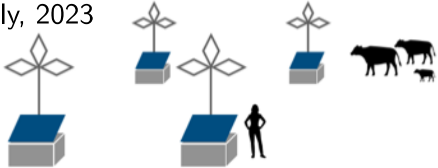
Enhancing Timing Accuracy in Air Shower Radio Detectors

E.T. de Boone[1]

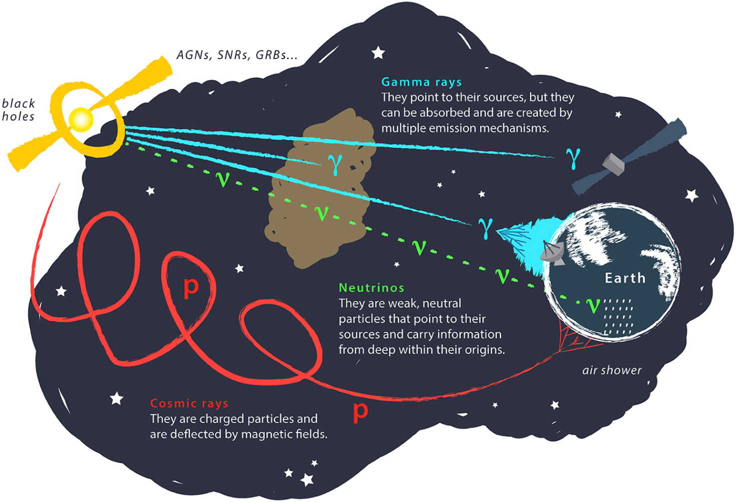
Supervisor: dr. Harm Schoorlemmer

July, 2023



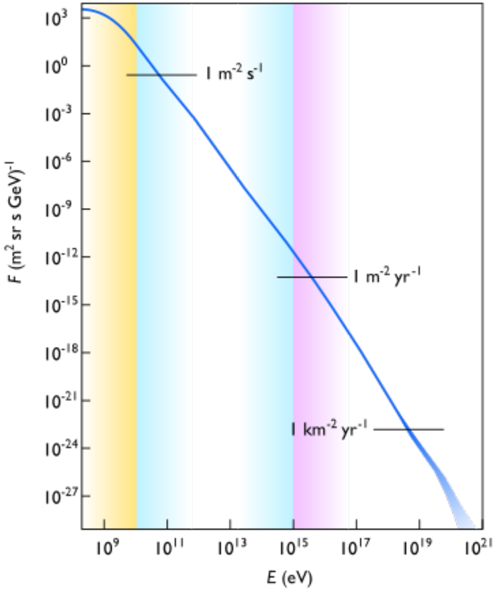
[1] e-mail: ericteunis@deboone.nl

Ultra High Energy particles



Credit: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

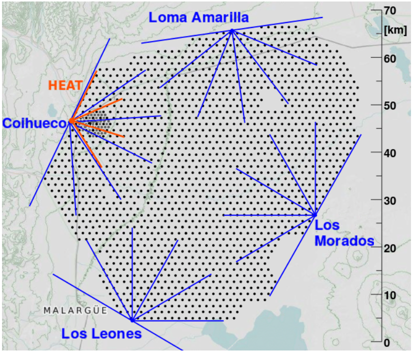
Ultra High Energy particle flux



Credit: Particle Data Group

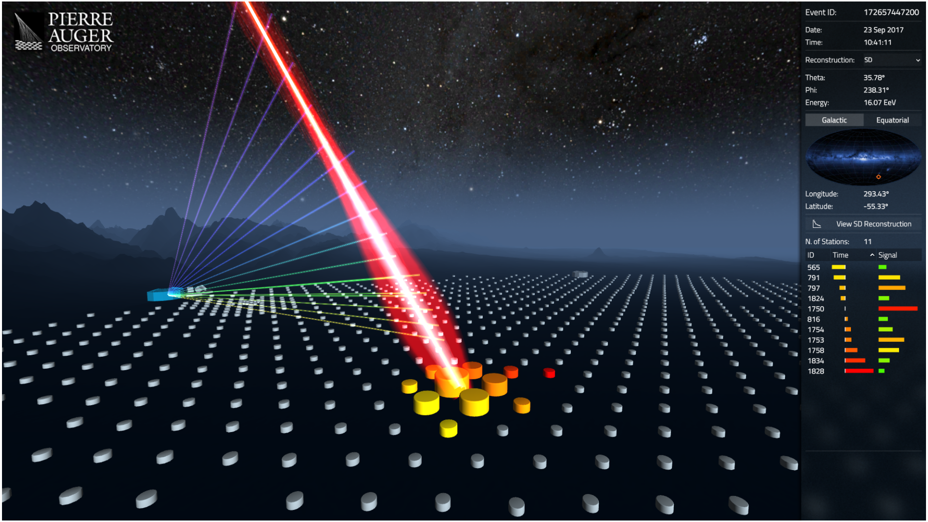
Large Area Experiments:

- Pierre Auger Observatory
- Giant Radio Array for Neutrino Detection



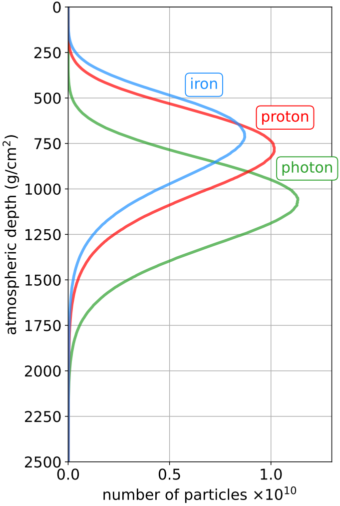
Credit: Hans O. Klages

Air Showers



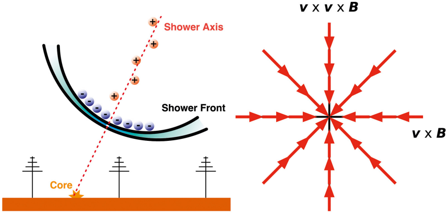
From: `https://opendata.auger.org/display.php?evid=172657447200`

Air Shower Radio Emission

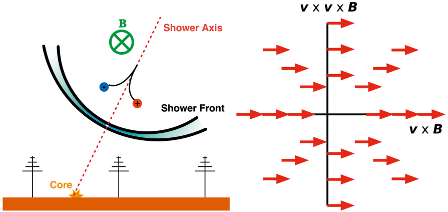


Credit: H. Schoorlemmer

Charge excess



Geomagnetic

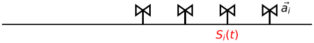


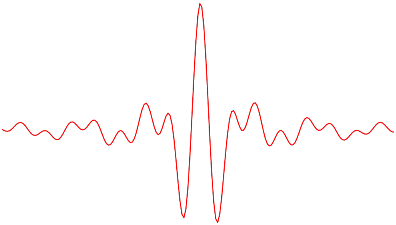
[5]. arXiv: 1701.02995

Radio Interferometry: Concept

Interferometry: Amplitude + Timing information of the $\vec{E}$-field

- Measure signal $S_i(t)$ at antenna $\vec{a_i}$





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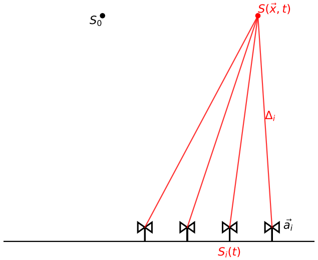
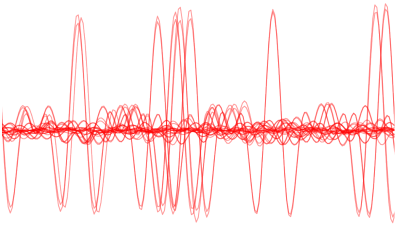


- Measure signal $S_i(t)$ at antenna $\vec{a}_i$
- Calculate light travel time

$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

- Sum waveforms accounting for time delay

$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$



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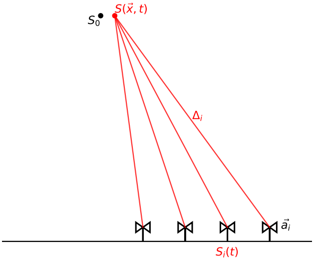

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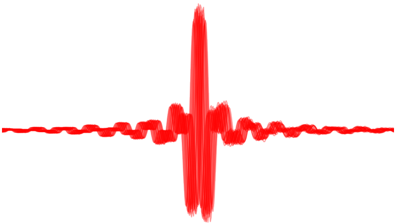

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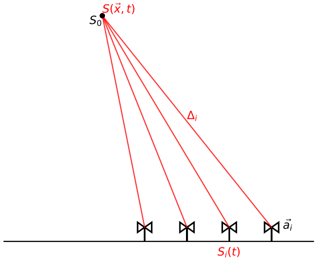

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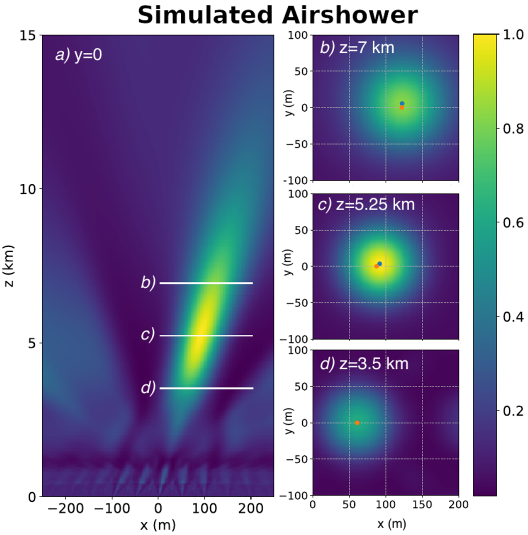
Radio Interferometry: Image



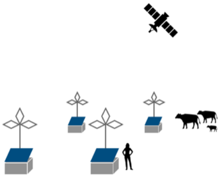
[6]. arXiv: 2006.10348

Timing in Air Shower Radio Detectors

Relative timing is important for Radio Interferometry.
($1\mathrm{ns}$ @$c \sim 30\mathrm{cm}$)

Large inter-detector spacing ($\sim 1\mathrm{km}$)
$\mapsto$ Default timing mechanism: Global Navigation Satellite Systems

What is the accuracy of such systems?



