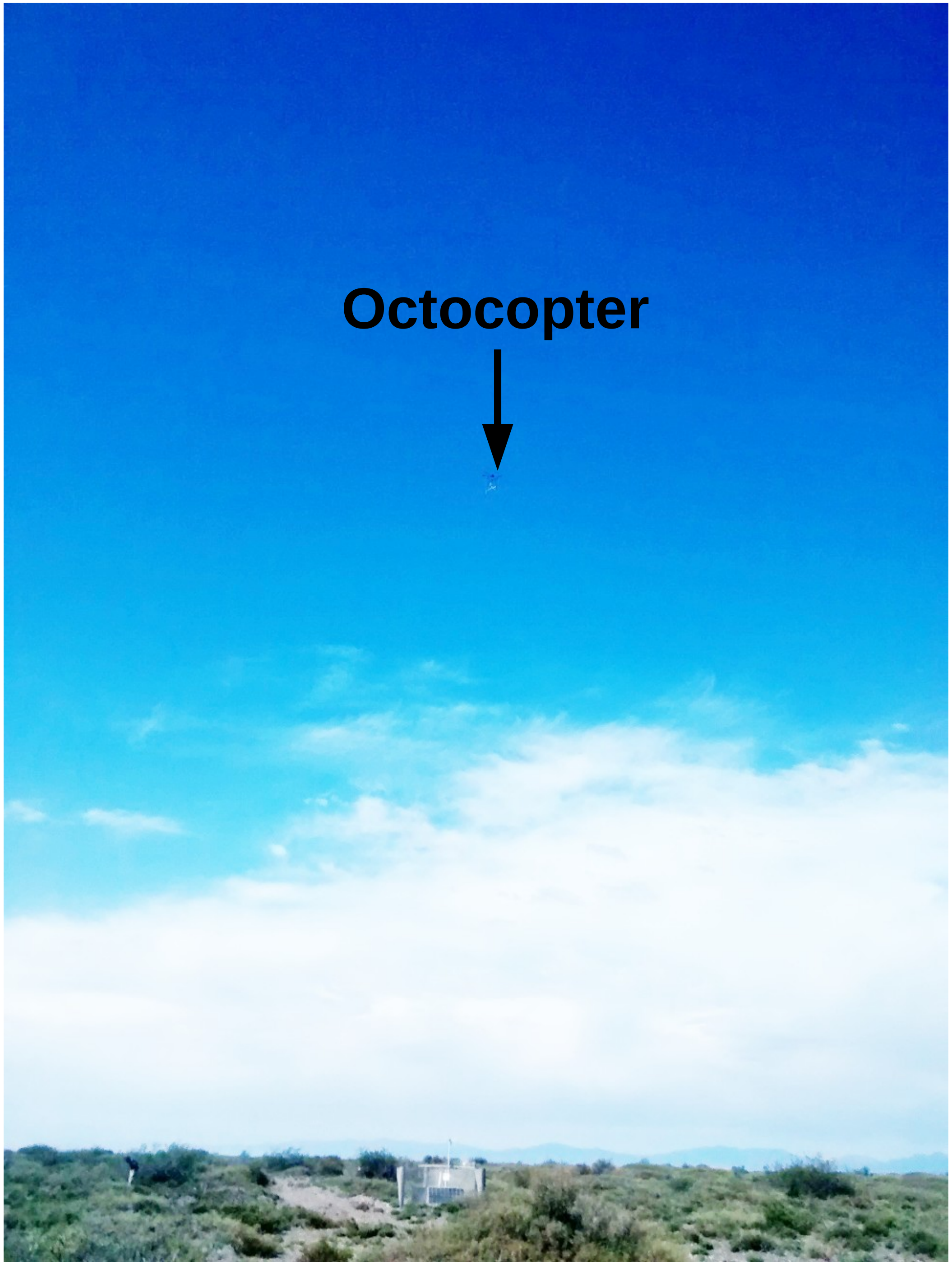
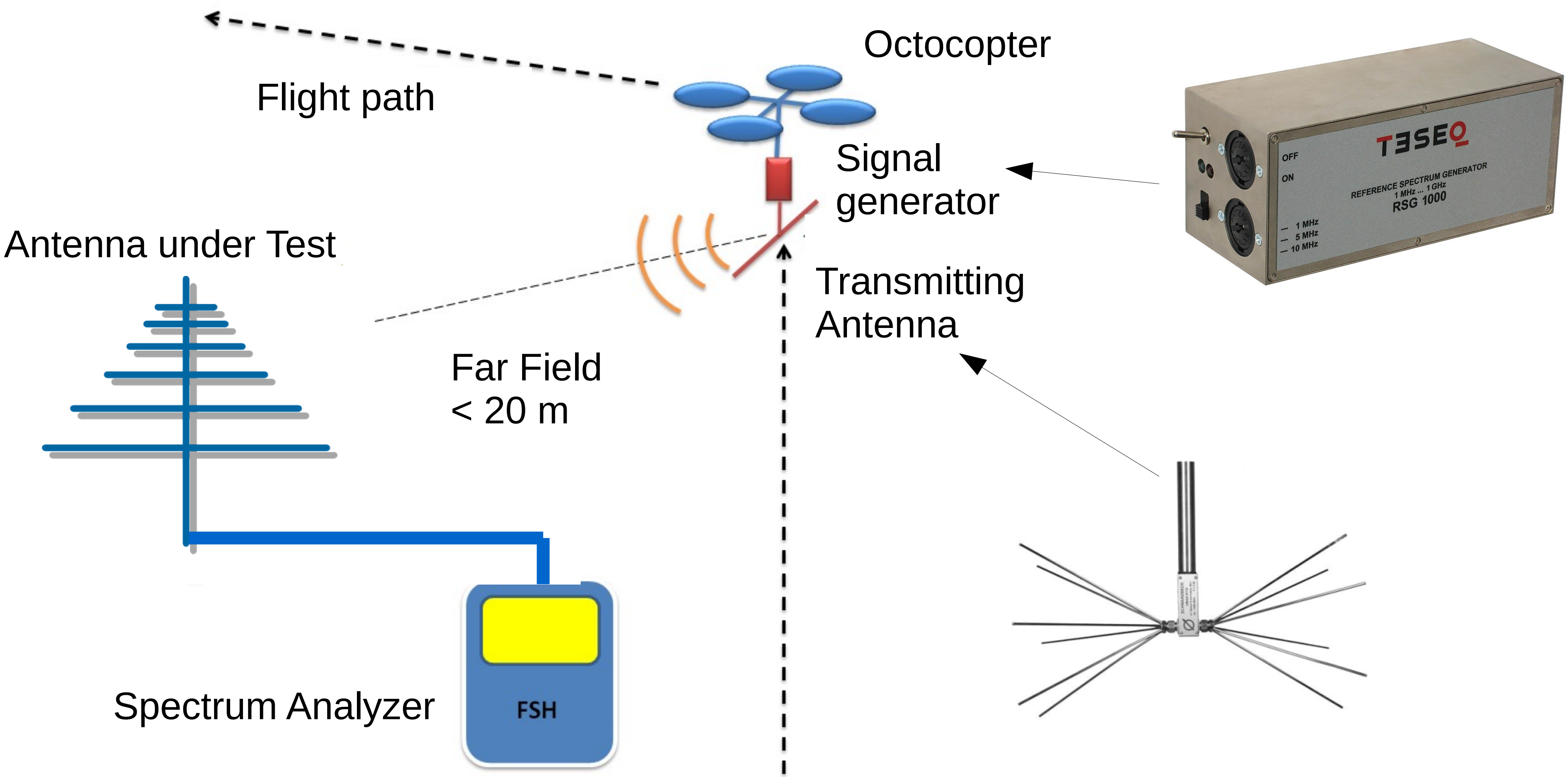
Field Measurements



