Lessons learned from radio detection of air showers

IceCube-Gen2 Calibration Workshop April 2021

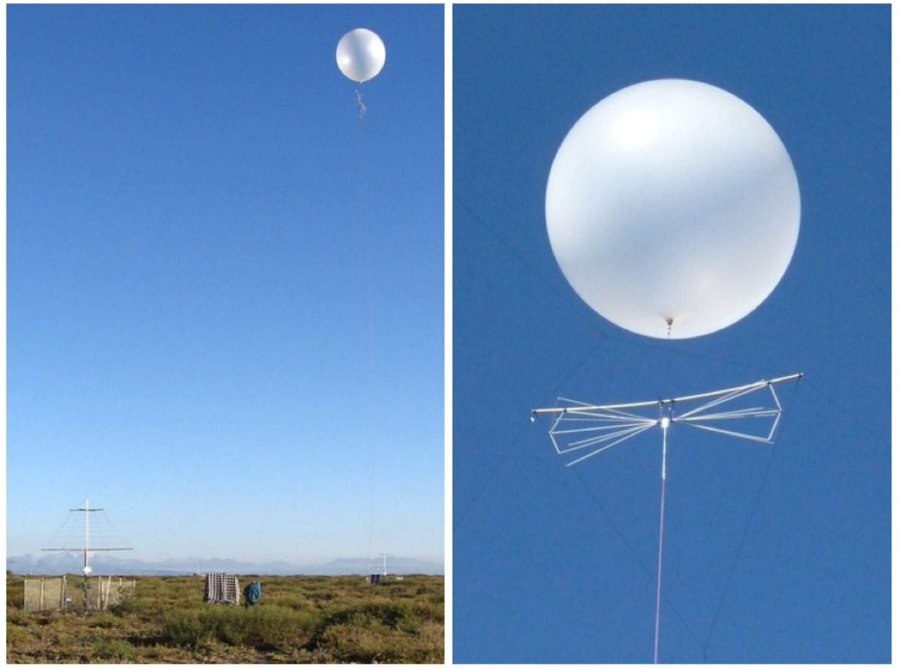
Christian Glaser, Anna Nelles

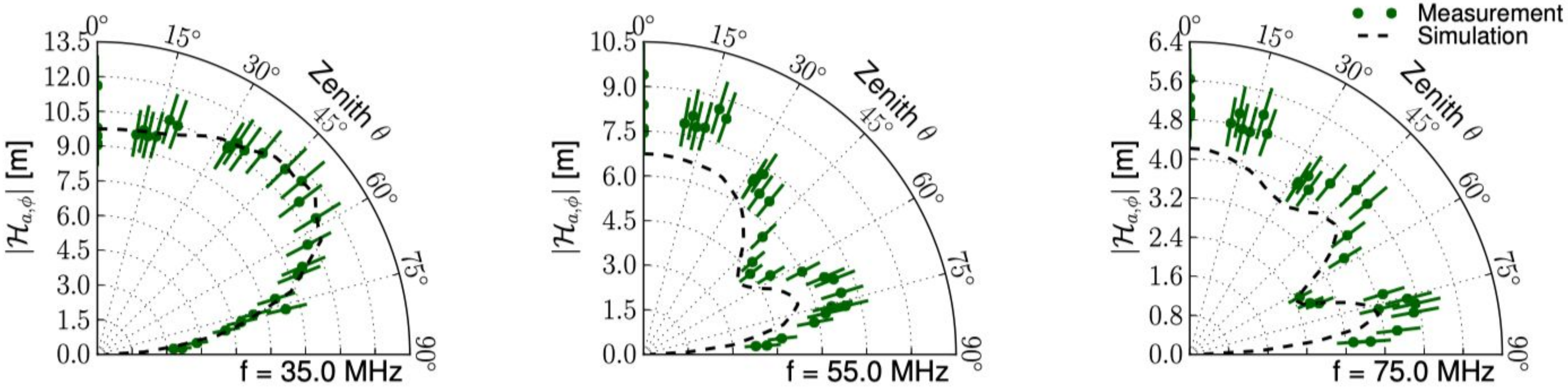
Overview

- Radio detection of air showers/cosmic rays is ~10 years ahead
  - It already reached high-precision physics, e.g. systematic uncertainties in energy measurement competitive to Fluorescence technique
  - All 1600 surface detectors of the Pierre Auger Observatory will be upgraded with radio antennas to measure cosmic-ray composition: Standard Tool
- Many aspects are very similar
  - We can profit from their experience in terms of **detector calibration**, data processing and analysis techniques
- Antenna amplitude and phase calibration:
  - Balloon, Octocopter, Crane in-situ measurements
  - Galactic noise
- Timing calibration
  - Airplane calibration, reference beacon
- Individual hardware component calibration (not covered in this talk)