Credit: H. Schoorlemmer

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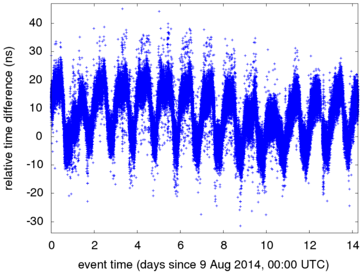
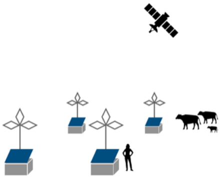
What is the accuracy of such systems?
@Auger: $\sigma_t \gtrsim 10\text{ns}$



[1]. arXiv: 1512.02216

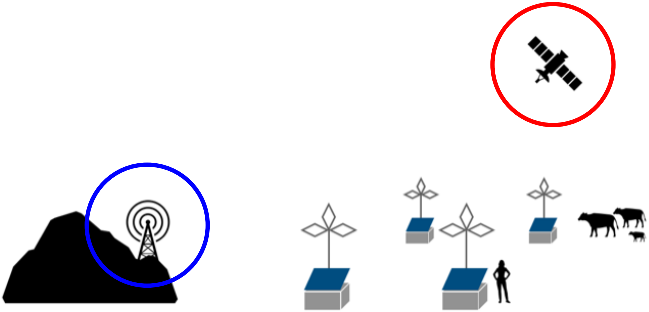


Credit: H. Schoorlemmer

Timing in Radio Detectors: Beacon Synchronisation

Relative timing is important for Radio Interferometry.

Default Timing mechanism: Global Navigation Satellite Systems
+Extra Timing mechanism: Beacon (Pulse, Sine)

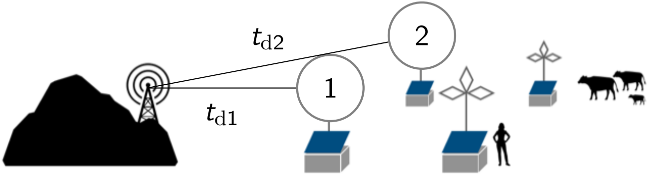


Credit: H. Schoorlemmer

Beacon Synchronisation: Geometry

Local antenna time t'_i due to time delay $t_{\mathrm{d}i}$, clock skew σ_i and transmitter time t_{tx}

$$t'_i = t_{tx} + t_{\mathrm{d}i} + \sigma_i$$

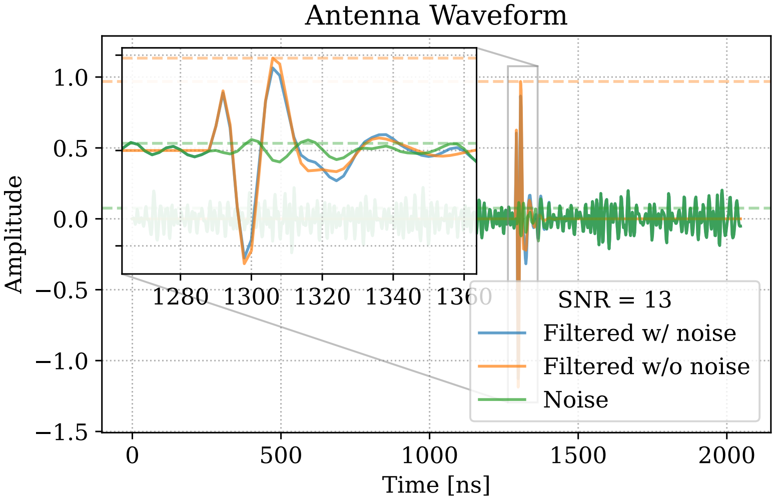


Credit: H. Schoorlemmer

Measured time difference:

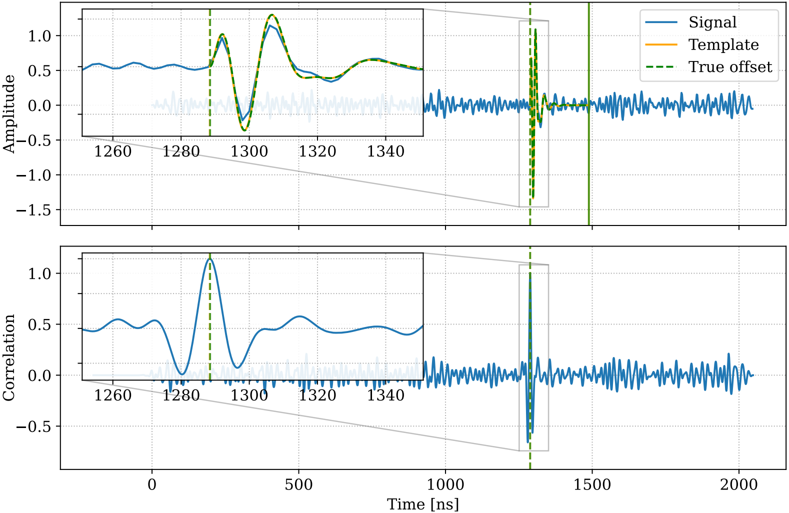
$$\Delta t'_{12} = t'_1 - t'_2 = \Delta t_{\mathrm{d12}} + \sigma_{12} + (t_{\mathrm{tx}} - t_{\mathrm{tx}})$$

Pulse Beacon

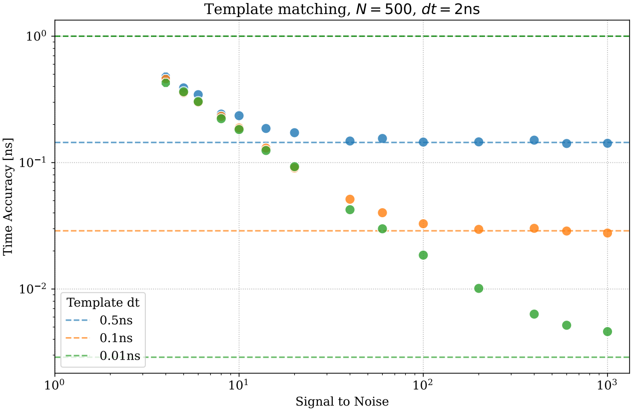


Pulse Beacon

Correlation: similarity between two signals.



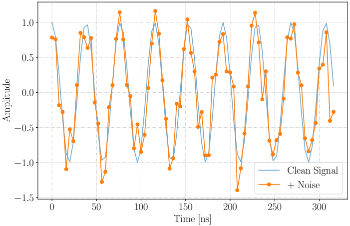
Pulse Beacon Timing

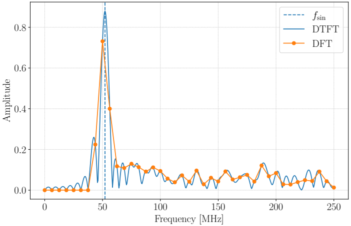


(Multi)Sine Beacon

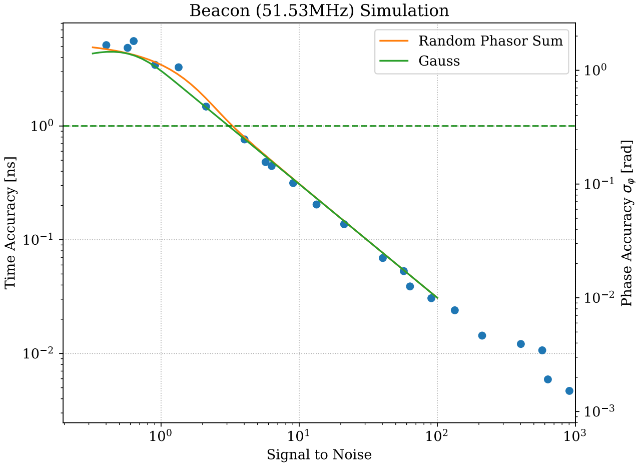
Phase measurement φ_i' using Fourier Transform, k unknown:

$$t_i' = \left[\frac{\varphi_i'}{2\pi} + k \right] T$$





(Multi)Sine Beacon Timing



Random Phasor Sum:
[4] "Statistical Optics", J. Goodman

$$p_\Phi(\phi; s, \sigma) = \frac{e^{-\left(\frac{s^2}{2\sigma^2}\right)}}{2\pi} + \sqrt{\frac{1}{2\pi}}\,\frac{s}{\sigma}\,e^{-\left(\frac{s^2}{2\sigma^2}\sin^2\phi\right)}\,\frac{\left(1 + \operatorname{erf}\frac{s\cos\phi}{\sqrt{2}\sigma}\right)}{2}\cos\phi$$