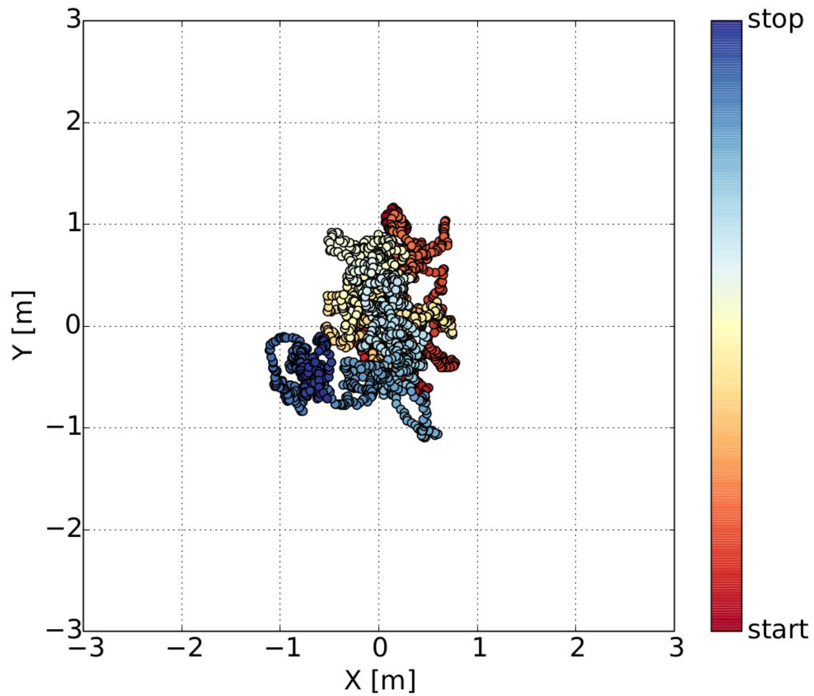
Setup of Antenna Response Calibration

$$U(f,\theta,\phi) = \vec{H}(f,\theta,\phi) \cdot \vec{E}(f,\theta,\phi)$$

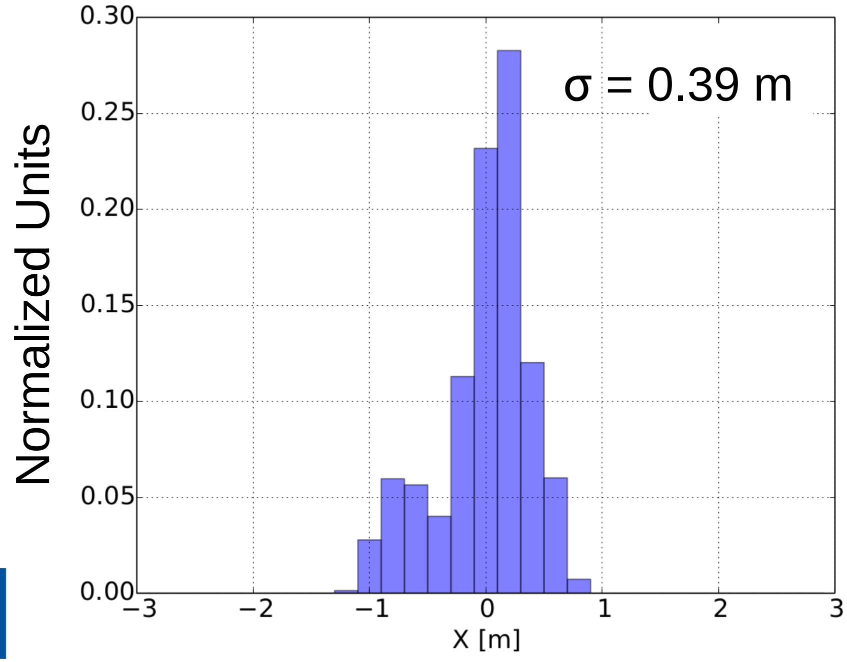
$$|H| = \sqrt{\frac{4 \cdot \pi \cdot Z_A}{Z_0}} \cdot R \cdot \sqrt{\frac{P_r}{G_t \cdot P_t}}$$

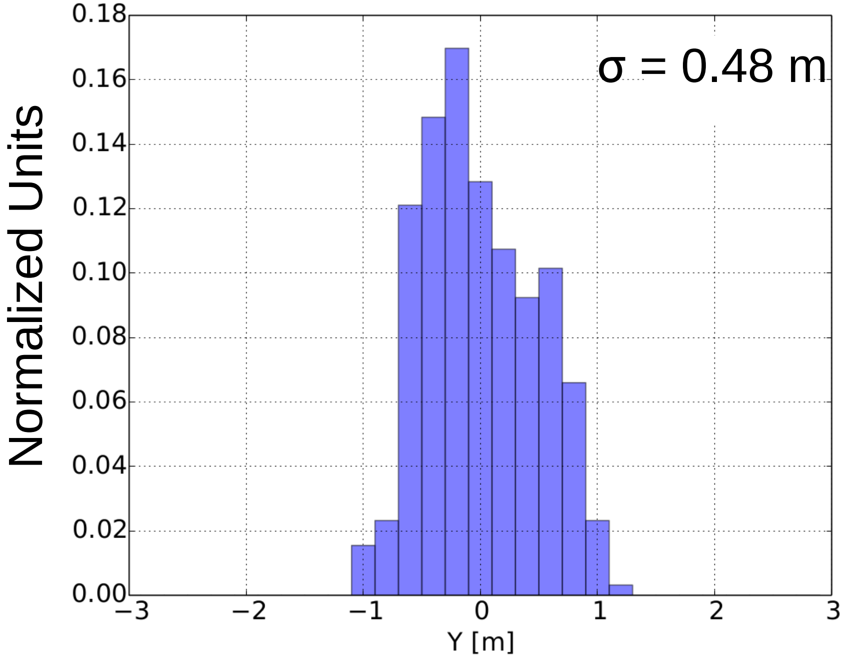


GPS Measurement of Octocopter Position



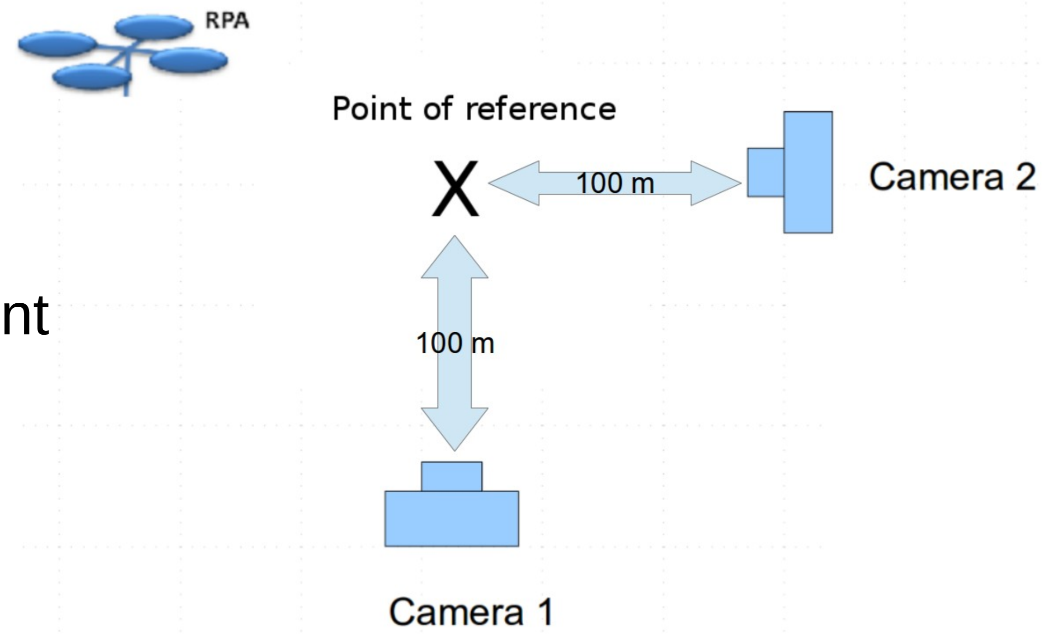
- Octocopter placed on ground and left running for ~40 minutes
- 60 cm statistical uncertainty
- GPS offset uncertain on the order of few meters

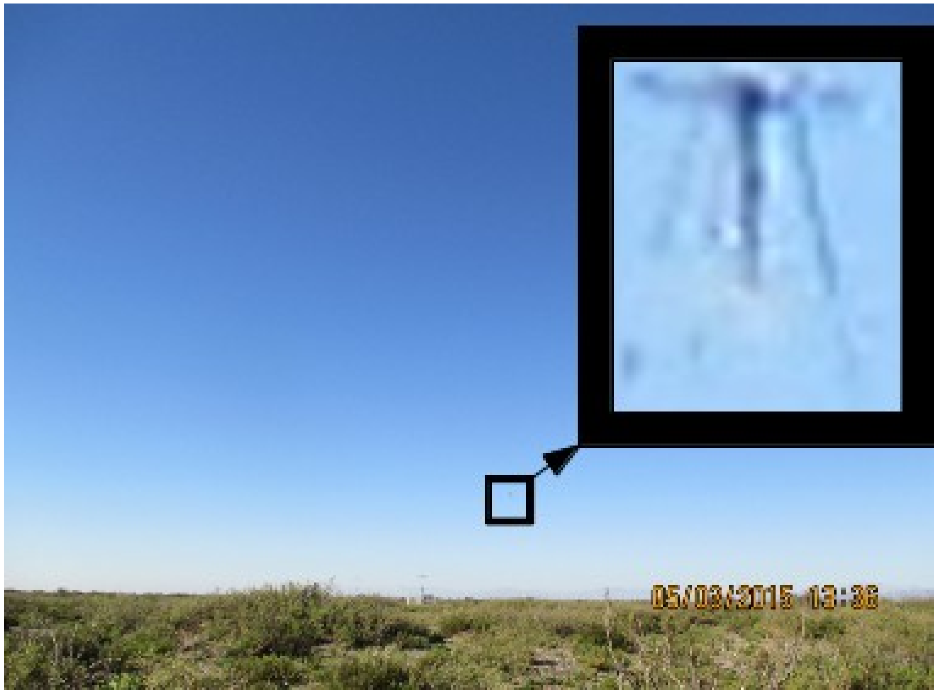




Position Reconstruction Using Two Cameras

- two 16 Megapixel standard digital cameras
- placed at orthogonal axes
- ~100 m distance to reference point
- take pictures every 3 seconds