Antenna calibration

- Measurement principle: Place calibrated signal source at all relevant incident direction sufficiently far away (far field)
- First approach:
  - Using weather balloon
  - Transmission measurement using network analyzer
    - Amplitude and phase for all frequencies ✓
    - Cable emits -> syst. uncertainty ✗





LOFAR, JINST 10(11), P11005 - P11005 (2015)

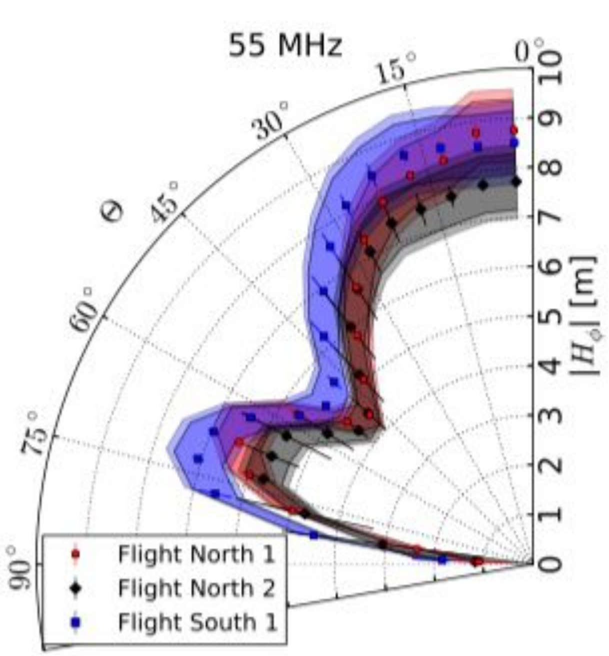
Antenna calibration using a crane

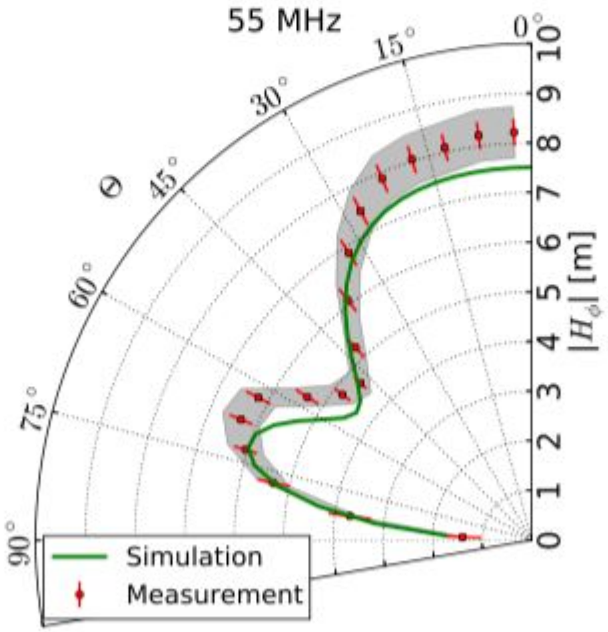
Uncertainty (σ)			Value [%]
Antenna-by-antenna		Variations between antennas	1
		Total	**1**
Event-by-event		Environmental (excl. source)	5
		Total	**5**
Calibration	Method-specific	Source emission	16
		Far-field	5
		Total	**17**
	Campaign-specific	Set-up	5
		Alignment	5
		Source temperature stability	6
		Measurement variations	1
		Total	**9**