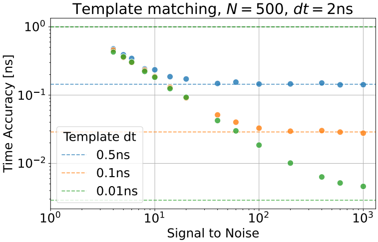
Beacon Synchronisation: Conclusion

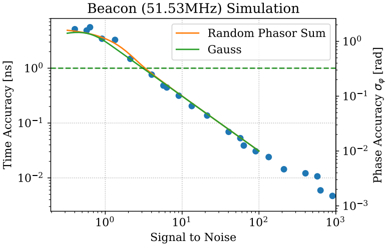
Pulse

- discrete
- requires template

Sine

- continuous
- longer trace
  $\mapsto$ better SNR
- k period unknown

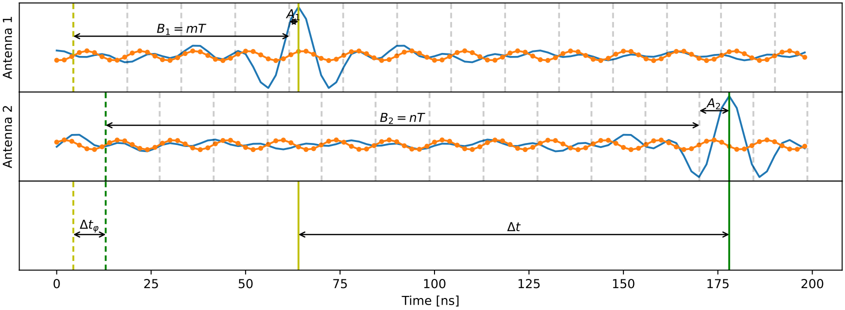




Single Sine Synchronisation

k is discrete, lift the period degeneracy using the air shower radiosignal

$$t'_i = (\frac{\varphi'_i}{2\pi} + n_i)T = A_i + B_i$$



$$\Delta t'_{ij} = (A_j + B_j) - (A_i + B_i) + \Delta t'_\varphi$$
$$= \Delta A_{ij} + \Delta t'_\varphi + k_{ij} T$$

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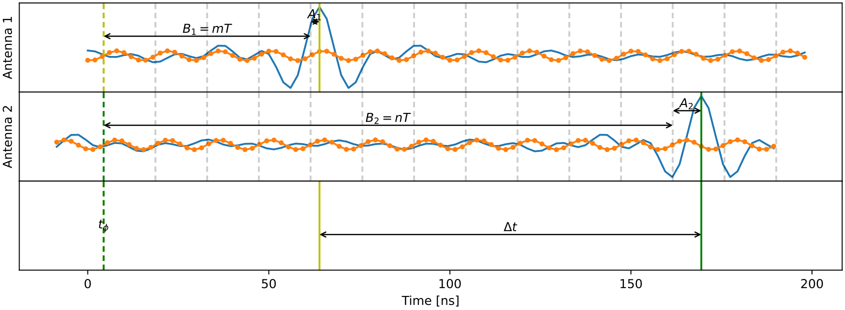

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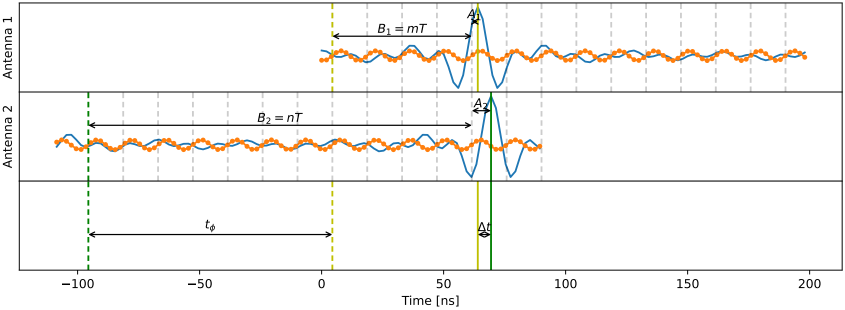

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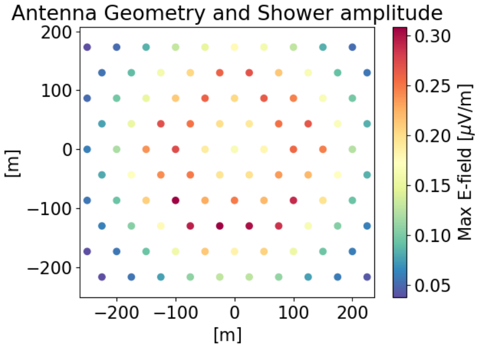
Single Sine Synchronisation Simulation

Air Shower simulation on a grid of 100x100 antennas.



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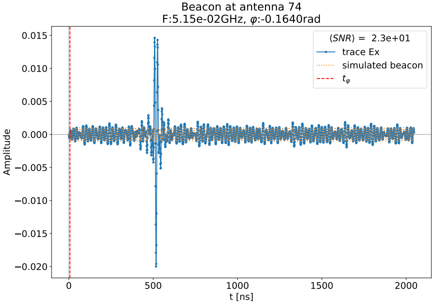
- Add beacon ($T \sim 20\mathrm{ns}$) to antenna
- Randomise clocks ($\sigma = 30\mathrm{ns}$)



Single Sine Synchronisation Simulation

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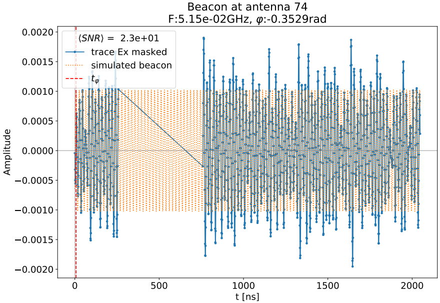
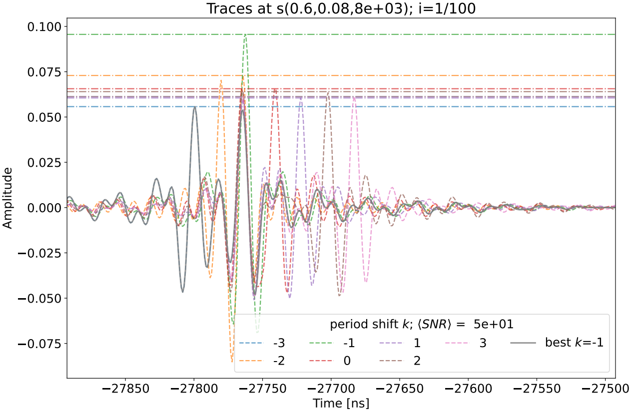
- Add beacon ($T \sim 20\mathrm{ns}$) to antenna
- Randomise clocks ($\sigma = 30\mathrm{ns}$)
- Measure phase with DTFT
- Repair clocks for small offsets
- Iteratively find best k_{ij}



Single Sine Synchronisation: Iterative k_{0i}-finding

"Interferometry" while allowing to shift by $T = 1/f_{\mathrm{beacon}}$

Iterative process optimizing signal power:
- Scan positions finding the best $\{k_{0i}\}$ set,
- then evaluate on a grid near shower axis and zoom in.