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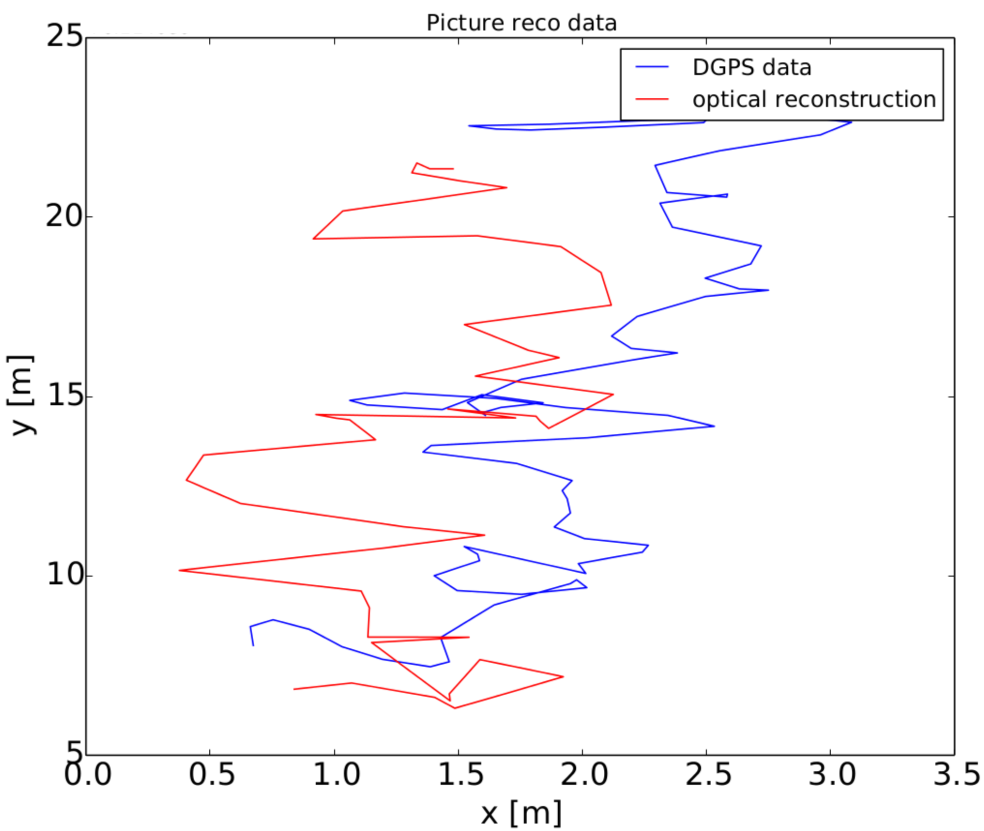
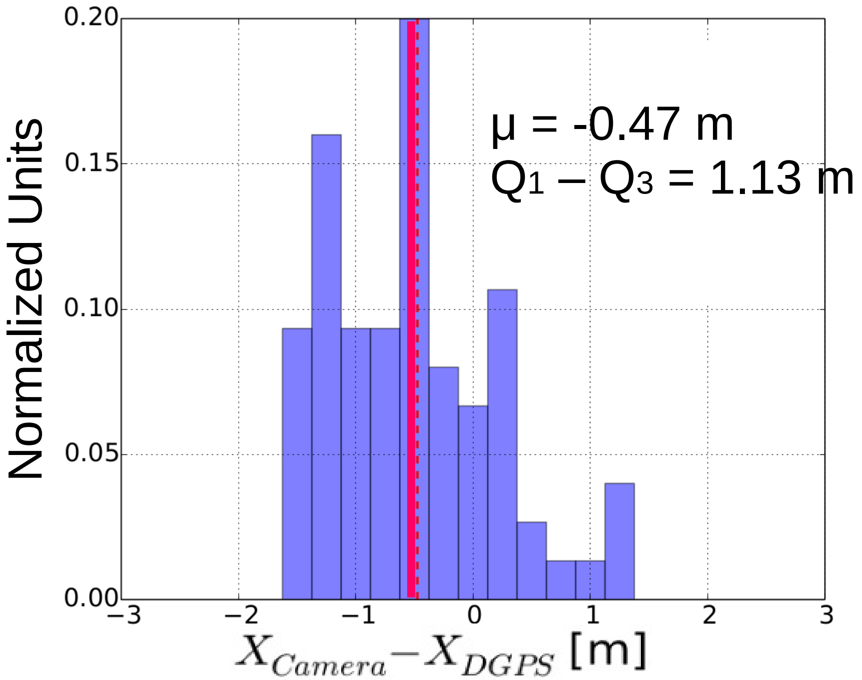
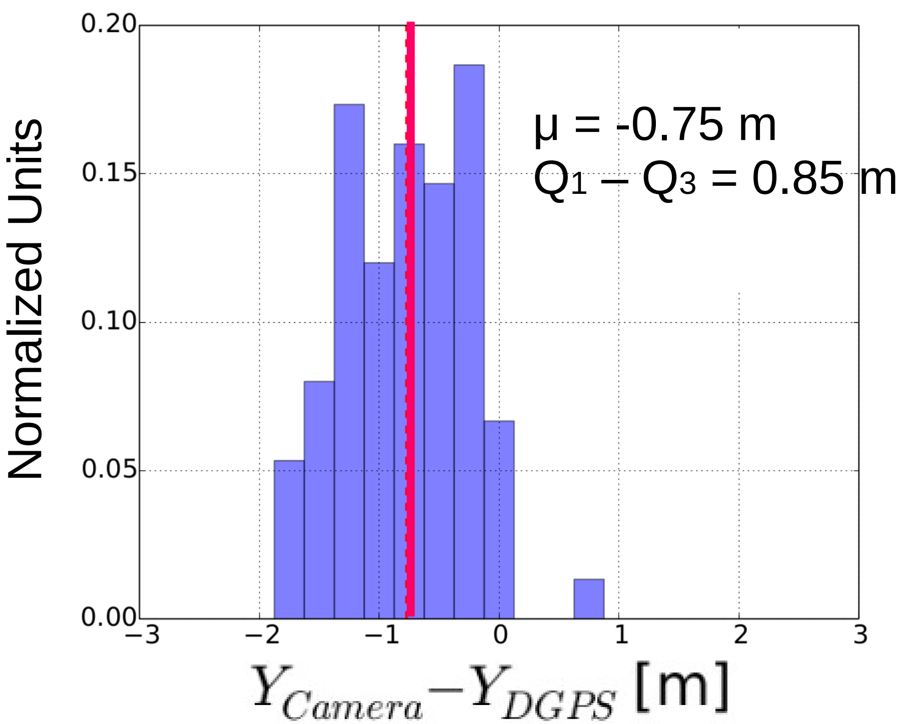
Optical Method ↔ Differential GPS (DGPS): x-y plane

- DGPS accurate < 10 cm
- Offset of ~1 m in x-y plane between optical method and DGPS
- Resolution optical method: 1.5 m







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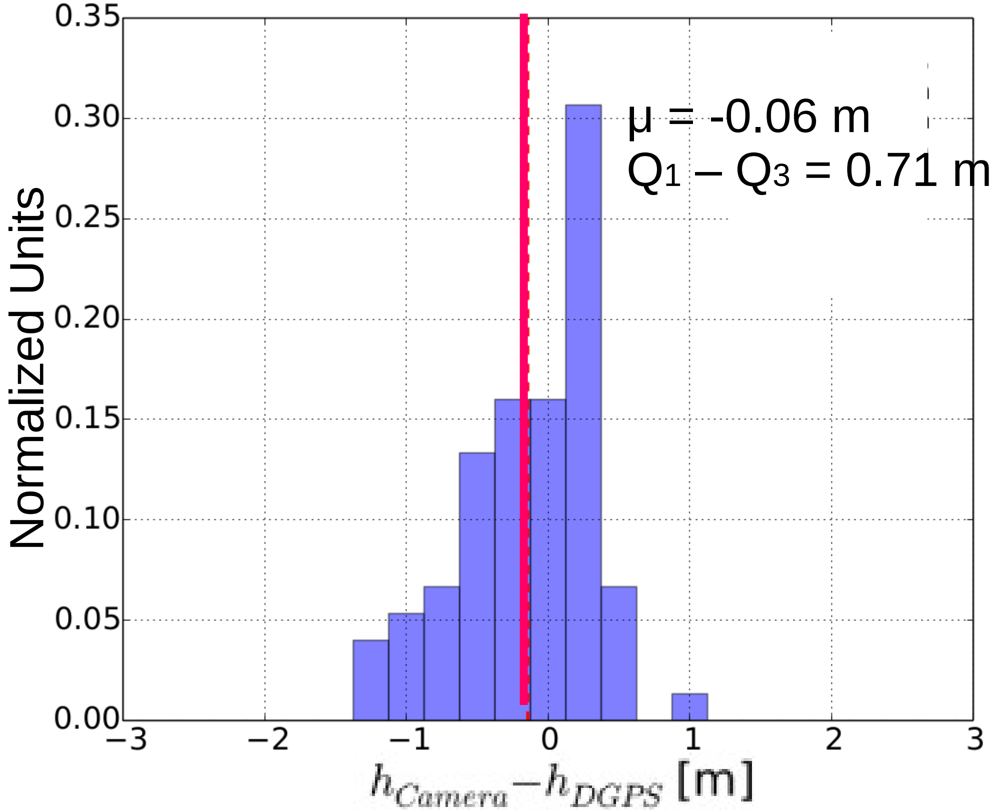
Optical Method ↔ Differential GPS (DGPS): height



- 6 cm offset between DGPS and optical reconstruction
- For calibration flights no DGPS available, only GPS + barometer and optical reconstruction