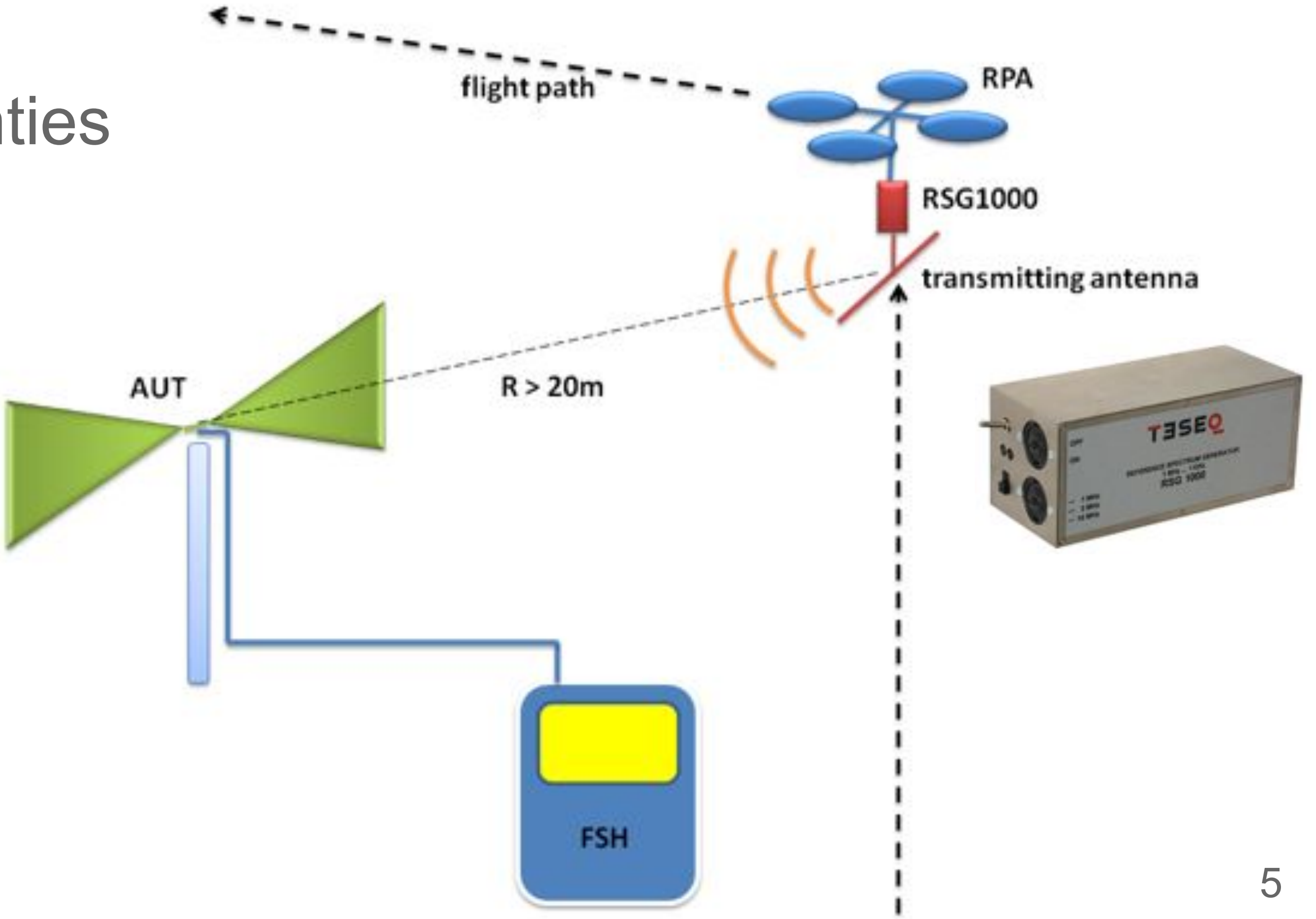
For absolute calibration: Source calibration dominates, different arrays can be calibrated with the same source
See. e.g. Tunka-Rex vs. LOPES, Physics Letters B 763 (2016) 179-185

Antenna calibration using Octocopter

- Current world record: 10% syst. uncertainty
- Signal source needs to be lightweight
  - No cable but reference frequency generator
- Several measurement campaigns were required to make it work
- Several flight required to reduce uncertainties







Required corrections

Table 1. VEL corrections taking into account different kinds of corrections for the three measured VEL components $|H_\phi|$, $|H_{\theta,\mathrm{hor}}|$ and $|H_{\theta,\mathrm{vert}}|$ of the example flights at a zenith angle of $(42.5 \pm 2.5)^\circ$ and a frequency of 55 MHz with $\Delta|H_k| = \frac{|H_k| - |H_{k,0}|}{|H_{k,0}|}$ and $k = \phi, (\theta, \mathrm{hor}), (\theta, \mathrm{vert})$.