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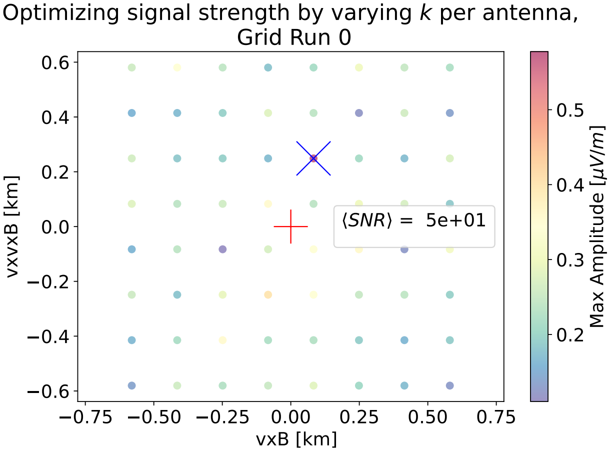

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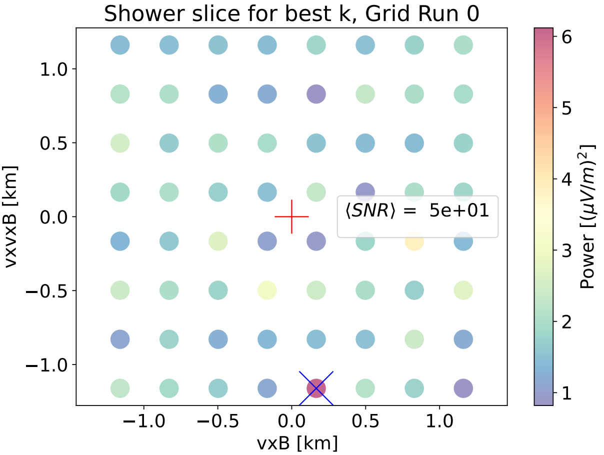

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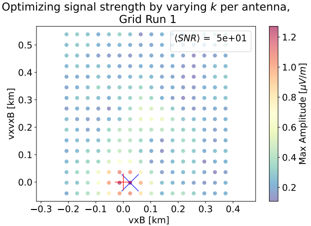
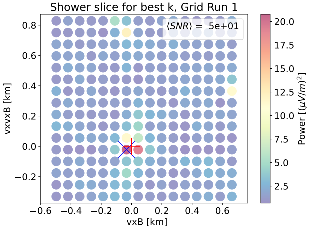
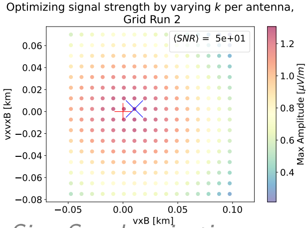
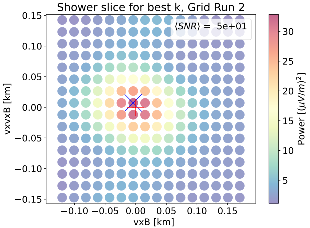


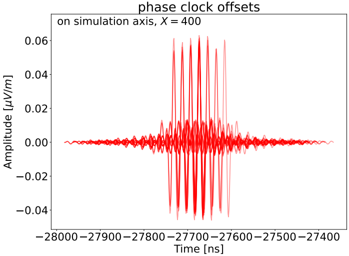


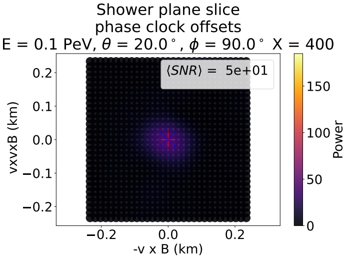




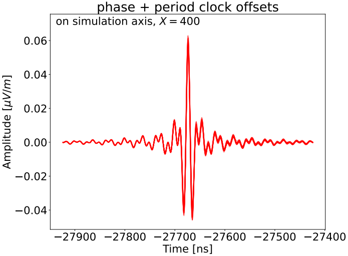
Single Sine Synchronisation: Timing Reparation

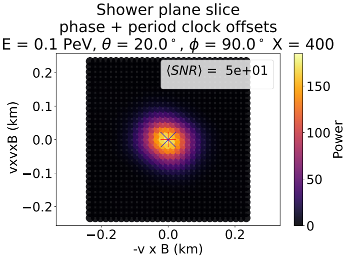
Phase reparation





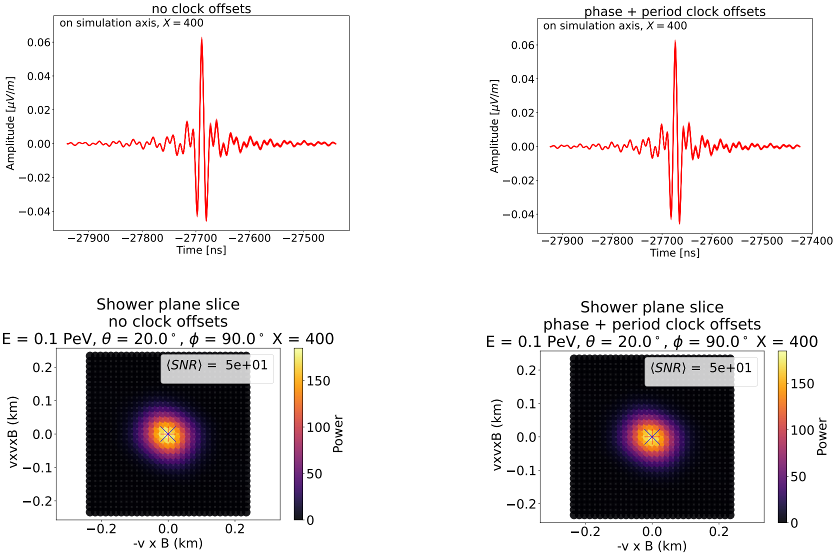
Phase + Period reparation





Single Sine Synchronisation: Comparison

True clock | Phase + Period reparation



Conclusion and Outlook

- Cosmic Particles induce Extensive Air Showers
- Relative Timing is crucial to Radio Interferometry
- Pulse and Sine beacons can synchronise effectively
- Single Sine + Air Shower works

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Outlook:

- Parasitic setups, i.e. the $67\,\mathrm{MHz}$ in Auger,
- Self-calibration using pulsed beacon

Supplemental material

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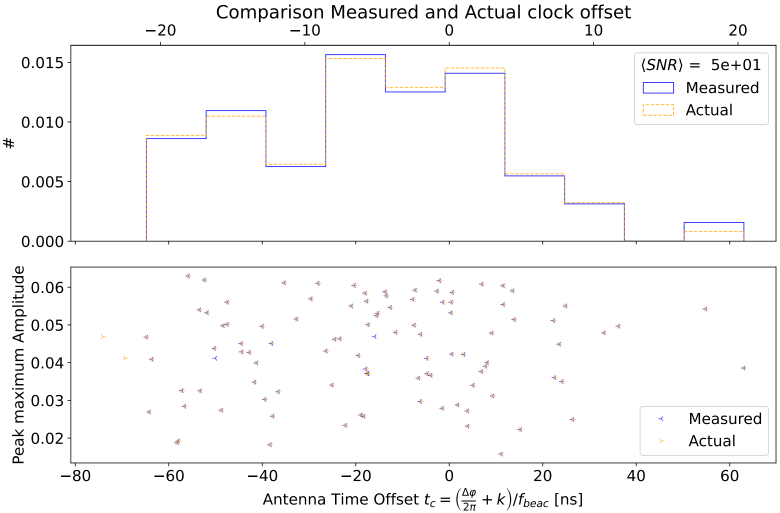
Single Sine Timing Result



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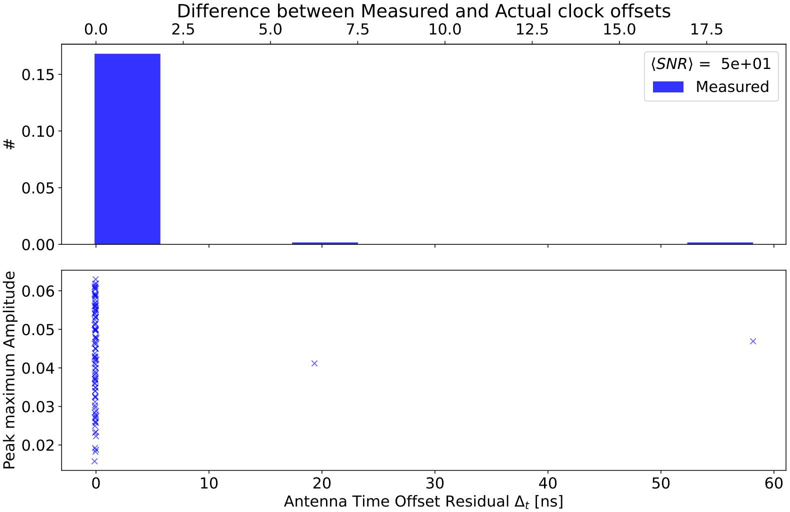
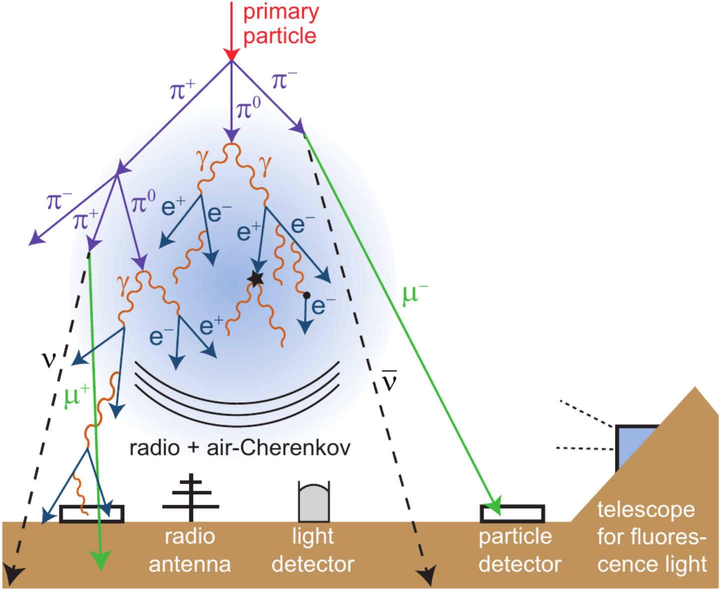
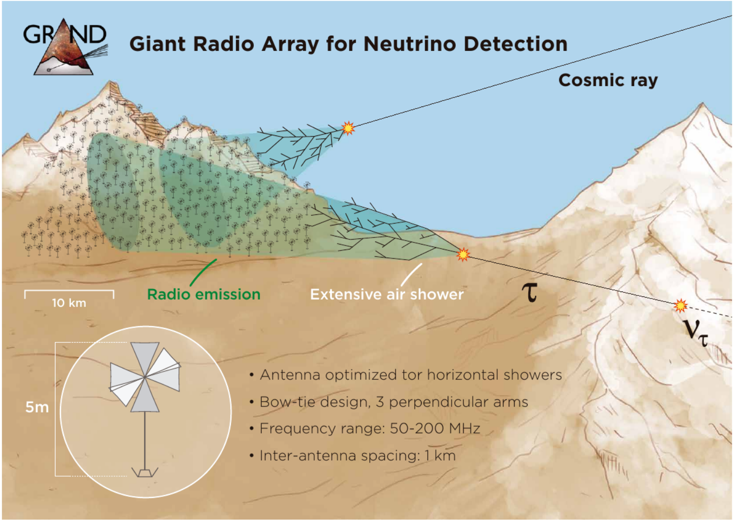


