Nanosecond time synchronization of distributed detectors

Yan Seyffert | 05.08.2024 at ICPS 2024 in Tbilisi, Georgia

University of Bremen: Erasmus Mundus Joint Master in Astrophysics and Space Science (MASS)

OUTLINE:

I. Cosmic Rays and Extensive Air Showers
II. The Pierre Auger Observatory, Argentina
III. Synchronization Methods of Distributed Detectors
    I. Global Navigation Satellite Systems
    II. Radio Beacon Reference Transmitter
IV. Results from my Thesis
V. Conclusions

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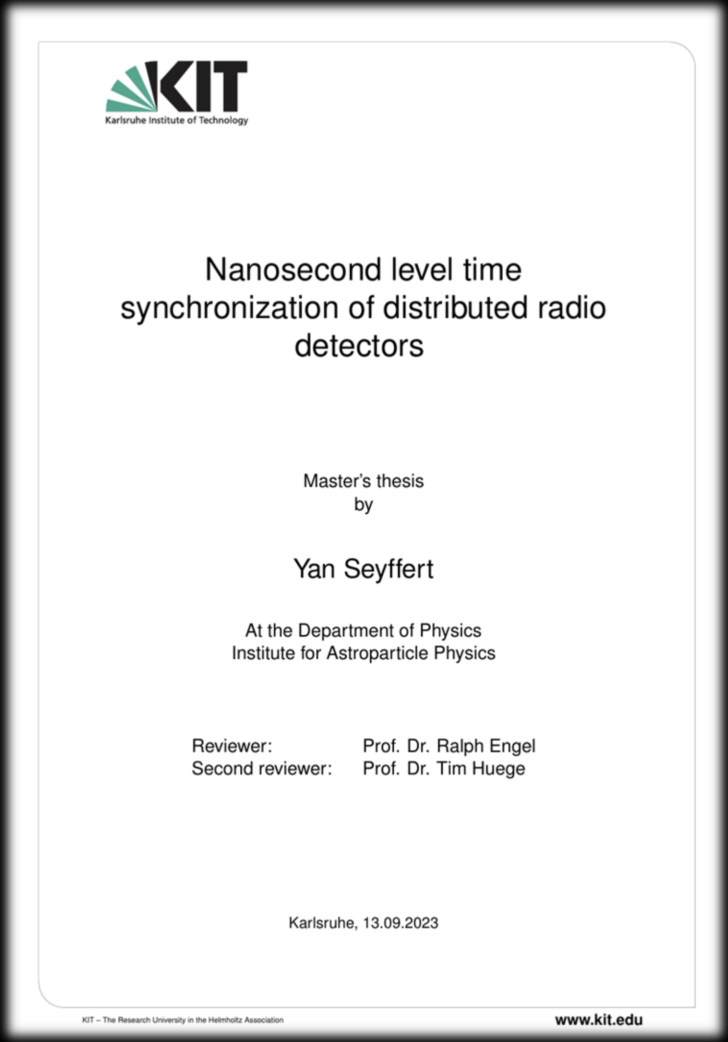
KIT
Karlsruhe Institute of Technology