Corrections	$\Delta\lvert H_\phi\rvert$ [%]	$\Delta\lvert H_{\theta,\mathrm{hor}}\rvert$ [%]	$\Delta\lvert H_{\theta,\mathrm{vert}}\rvert$ [%]
background noise	−0.1	−0.5	−0.9
cable attenuations	+44.4	+44.4	+53.2
background noise + cable attenuation	+44.3	+43.7	+51.8
octocopter influence	+0.6	+0.6	−0.2
octocopter misalignment and misplacement	+0.3	–	–
height at take off and landing	+1.8	+15.8	+5.8
height barometric formula	−5.2	−10.2	−2.5
combined height	−3.6	−5.4	+1.3
shift to optical method	−14.5	−4.8	+0.2
combined height + shift to optical method	−14.6	−5.5	−0.3
all	+24.6	+36.4	+51.1

Systematic uncertainties

Note:
All antenna calibration measurements required significant ressources and several dedicated measurement campaigns.

Reconstructions still have to be carried out with (corrected) antenna simulations due to the incomplete sampling, only for discrete frequencies/angles.

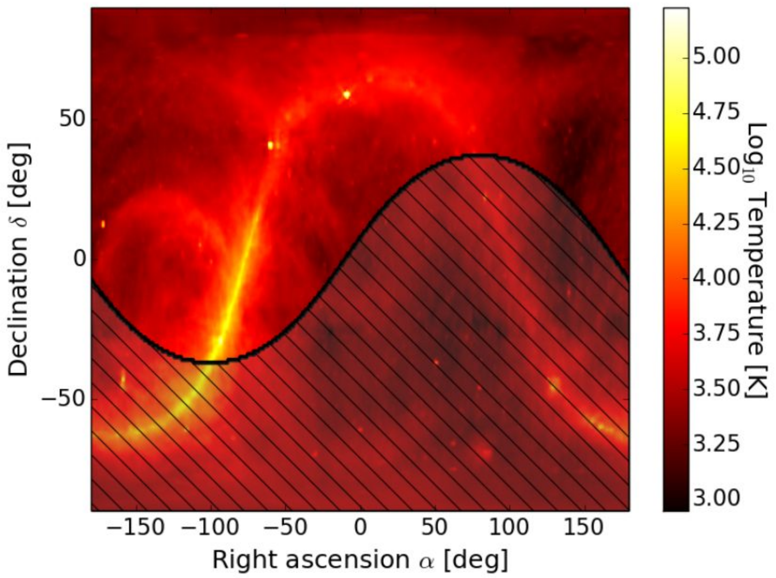
Source of uncertainty / %	Systematic	Statistical
flight dependent uncertainties	**6.9**	**2.7**
transmitting antenna XY-position	1.5	1.0
transmitting antenna height	0.1	0.6
transmitting antenna tilt	< 0.1	< 0.1
size of antenna under test	1.4	–
uniformity of ground	< 0.1	–
RSG1000 output power	2.9	2.3
influence of octocopter	< 0.1	–
electric-field twist	0.4	0.2
LNA temperature drift	1.0	0.6
receiving power	5.8	–
background	0.4	–
global uncertainties	**6.3**	**< 0.1**
injected power	2.5	< 0.1
transmitting antenna gain	5.8	–
cable attenuation	0.5	< 0.1
all / %	**9.3**	**4.7**

Galactic noise calibration

- Use galactic radio background as external calibration source
    - absolute calibration of antenna and complete signal chain
    - only angular dependence (for each frequency bin) is required
    - Systematic uncertainties comparable to reference transmitter (sky model carries uncertainties of prior detectors)
    - Continuous monitoring of system possible ("for free")