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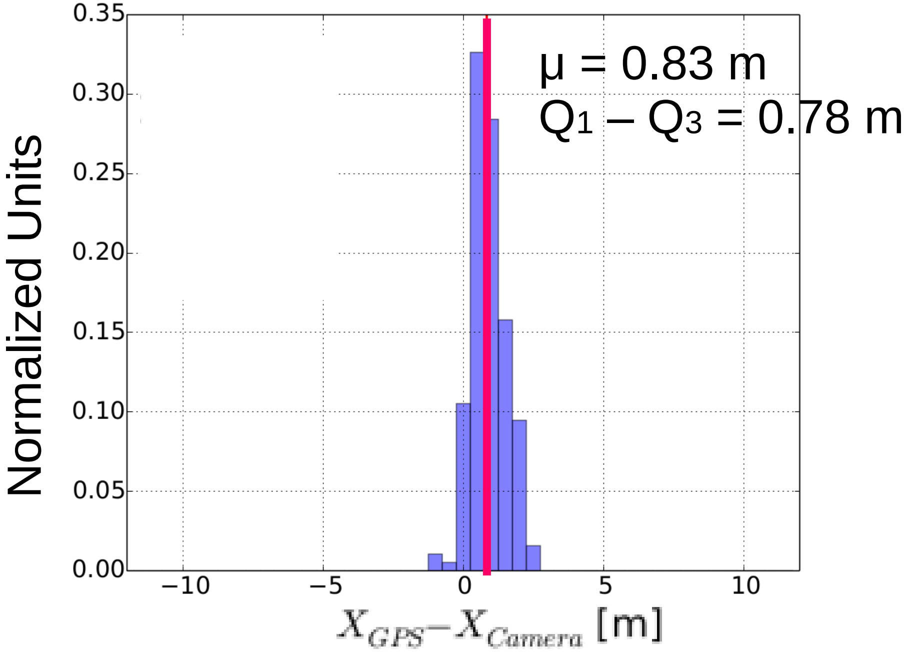
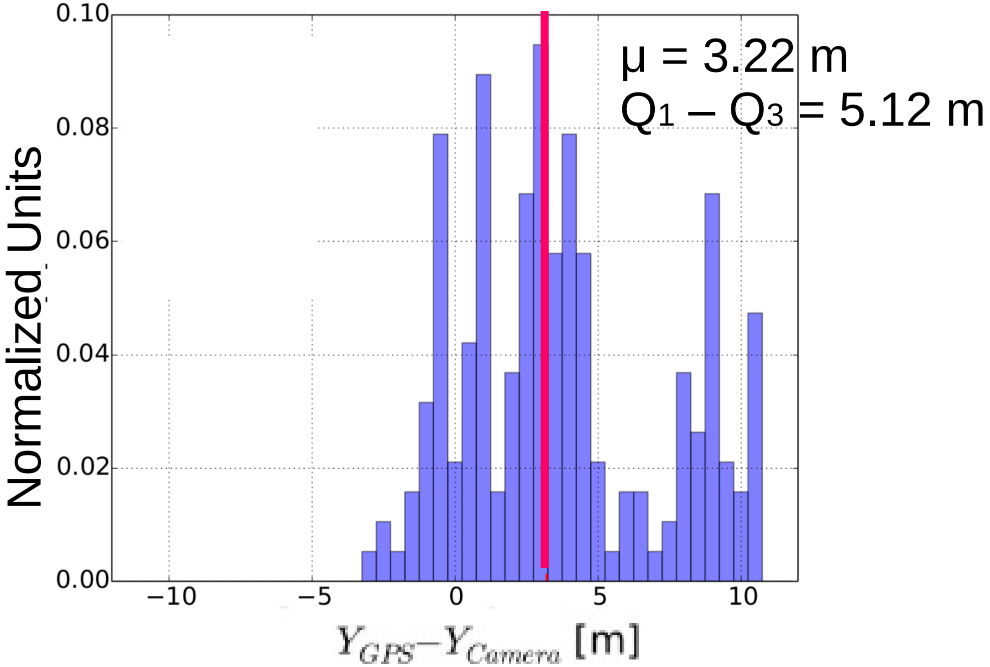
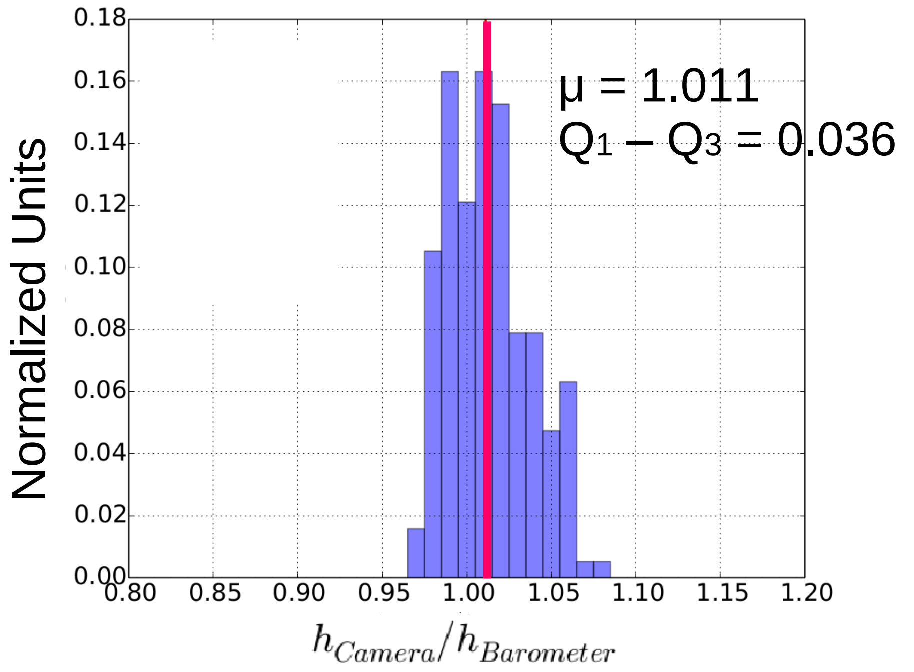
GPS + Barometer Correction by Optical Method

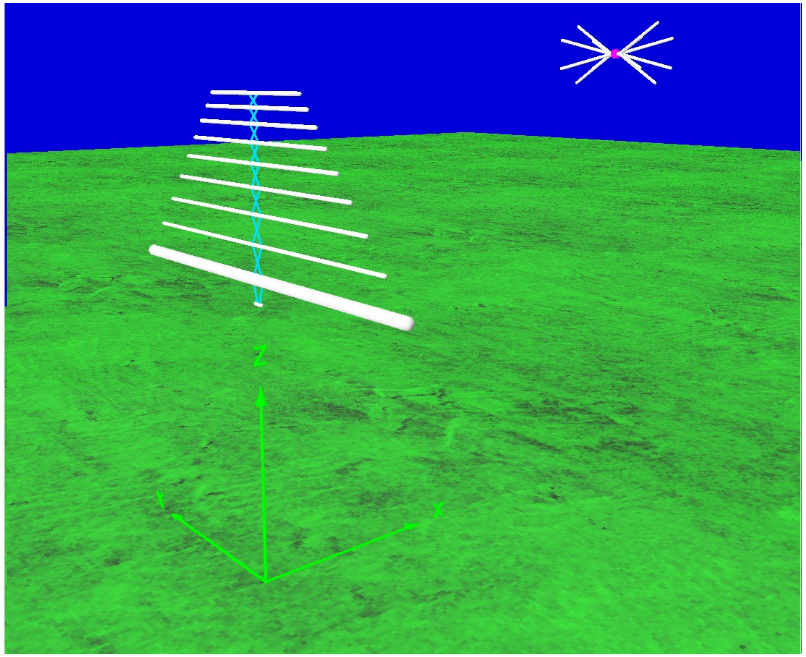


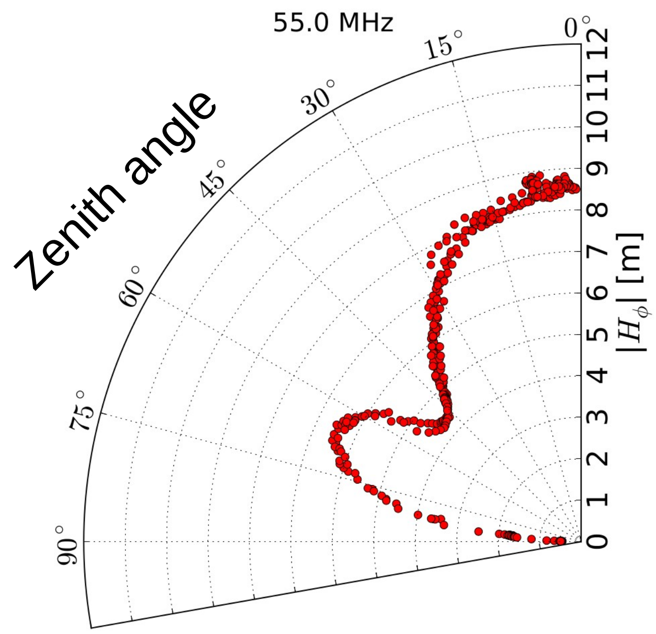


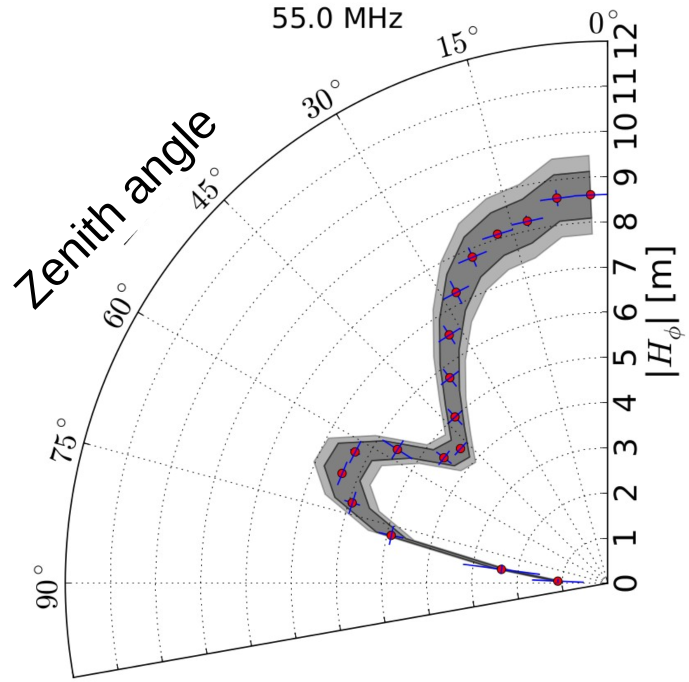


- Optical reconstruction has smaller systematical but larger statistical uncertainties than GPS + barometer
  - → **Use GPS + barometer, correct by using optical reconstruction**
- x-y plane: Shift by absolute offset
- Height: Shift by relative factor