Nanosecond level time synchronization of distributed radio detectors

Master's thesis
by

Yan Seyffert

At the Department of Physics
Institute for Astroparticle Physics

Reviewer: Prof. Dr. Ralph Engel
Second reviewer: Prof. Dr. Tim Huege

Karlsruhe, 13.09.2023

KIT – The Research University in the Helmholtz Association
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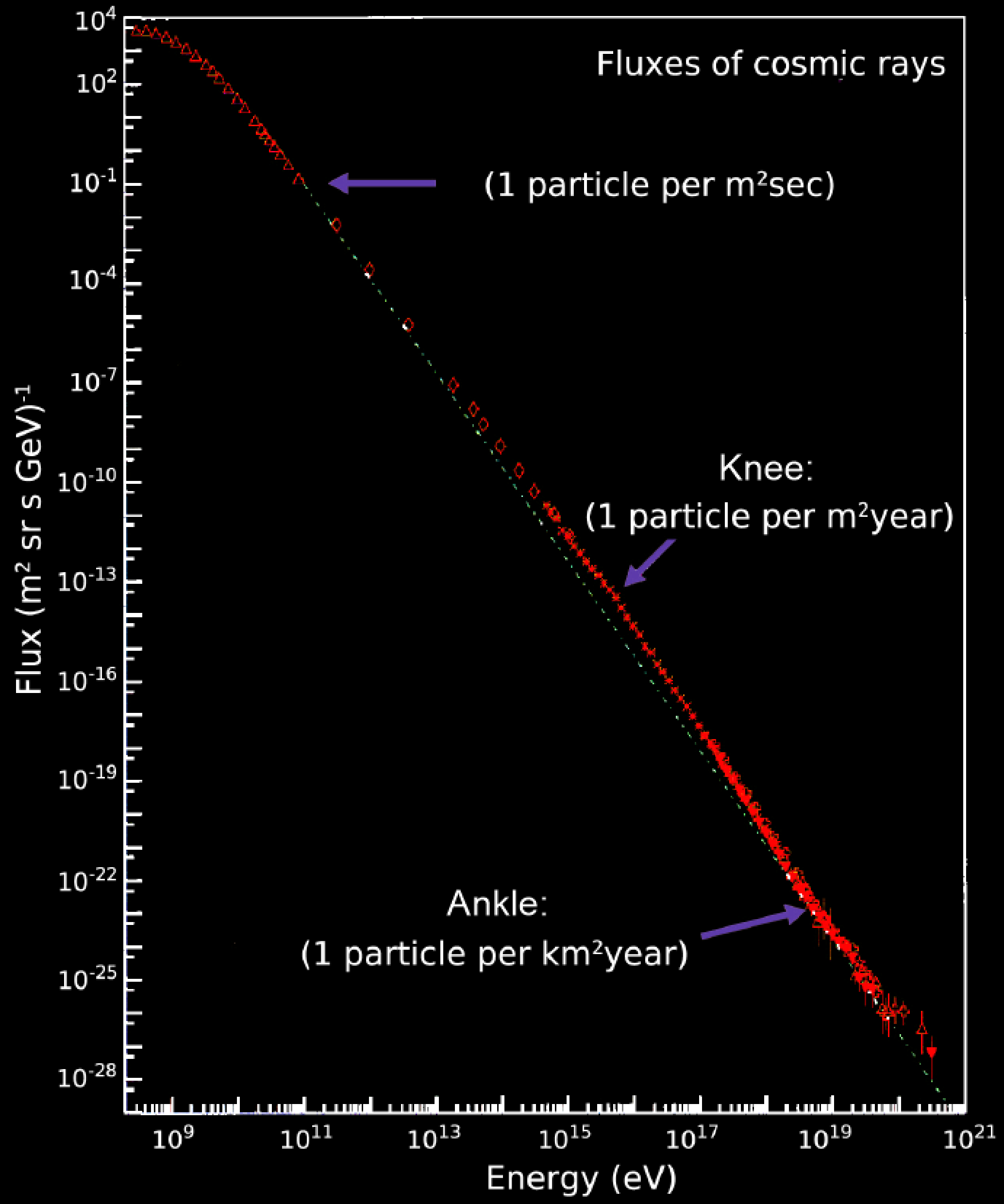
I. COSMIC RAYS AND EXTENSIVE AIR SHOWERS