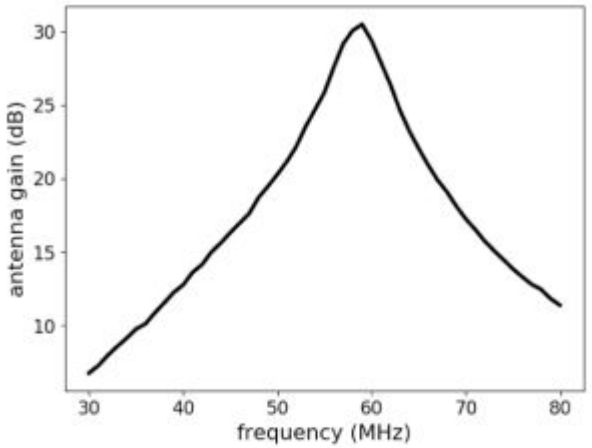
Systematic Uncertainty	Percentage
antenna model	2.5
sky model	11
electronic noise < 77 MHz	6.5
electronic noise > 77 MHz	20
total < 77 MHz	**13**

Galactic radio emission



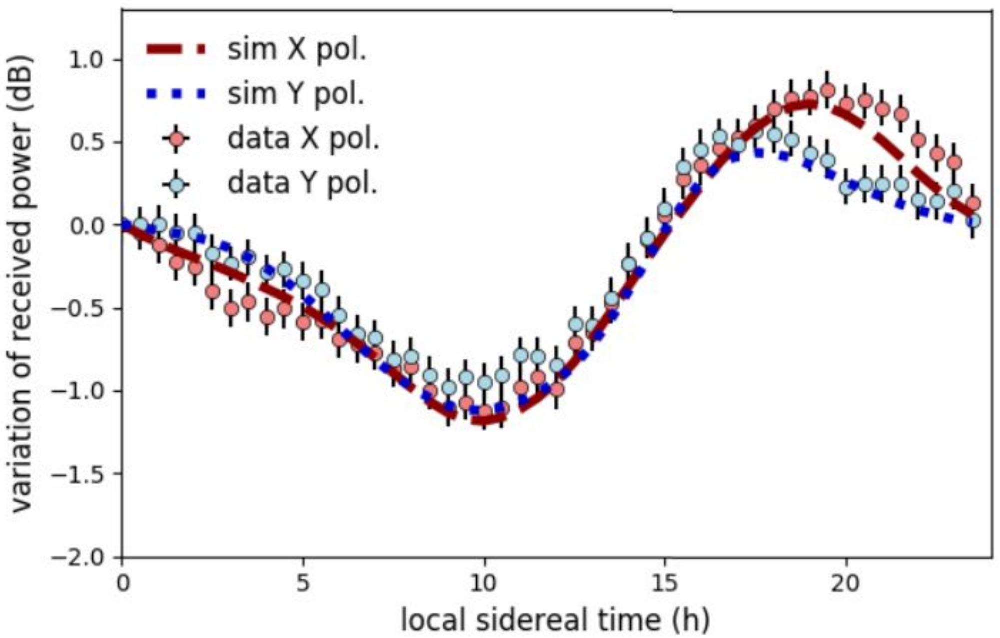
\+

Antenna response



=

Detector noise variation

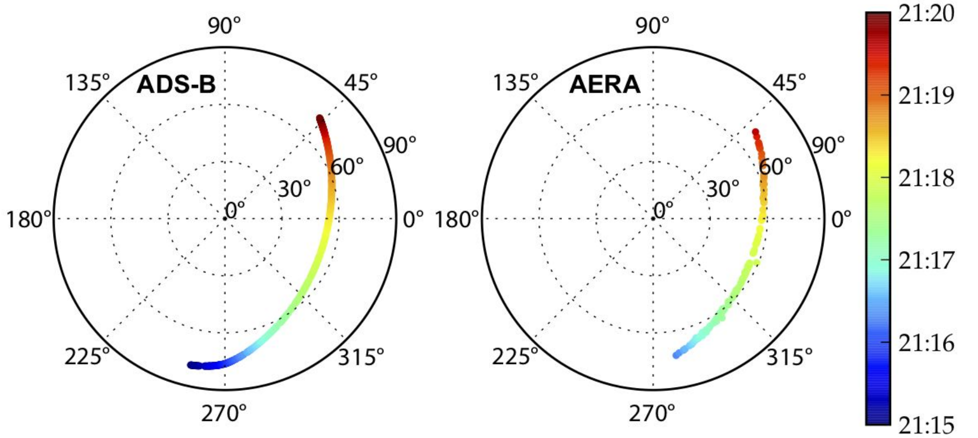


Pierre Auger Collaboration, JINST 11 P01018 2016

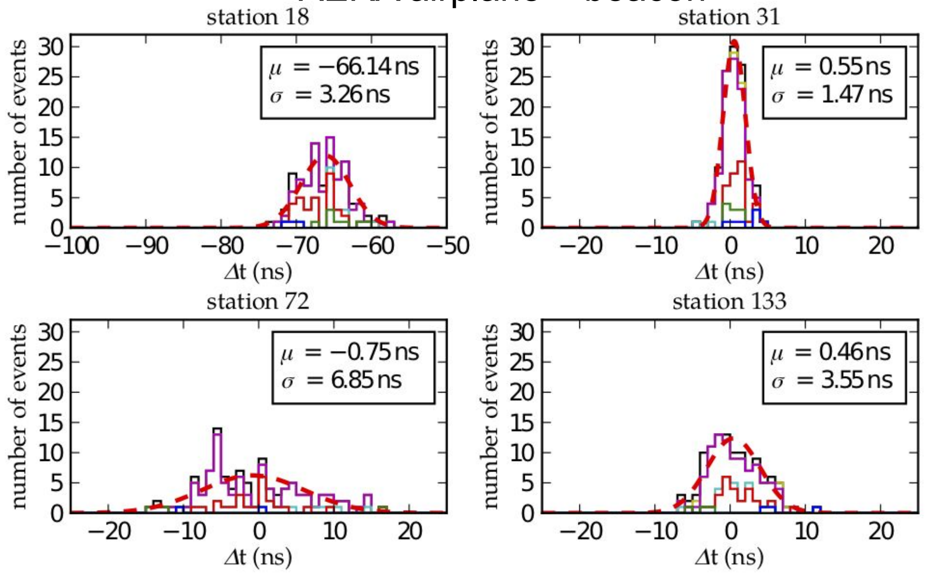
LOFAR, A&A 590, A41 (2016)

Timing calibration

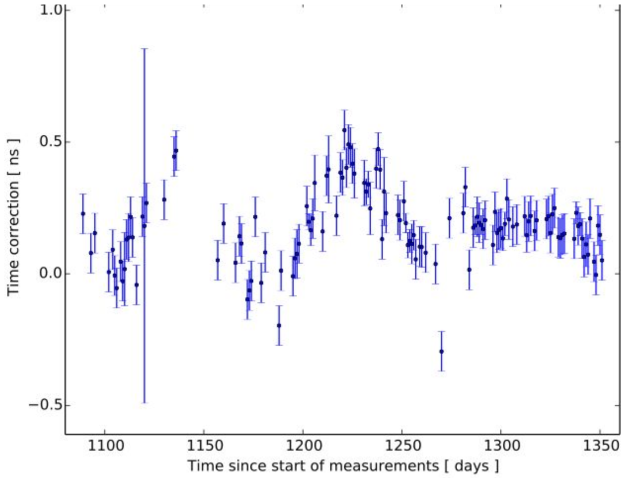
- GPS clocks drift by >10ns
- Use airplane signal for absolute timing calibration
  - Air planes provide parasitic impulsive signals that illuminate a whole array
  - Use plane tracking device to find absolute references position (or enable trigger)
  - Use this to check absolute pointing of individual stations or correct timing difference across the array
- Use continuous wave transmitter (CW) for absolute timing (phase difference of signal at two stations should be constant)
  - At Pierre Auger Observatory: custom installed CW transmitter (beacon)
  - Impacts self-trigger, needs filtering etc.
    -> likely not a good solution for neutrino experiments
  - Parasitic calibration on launching signal of balloon, air traffic radio etc. similarly effective, however, possibly not optimal number of frequencies



AERA airplane + beacon



LOFAR: parasitic CW lines
Clock-drifts of shared Rb clock



Take-away messages

- Dedicated campaigns (drone, crane etc.) are nice to improve antenna models, but work intensive, failure prone and *only probes small angular region of in-ice detectors*
- Absolute scale tricky, because it requires and absolutely calibrated antenna (expensive)
- Continuous calibration from the data (Galaxy, regularly occurring CW, etc.) is much less effort and captures (time-dependent) systematic uncertainties of the detector *(but no phase and angular dependence of the antenna)*
- Air shower signal (in air) currently understood to extreme precision, however, flux scale uncertain: Air shower signals can be used as calibration signal themselves

Backup

GPS clock drifts

Drift of GPS time between two ar