Horizontal Polarization – Example Flight







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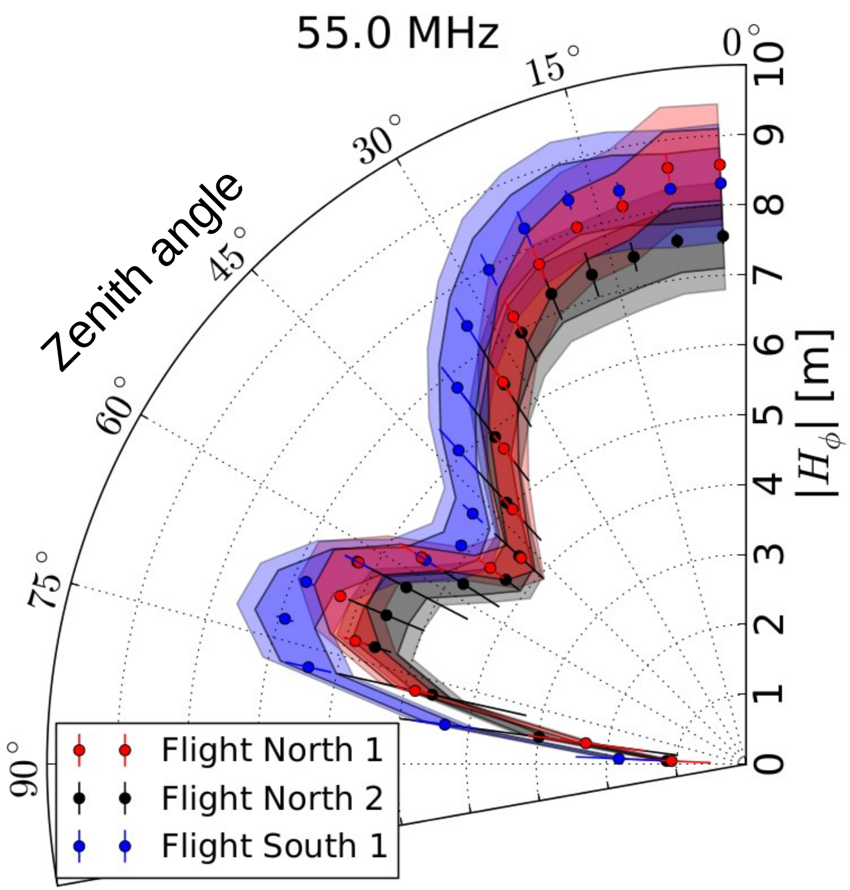
Horizontal Polarization - Reproducibility



- Performed several flights
- All agree on a level of 10 %
- Uncertainties:
  - Bars: Statistical (4.4 % for 55 MHz at 45°)
  - Color bands: Systematic (8.1 % for 55 MHz at 45°)
    - Dominated by spectrum analyzer
  - Significant improvement to previous calibrations (~12.5 %)

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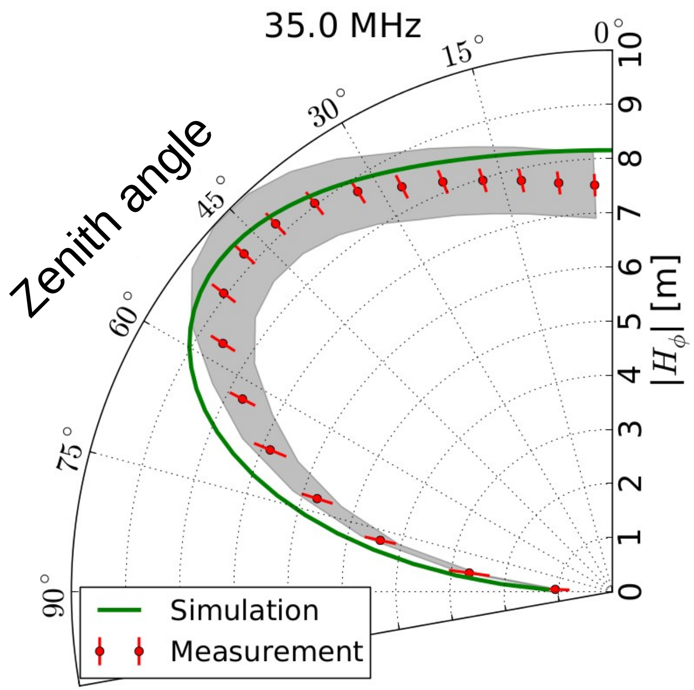
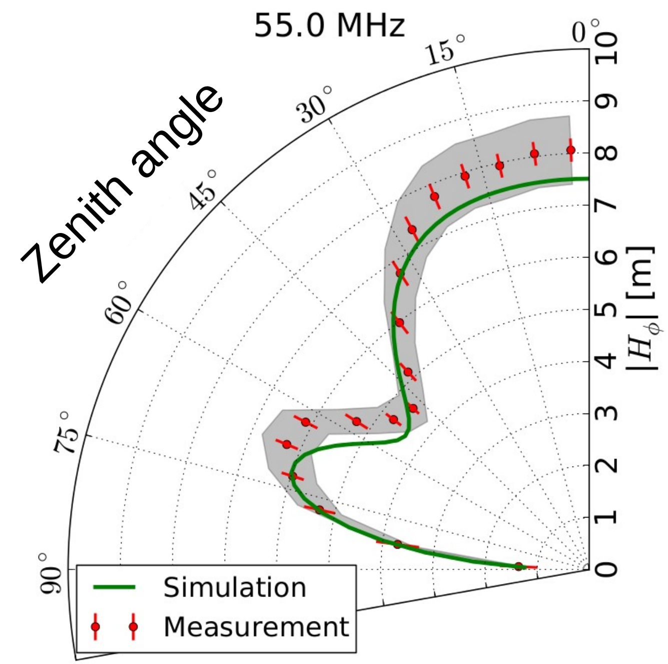
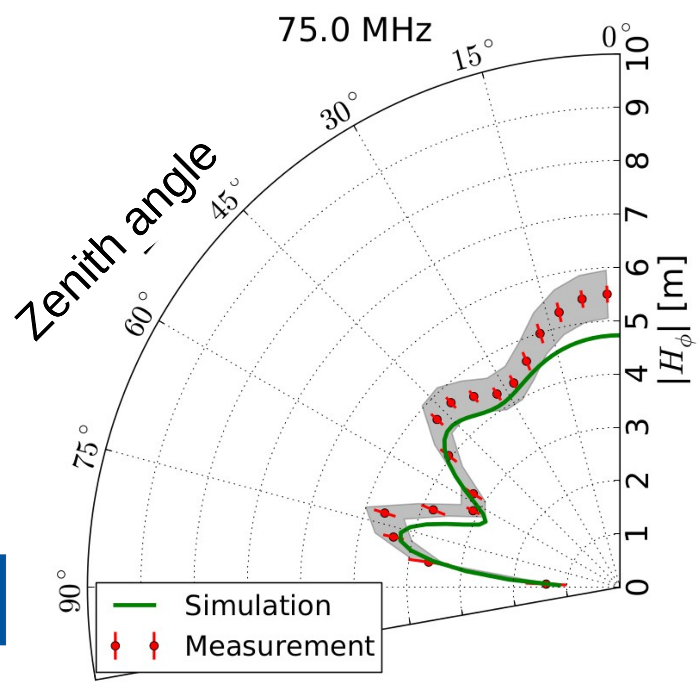
Horizontal Polarization – Comparison with Simulation