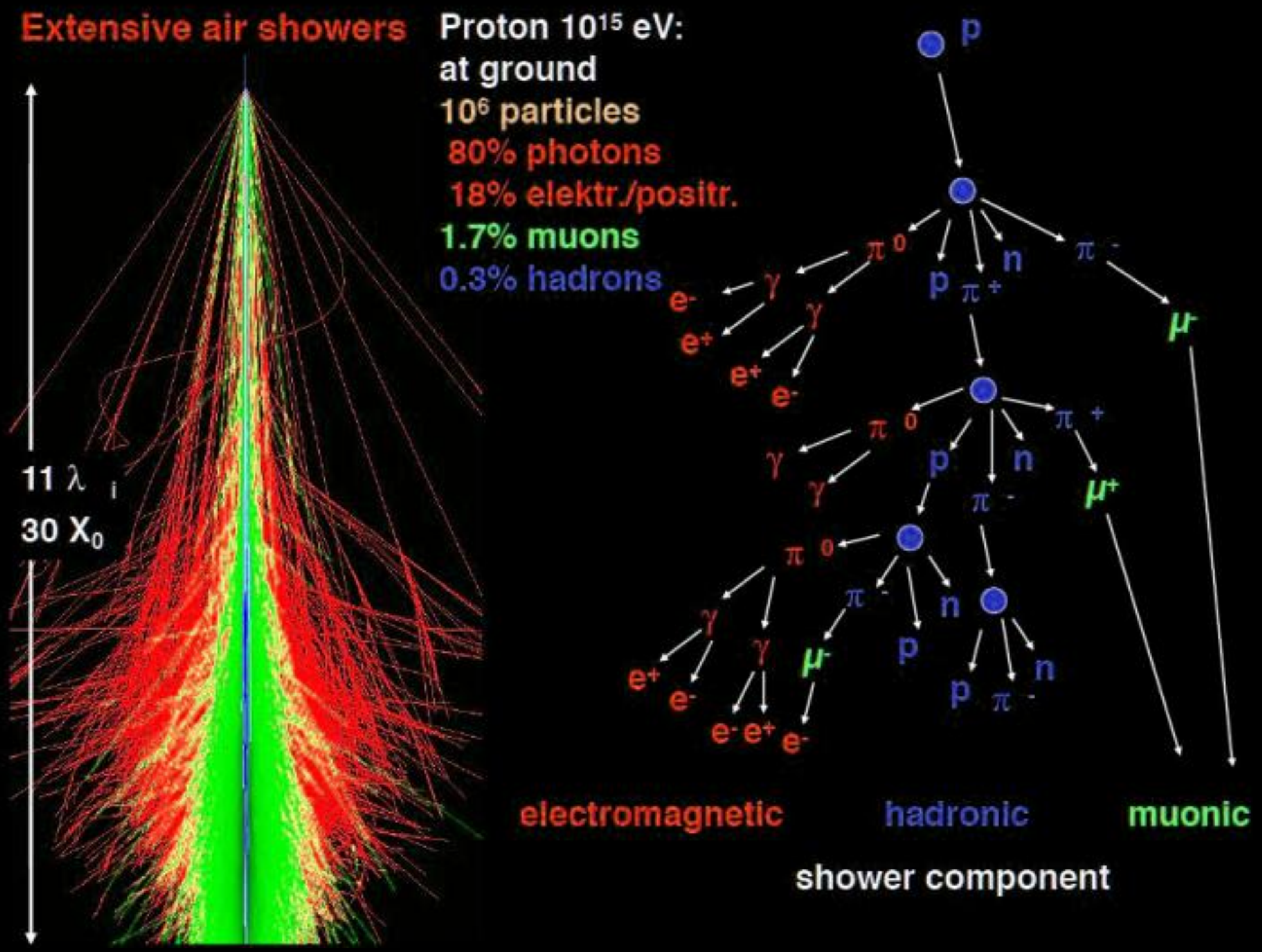
COSMIC RAYS AND EXTENSIVE AIR SHOWERS

- Cosmic Ray's (CRs) were discovered by Victor Franz Hess in 1912 (Ballon flights) as Height Radiation; Noble Price 1936
- Discovery of Extensive Air Showers (EAS) by Pierre Auger in 1939 (Swiss Alps conincidence experiments)
- Primary Particles are charged atomic nuclei with various kinetic energies
- Supernova Remnants (SNR) are confirmed origins, Other possible Origins Still under Investigation (like AGNs, GRBs etc.)