Airshower development



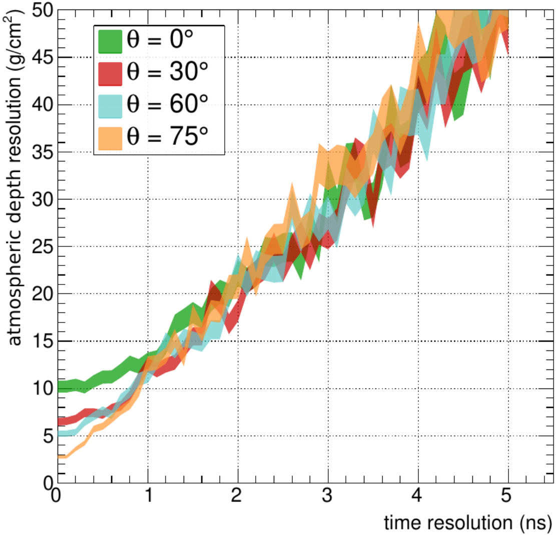
[7] arXiv: 1607.08781

Radio footprint; GRAND



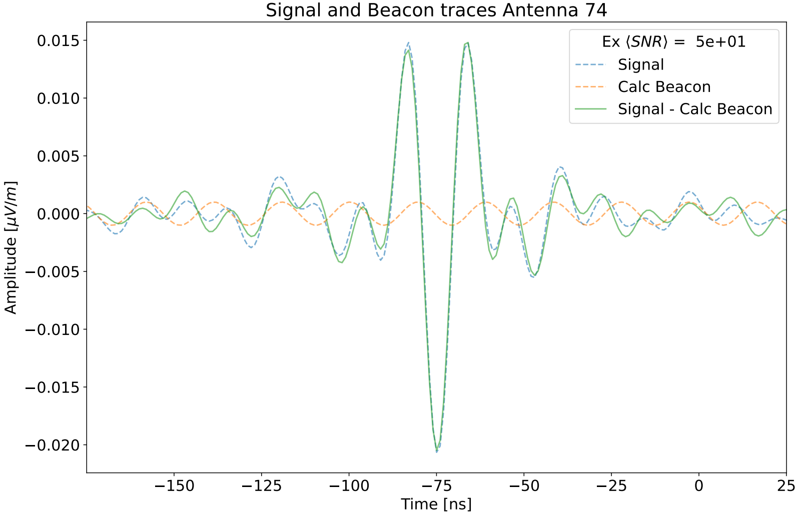
Credit: [2]. arXiv: 1810.09994

Radio Interferometry: Xmax Resolution vs Timing Resolution

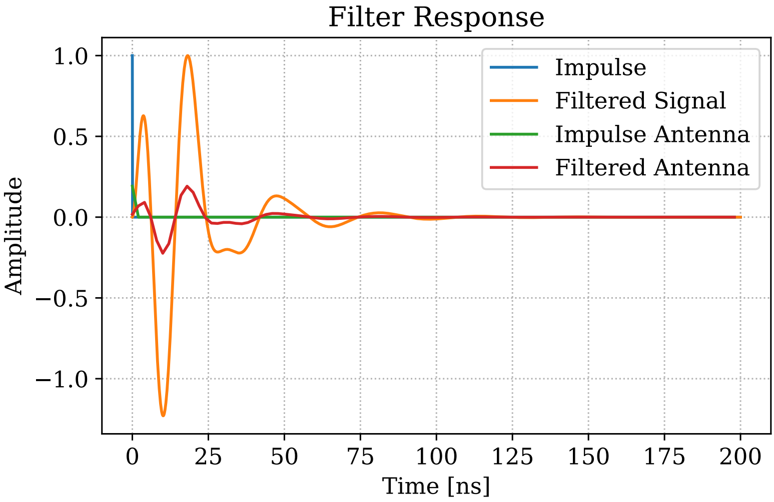


Credit: [6]. arXiv: 2006.10348

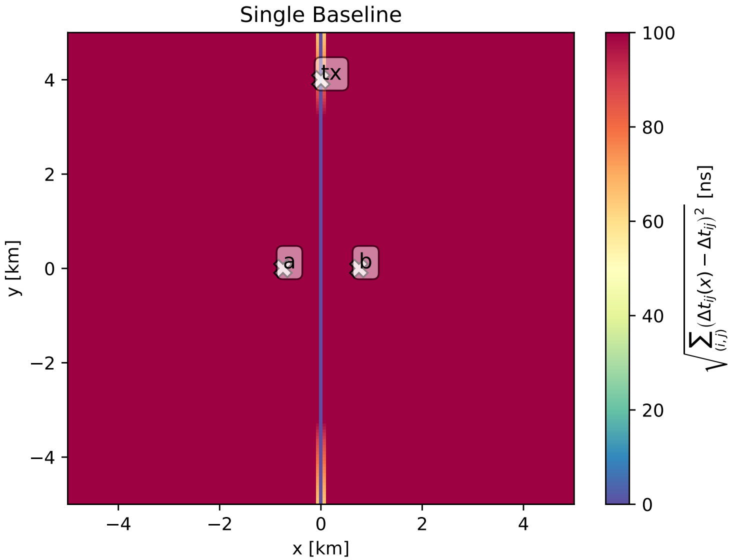
Sine: Air Shower - Beacon



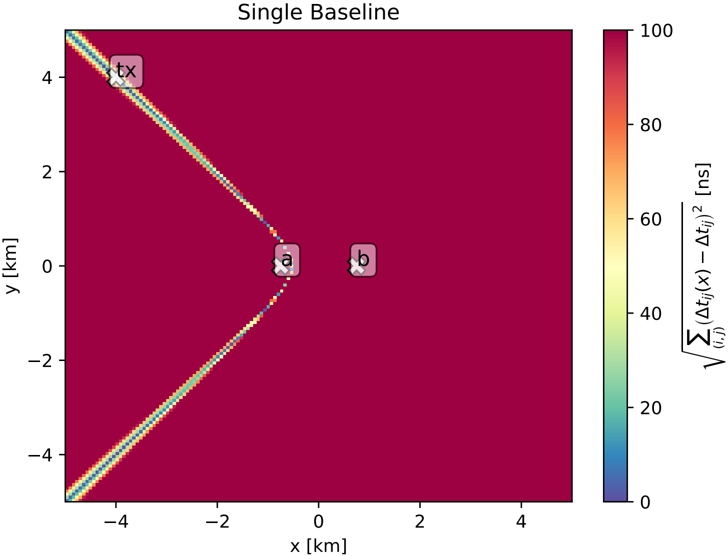
Filter Response and Sampling



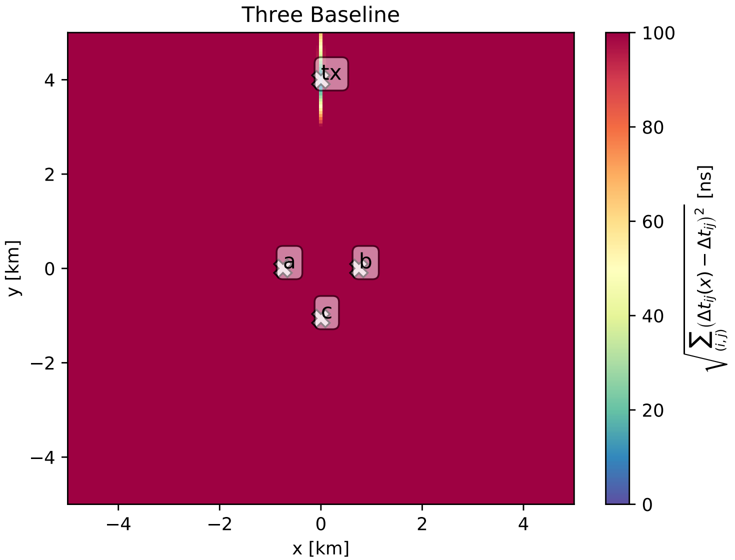
Beacon: Pulse (single baseline)