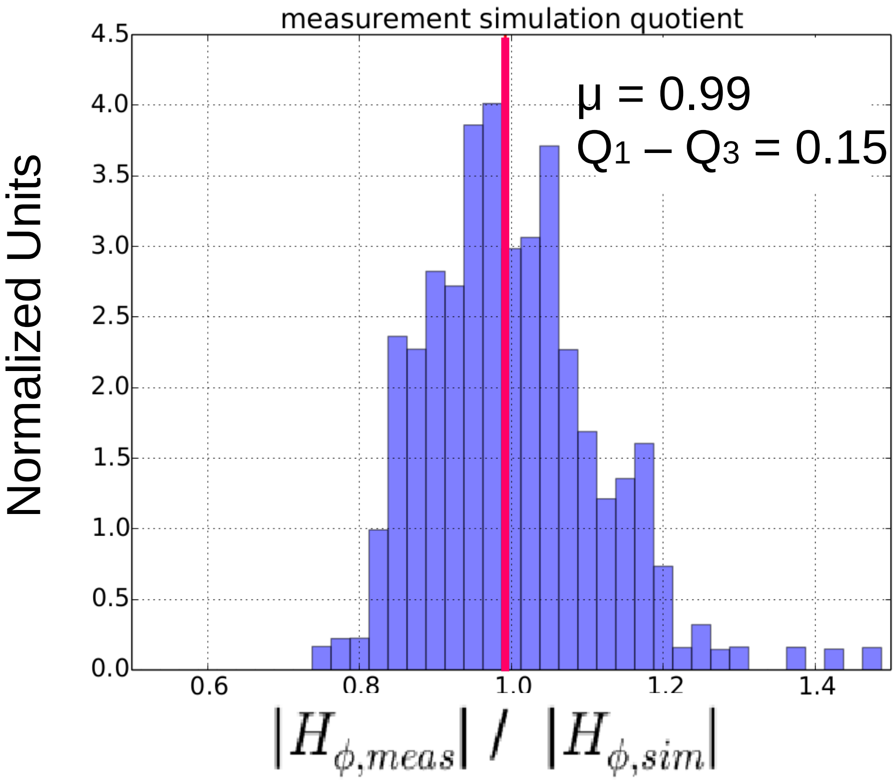


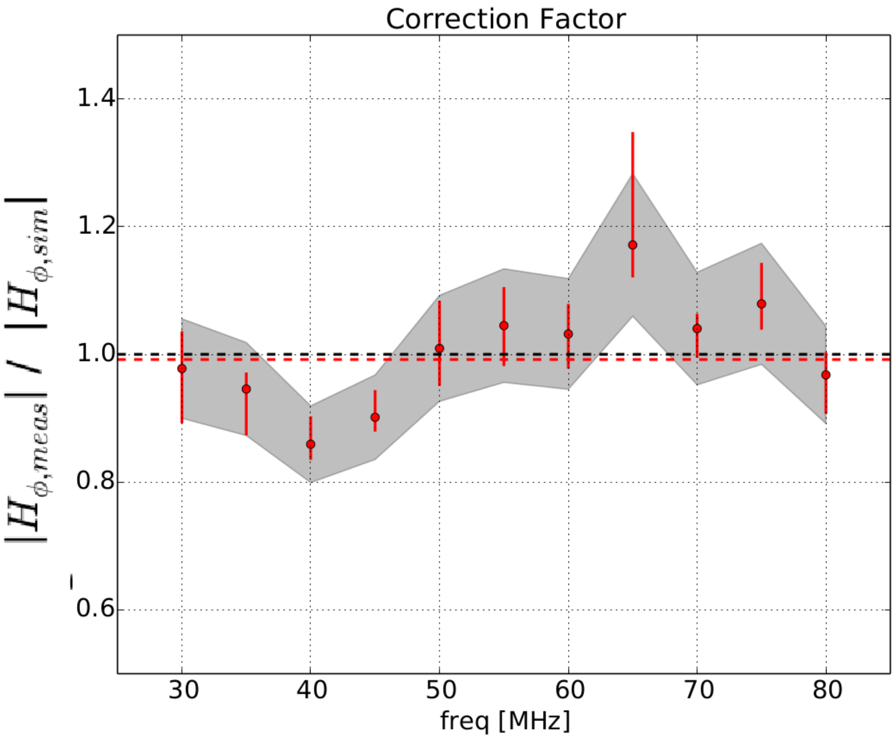




- Simulation and Measurement agree
- For the most part within uncertainties

Correction Factors for Simulation





- Use Simulation with applied correction factor

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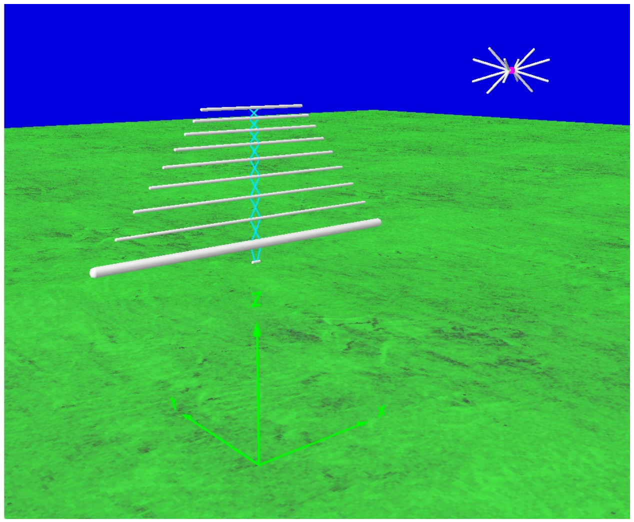
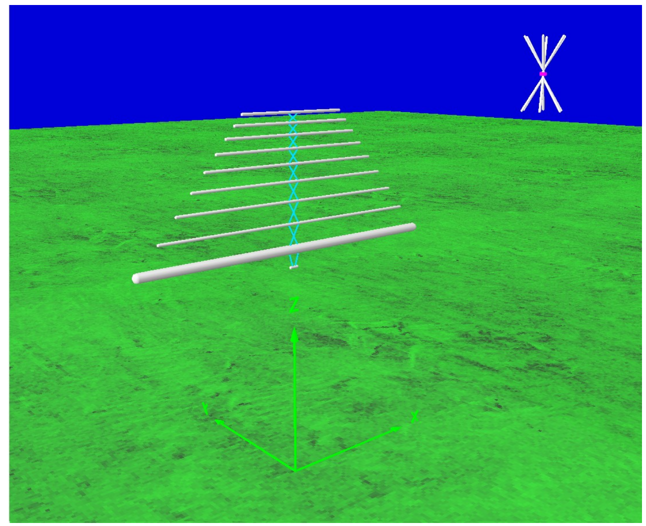
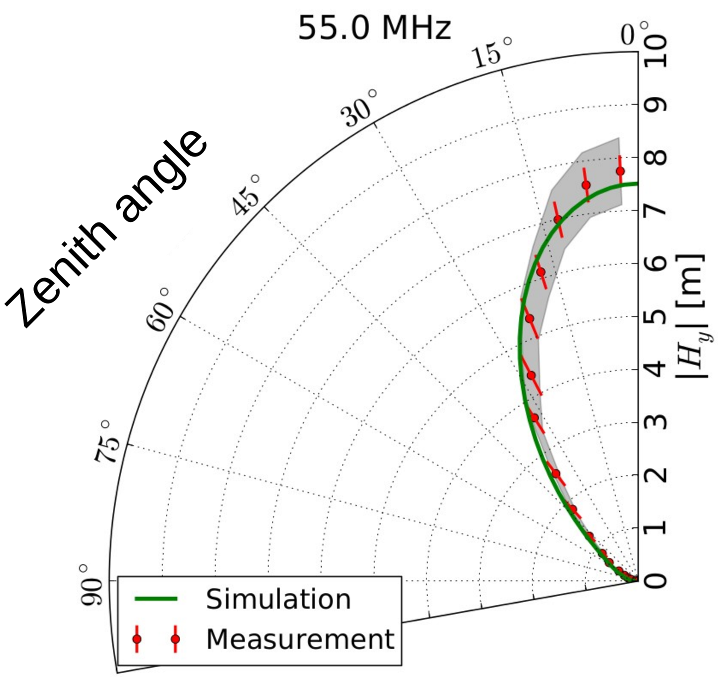
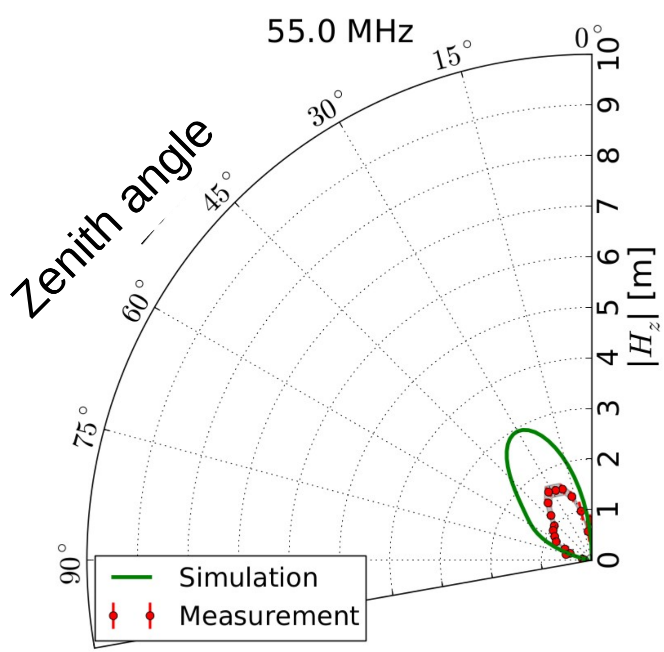
Vertical Polarizations

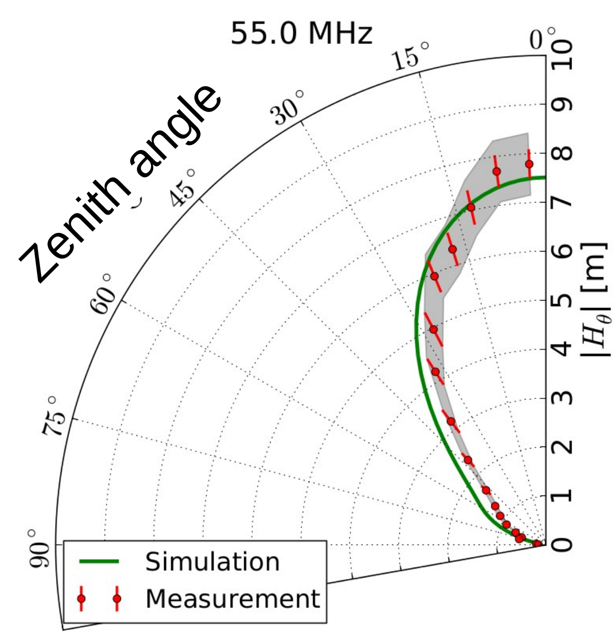
Vertical-horizontal	Vertical-vertical	Combination