Cosmic ray energy spectrum

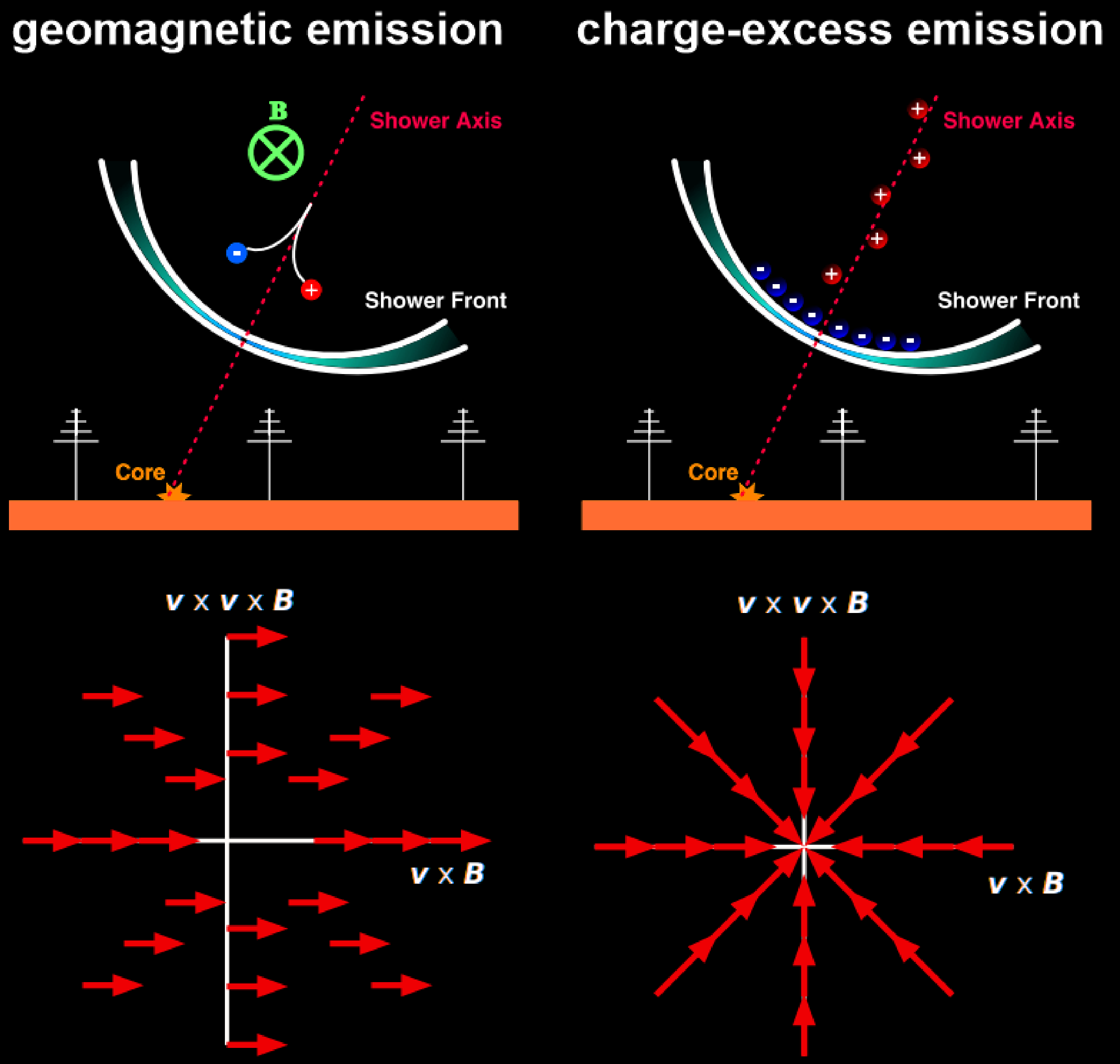


[1] Adopted from W. Bietenholz. “The Most Powerful Particles in the Universe: A Cosmic Smash”. In: Revista Cubana de Física 31.1 (2014), pp. 45–50. issn: 2224-7939. arXiv: 1305.1346 [physics.hist-ph]