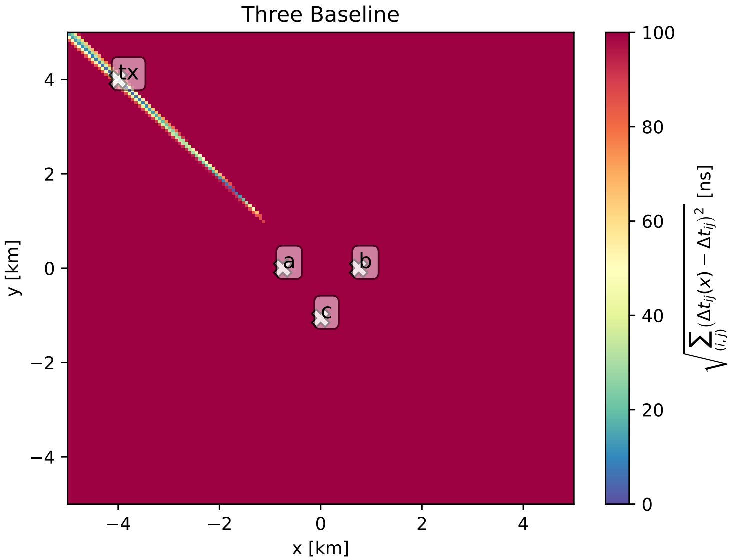
Beacon: Pulse (single baseline)



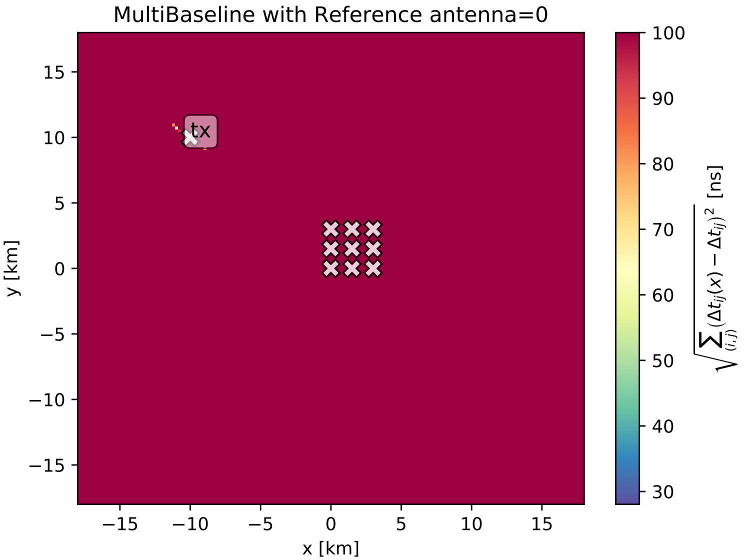
Beacon: Pulse (3 baselines)



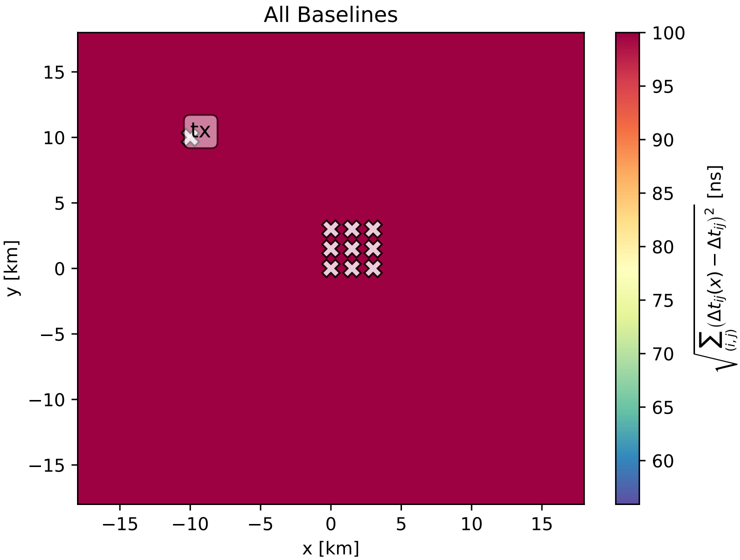
Beacon: Pulse (3 baselines)



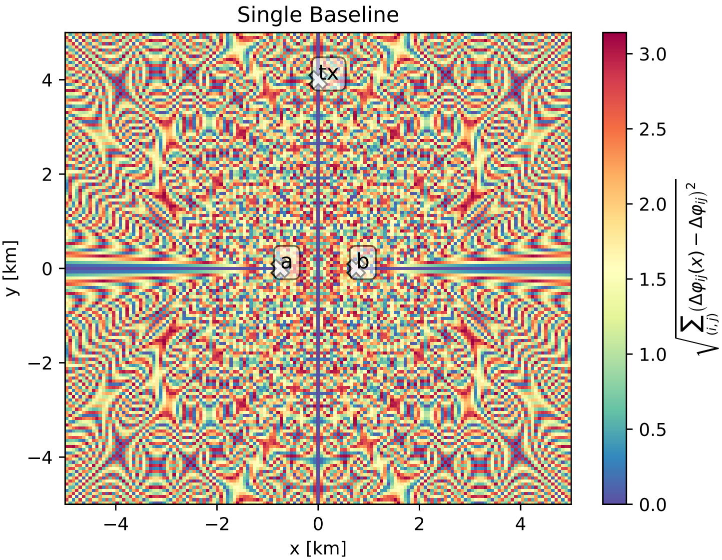
Beacon: Pulse (multi baseline)



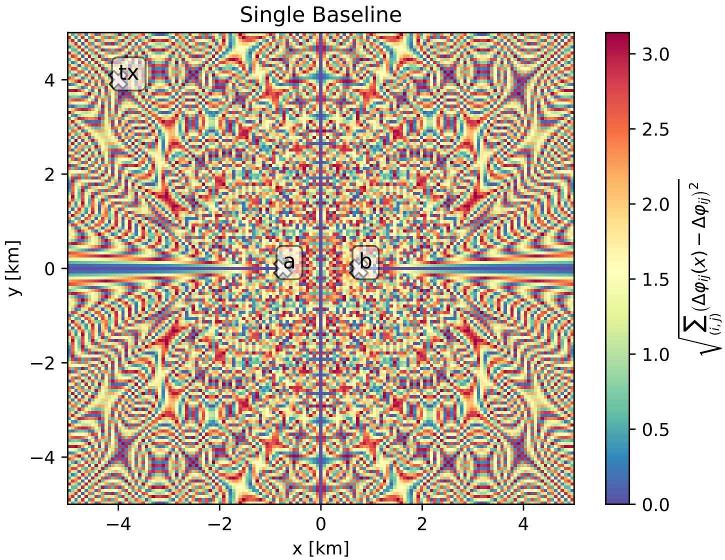
Beacon: Pulse (multi baseline)



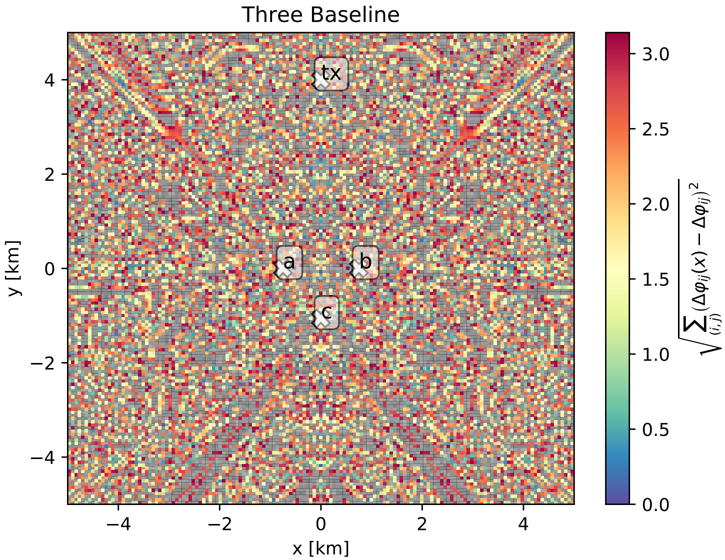
Beacon: Sine (single baseline)



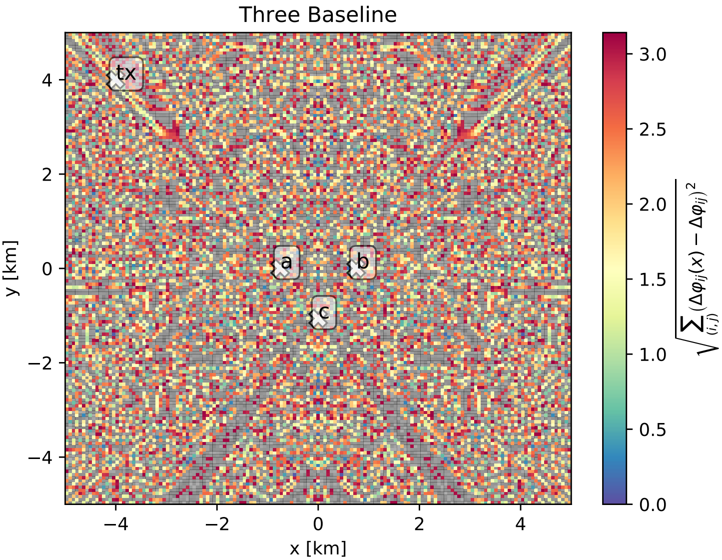
Beacon: Sine (single baseline)