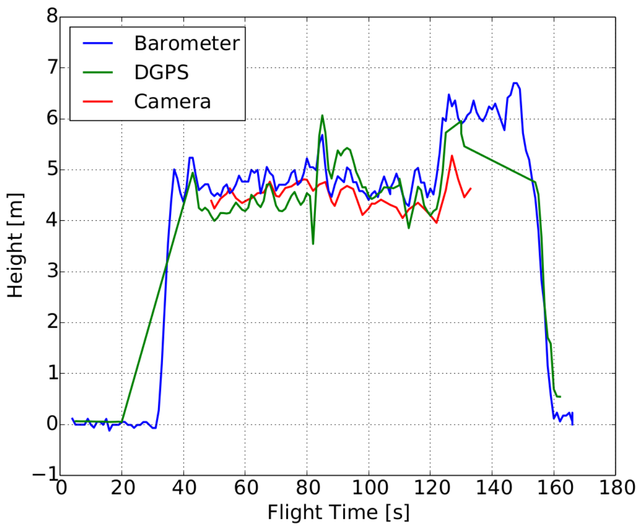


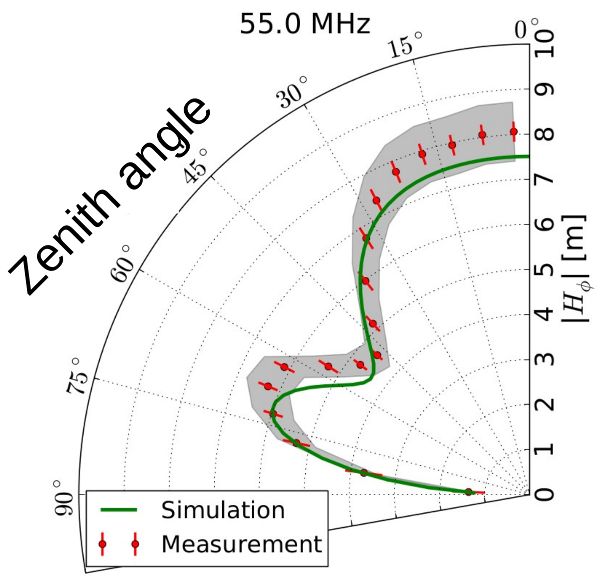




Summary and Outlook

- Calibration important for reconstructing cosmic rays
  - Vector Effective Length of the LPDA stations measured using an octocopter
- Special focus on position reconstruction
  - New optical method
- VEL has been measured with preliminary uncertainties of 8.1% (sys.) + 4.4% (stat.)
- Crucial component in determination of independent cosmic-ray energy scale from radio measurement
  - Publication in preparation





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BACKUP

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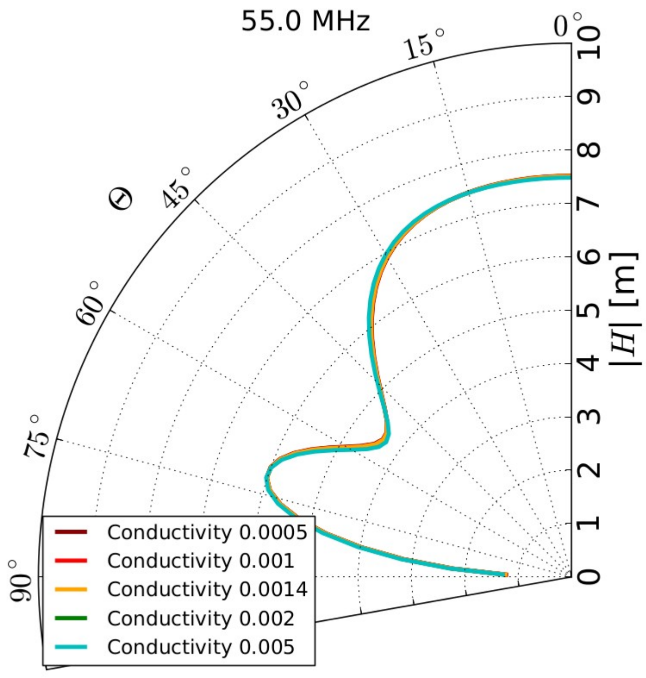
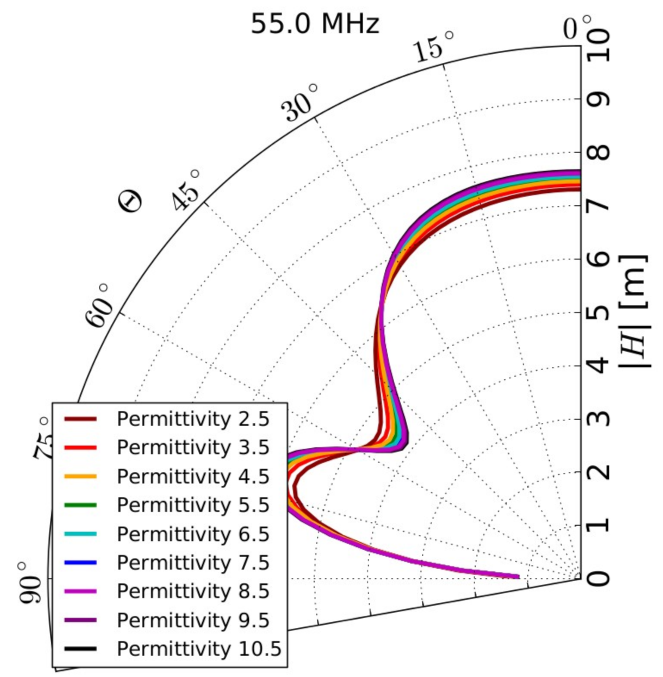
Influence of Ground





- Ground conditions influence Vector Effective Length
  - ➔ Influence is within systematic uncertainties

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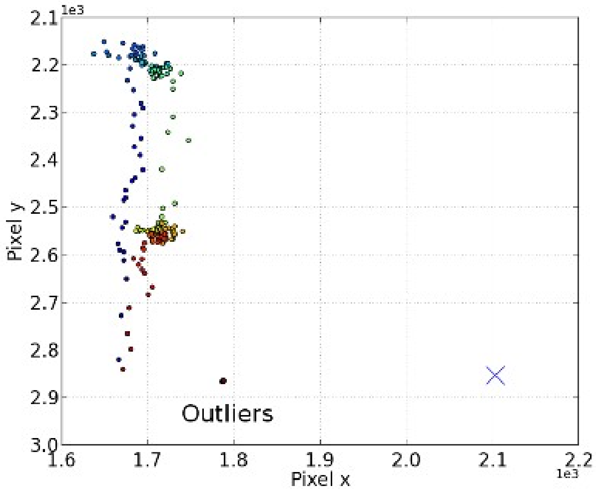
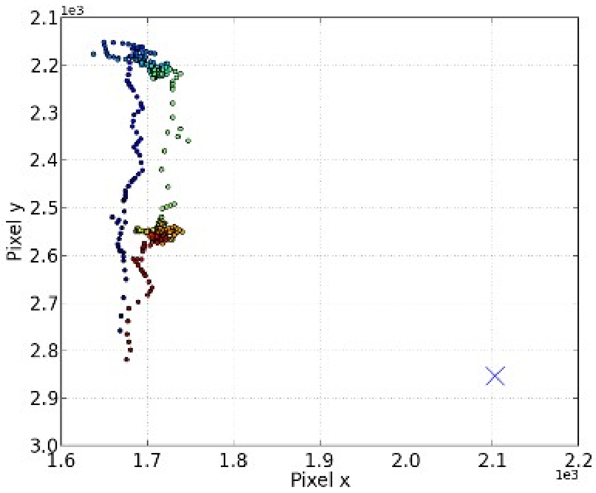
Reconstruction Workflow





- determine Pixel tuple of Octocopter and Point of Reference from Pictures
  - "Template Matching"
- apply corrections for skewness of horizon
- linear interpolation between pictures to get a pixel tuple for every second of flight