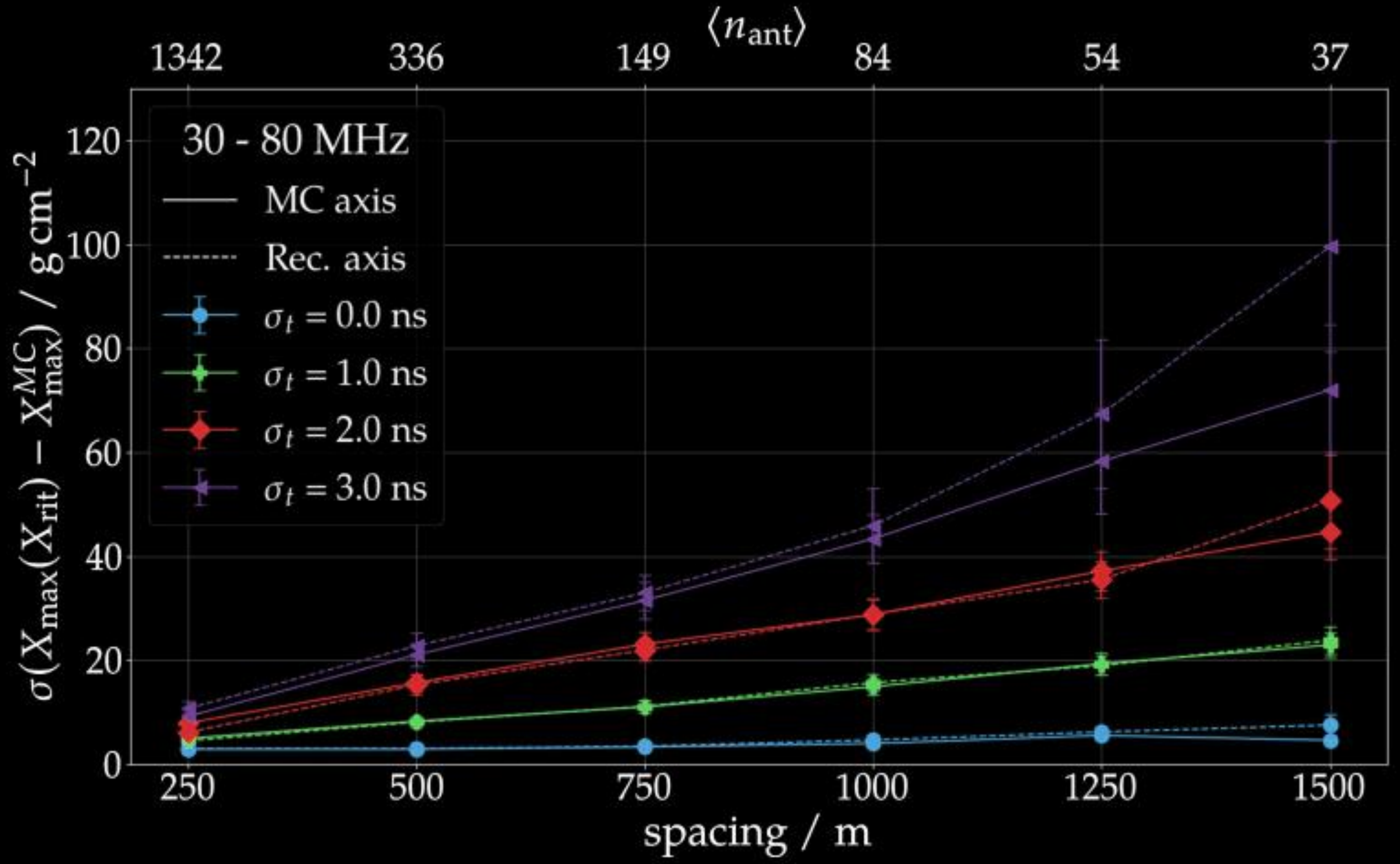
Left: **Simulated Extensive Air Shower** (EAS) cascade. λ denotes the hadronic interaction length and X_0 the radiation length.
Right: Schematic illustration detailing the various components of the shower, together with their possible decay pathways