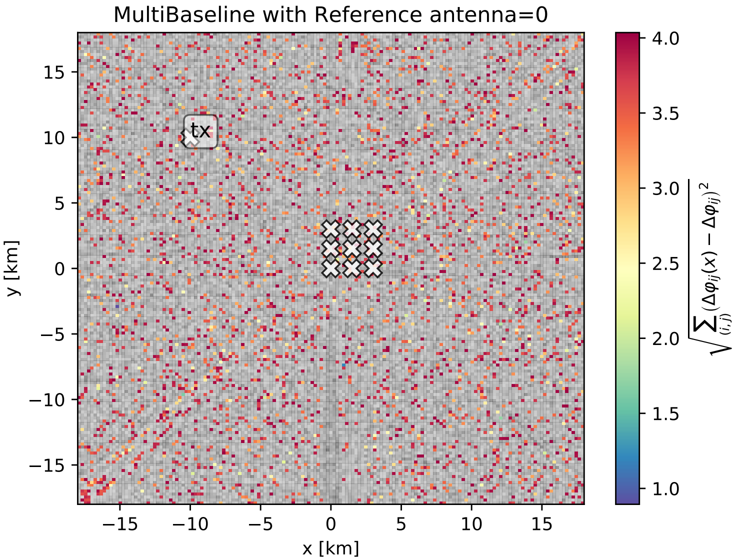
Beacon: Sine (3 baseline)



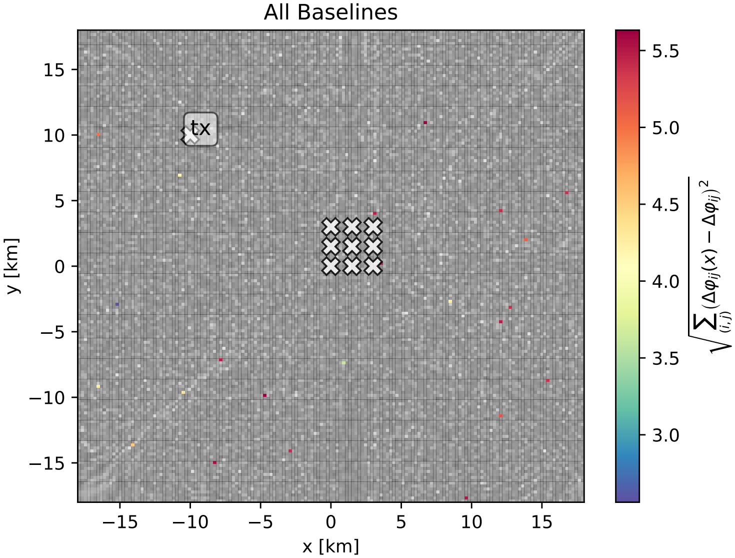
Beacon: Sine (3 baseline)



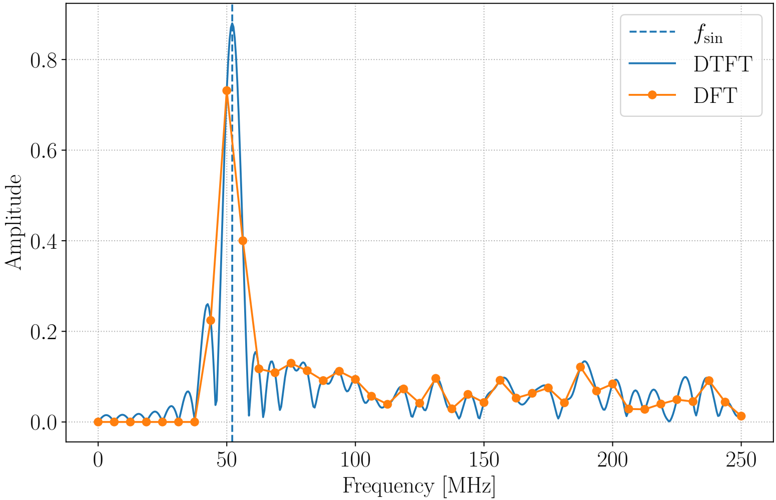
Beacon: Sine (multi baseline reference antenna)



Beacon: Sine (all baselines)



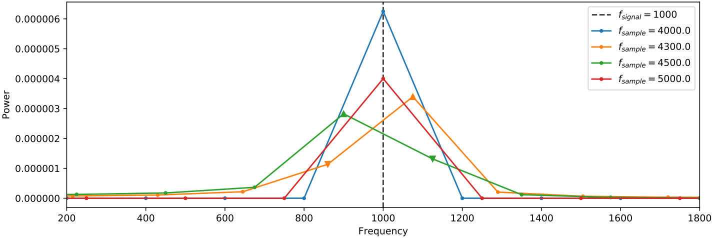
DTFT vs DFT



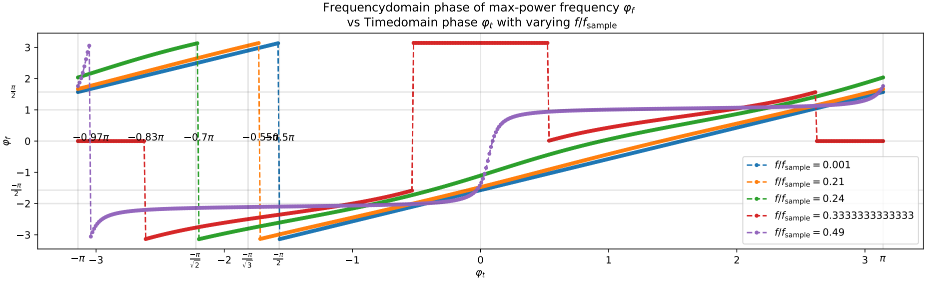
f_{sin}
DTFT
DFT
0.8
0.6
0.4
0.2
0.0
Amplitude
0
50
100
150
200
250
Frequency [MHz]

(Discrete) Fourier and Phase

$$u(t) = \exp(i2\pi ft + \phi_t) \xrightarrow{\text{Fourier Transform}} f', \phi_f$$



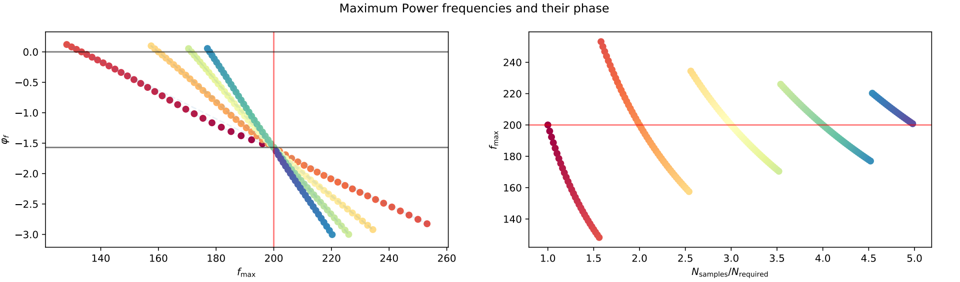
Phase reconstruction?



Phase reconstruction is easy if sample rate “correct”

Phase reconstruction?

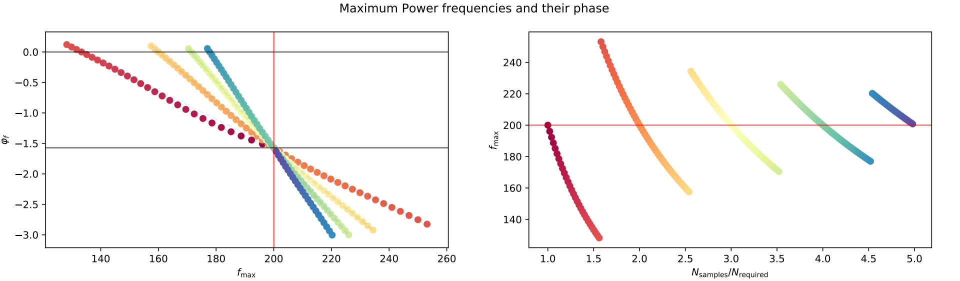
What if sample rate “incorrect”?



Phase reconstruction?

What if sample rate “incorrect”?

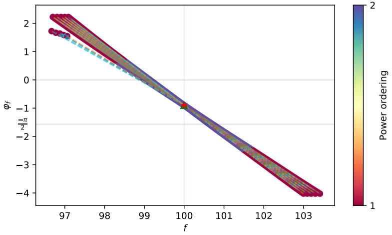
$\rightarrow$ Linear interpolation (f_{signal}, f_{max}, f_{submax}, ϕ_{max} and ϕ_{submax})

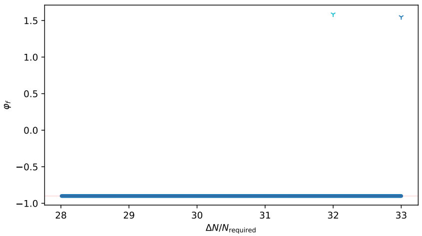


Phase reconstruction?