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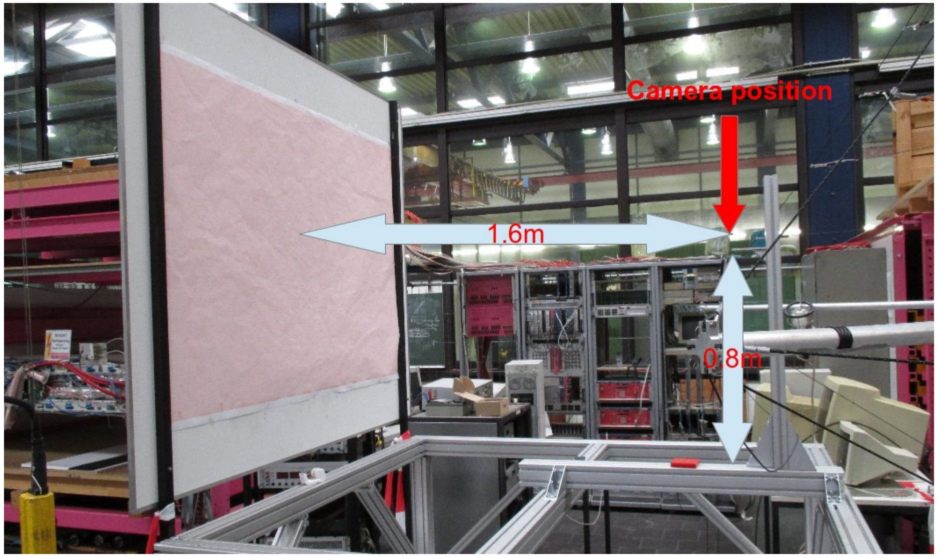
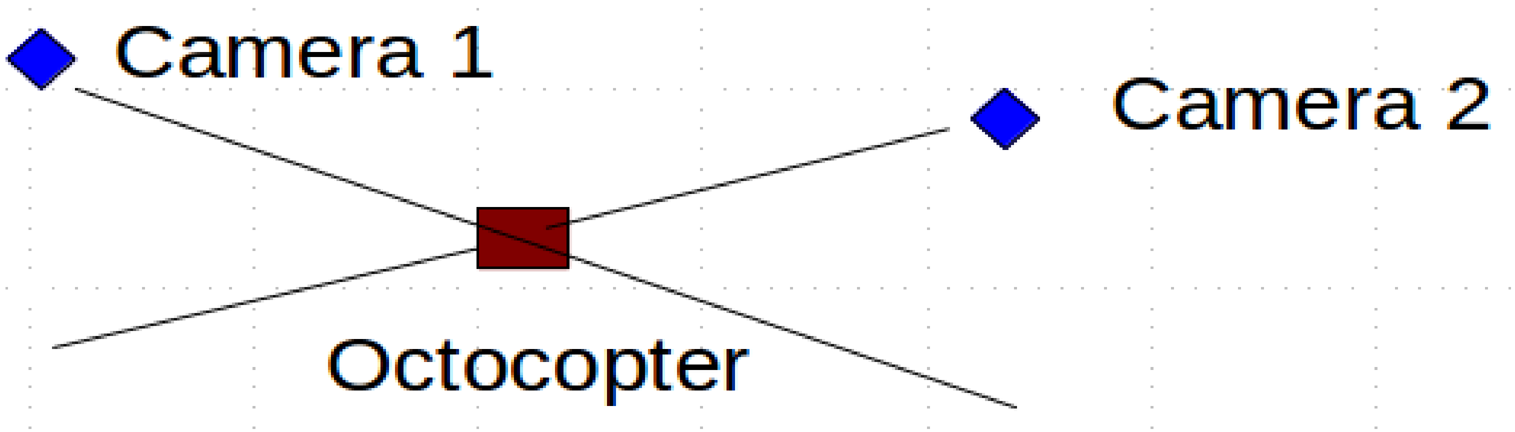
Reconstruction Workflow

- transform pixel tuple to direction vector
  - calibration in the lab
- calculate geometry





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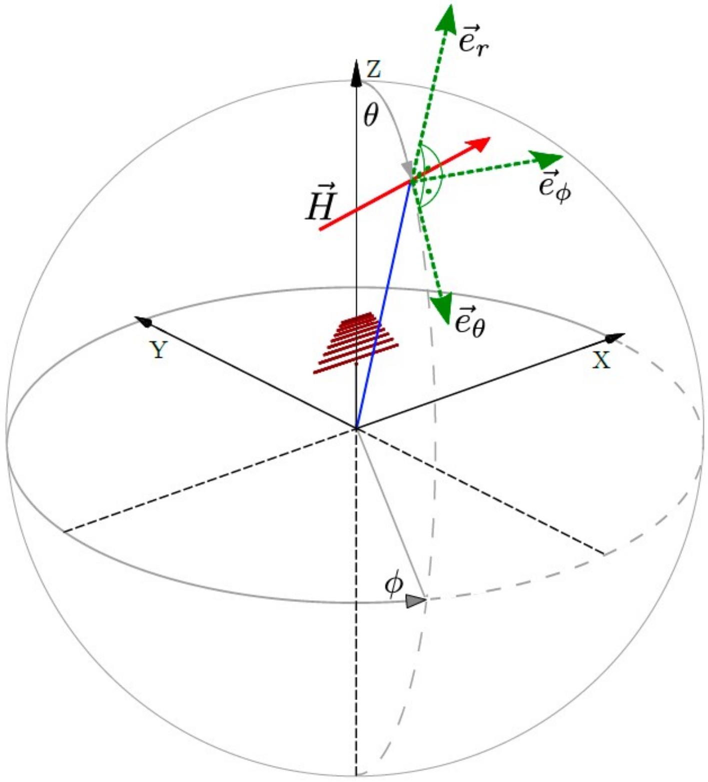
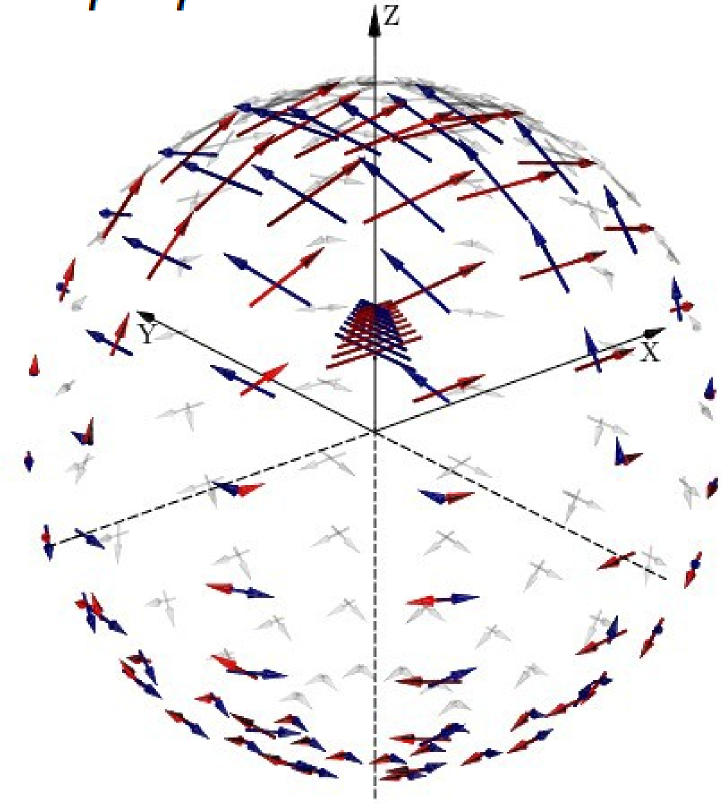
Vector Effective Length

$$U(f,\theta,\varphi) = \vec{H}(f,\theta,\varphi) \cdot \vec{E}(f,\theta,\varphi)$$

$$\vec{H} = H_\theta \vec{e}_\theta + H_\varphi \vec{e}_\varphi$$





- H: relation of voltage to incoming e-field
- horizontal antenna most sensitive to zenith direction

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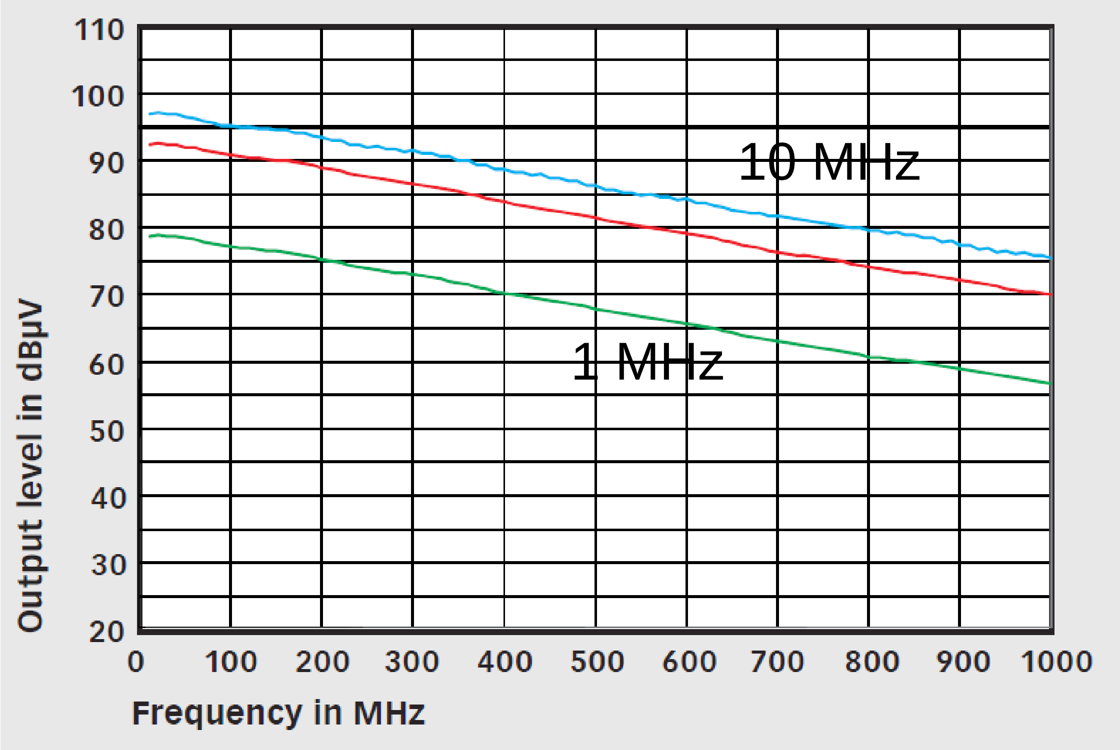
Reference Spectrum Generator (RSG)



dimensions (W/H/D) in cm: 6/6/17.5
weight: ~580g

frequency range: 1 – 1000 MHz
comb spacing: 1, 5 or 10 MHz
max power: ~ 97dBµV = -10dBm

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