[2] Adopted from S. Paredes Saenz. 2019 CERN Latin-American School of HEP: Student Project Presentation: Cosmic Ray Studies at the Pierre Auger Observatory. [online]. url: https://indico.cern.ch/event/763013/contributions/3358878/



Lesser known **radio pulse component of an EAS**: mechanism for geomagnetic emission and charge excess emissions visualized. Bottom: the respective polarization directions.

[3] Adopted from T. Huege. "Radio detection of cosmic ray air showers in the digital era". In: Phys. Rept. 620 (2016), pp. 1–52. doi: 10.1016/j.physrep.2016.02.001. arXiv: 1601.07426 [astro-ph.IM]



Reconstruction **resolution of X_max shown for different time jitter scenarios** and depending on different antenna spacings

[4] F. Schlüter and T. Huege. "Expected performance of air-shower measurements with the radio-interferometric technique". In: Journal of Instrumentation 16.07 (July 2021), P07048. doi: 10.1088/1748-0221/16/07/p07048.

II. THE PIERRE AUGER OBSERVATORY

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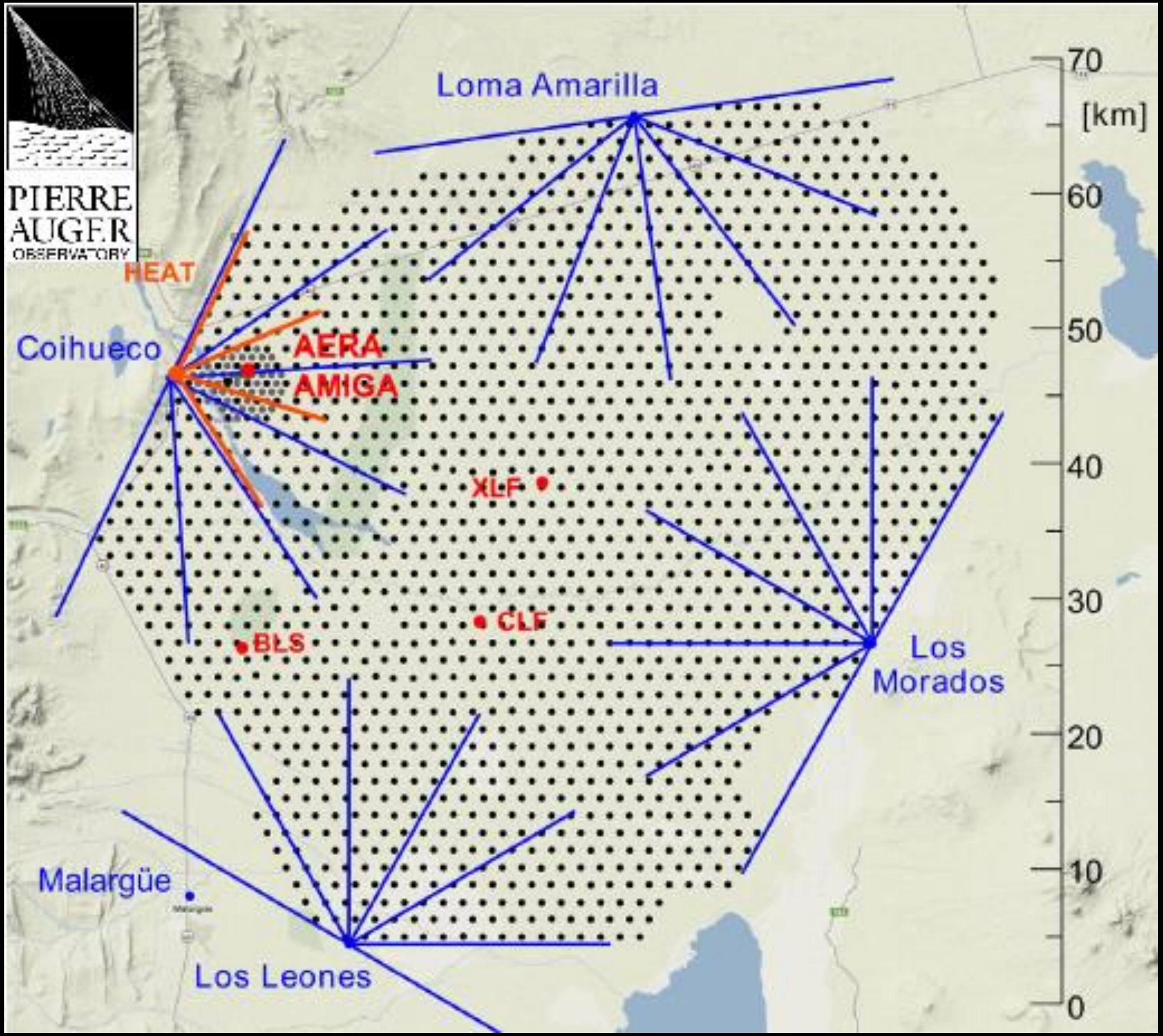
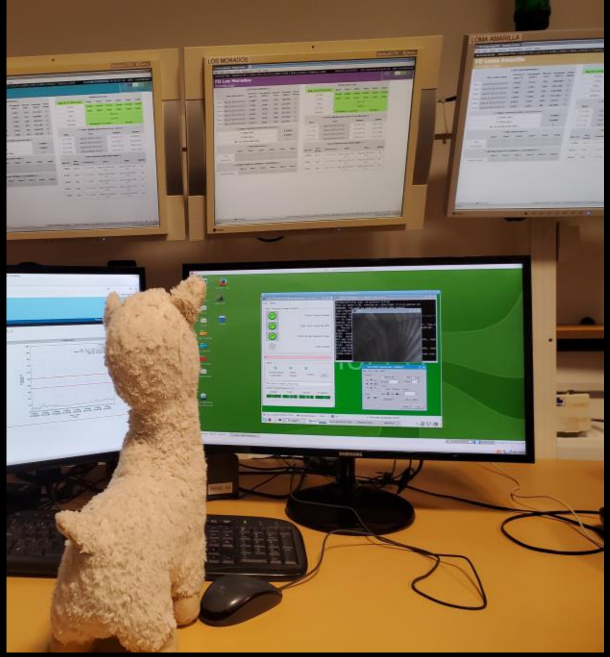
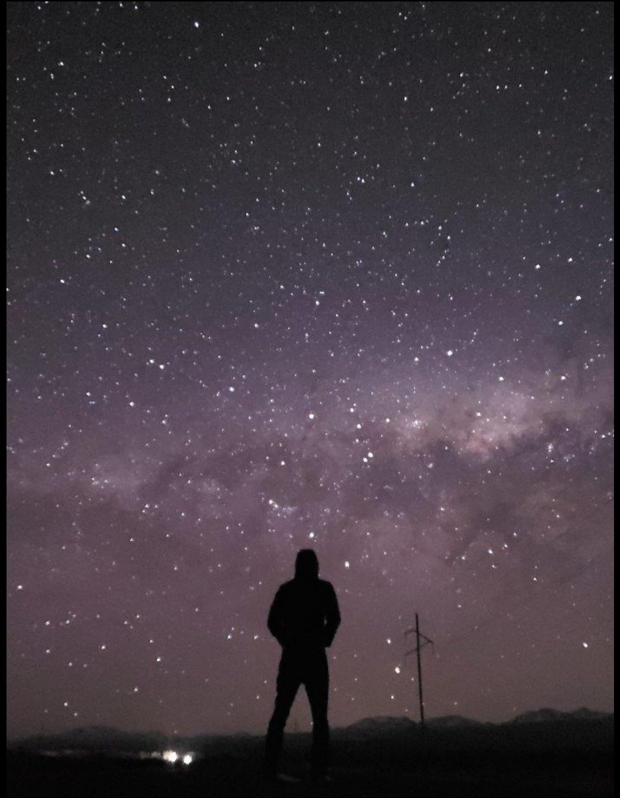
- CR EXPERIMENTS NEED TO INSTRUMENT LARGE AREAS WITH AUTONOMOUS DETECTOR STATIONS
- THE PIERRE AUGER OBSERVATORY IN ARGENTINA (PROVINCE MENDOZA) COVERS 3000 KM^2 WITH 1600 SURFACE DETECTORS (SD) AND 1.5KM SPACING BETWEEN DETECTORS
- A CURRENT DETECTOR UPGRADE IS ADDING RADIO ANTENNAS TO ALMOST ALL SDS