What if sample rate “incorrect”?

→ Linear interpolation (f_{signal}, $f_{\max}$, f_{submax}, $\phi_{\max}$ and ϕ_{submax})

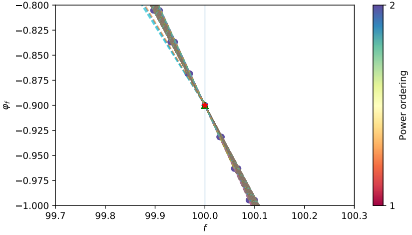


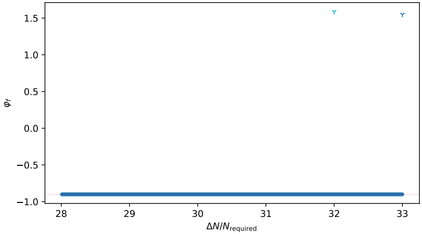


Phase reconstruction?

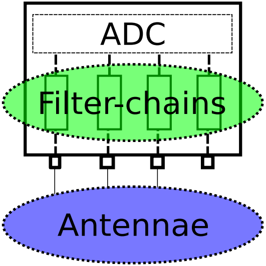
What if sample rate "incorrect"?

→ Linear interpolation (f_{signal}, f_{max}, f_{submax}, ϕ_{max} and ϕ_{submax})

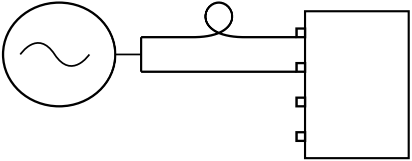




GNSS clock stability I



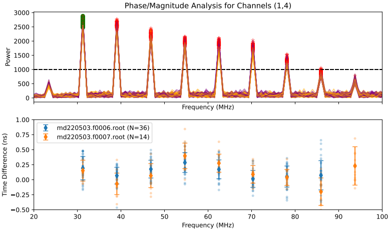
GRAND Digitizer Unit's
ADC to antennae



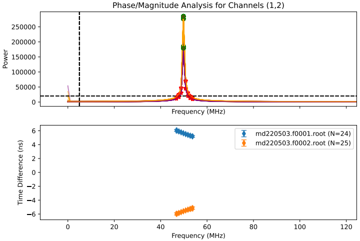
Channel filterchain delay experiment

GNSS filterchain delay experiment

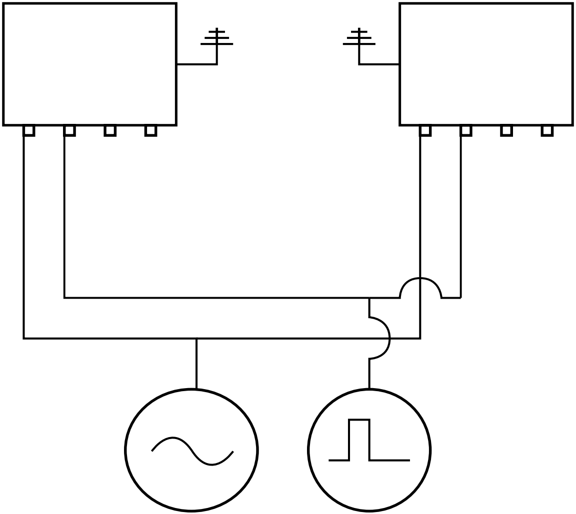
Pulse



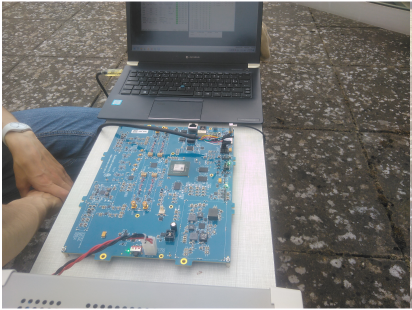
50MHz Sinewave delay(ch1, ch2) $= 46\mathrm{ps} \pm 10$

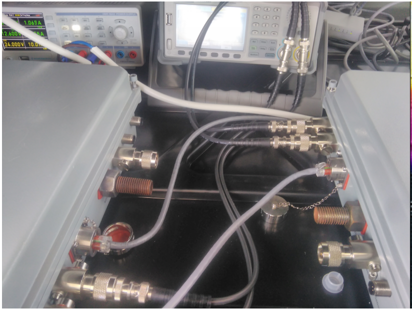


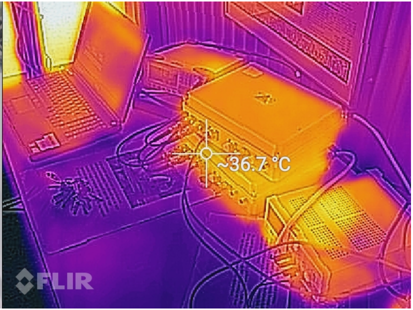
GNSS clock stability II



GNSS stability experiment



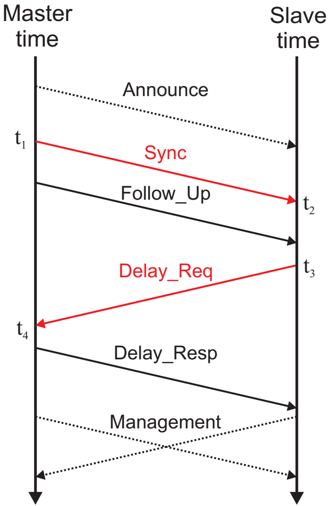

1.069 A


~36.7 °C
FLIR

GNSS clock stability III

Precision Time Protocol

- Time synchronisation over (long) distance between (multiple) nodes



[3] Precision Time Protocol messages.

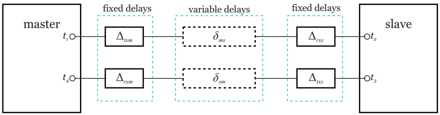
White Rabbit

White Rabbit:

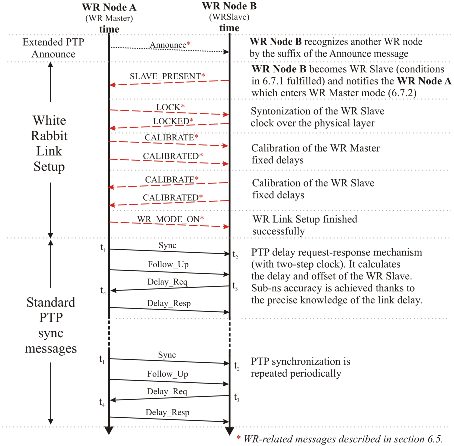
- SyncE (common oscillator)
- PTP (synchronisation)

Factors:

- device (Δ_{txm}, Δ_{rxs}, ...)
- link (δ_{ms}, ...)

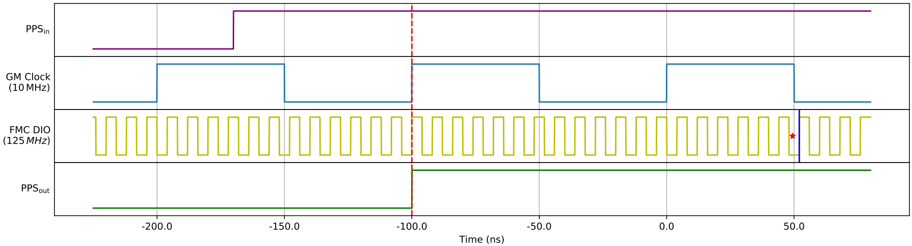


Credit: [3]



Credit: [3]

White Rabbit Clock Reference



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[3] E. Cota et al. *White Rabbit Specification: Draft for Comments*. www.ohwr.org/attachments/1169/WhiteRabbitSpec.v2.0.pdf. July 2011.

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[4] Joseph W. Goodman. 'Statistical Optics'. en. In: 2nd ed. Wiley Series in Pure and Applied Optics. Nashville, TN: John Wiley & Sons, Apr. 2015. Chap. 2.9. ISBN: 978-1-119-00945-0.

[5] Tim Huege. 'Radio detection of extensive air showers'. In: *Nucl. Instrum. Meth. A* 876 (2017). Ed. by P. Krizan et al., pp. 9–12. DOI: 10.1016/j.nima.2016.12.012. arXiv: 1701.02995 [astro-ph.IM].

[6] Harm Schoorlemmer et al. 'Radio interferometry applied to the observation of cosmic-ray induced extensive air showers'. In: *Eur. Phys. J. C* 81.12 (2021), p. 1120. DOI: 10.1140/epjc/s10052-021-09925-9. arXiv: 2006.10348 [astro-ph.HE].

References III

[7] Frank G. Schröder. 'Radio detection of Cosmic-Ray Air Showers and High-Energy Neutrinos'. In: *Prog. Part. Nucl. Phys.* 93 (2017), pp. 1–68. DOI: 10.1016/j.ppnp.2016.12.002. arXiv: 1607.08781 [astro-ph.IM].