Detector map of the Pierre Auger Observatory located in Argentina

[5] D. Veberič. Auger Array. [online]. [Last access: 07.09.2023]. url: https://wwwf9.ijs.si/~darko/auger/auger-array/auger_array-jpg/


LOS MORADOS
LOMA AMARILLA

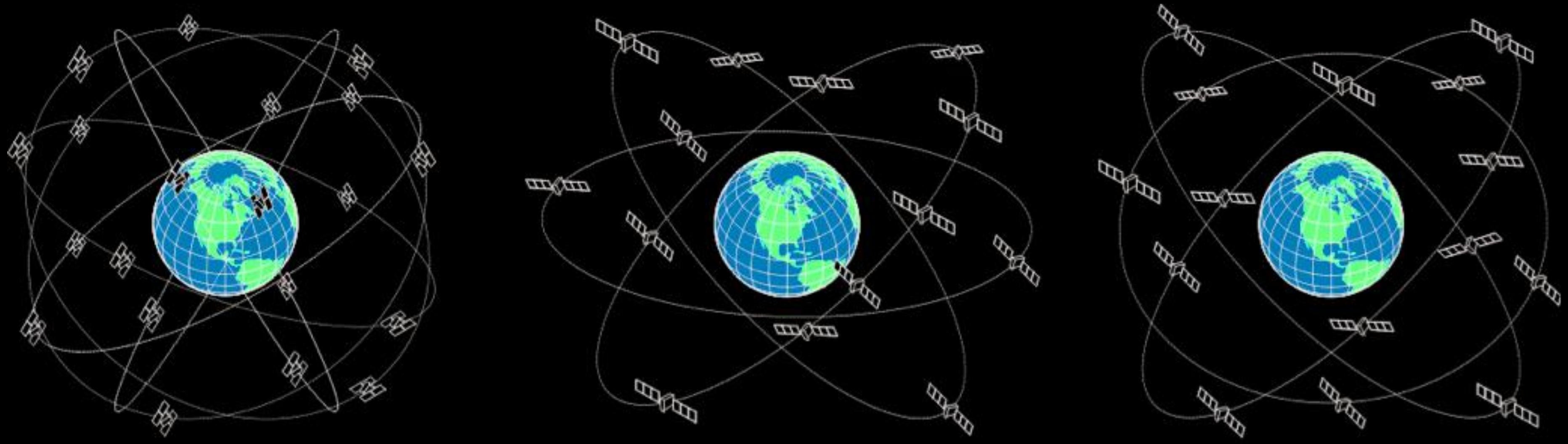



OBSERVATORIO PIERRE AUGER
AE 689 YR

III. TIME SYNCHRONIZATION METHODS

III. Time Synchronization Methods

- Wired:
  - On Wired Package-Based Networks via Precision Time Protocol (PTP) or White Rabbit PTP developed by CERN
    - for sub-NS and PicoSecond precision
- Wireless:
  - Global Navigation Satellite Systems (GNSS) e.g. GPS
    - typically: absolute accuracy of 10-100ns, relative accuracy 20 ns
  - Beacon Reference Transmitter (specific to Pierre Auger Engineering Radio Array)
    - Designed for ~1ns relative accuracy



GPS

- Altitude 20,200km
- 24 Satellites + Spare

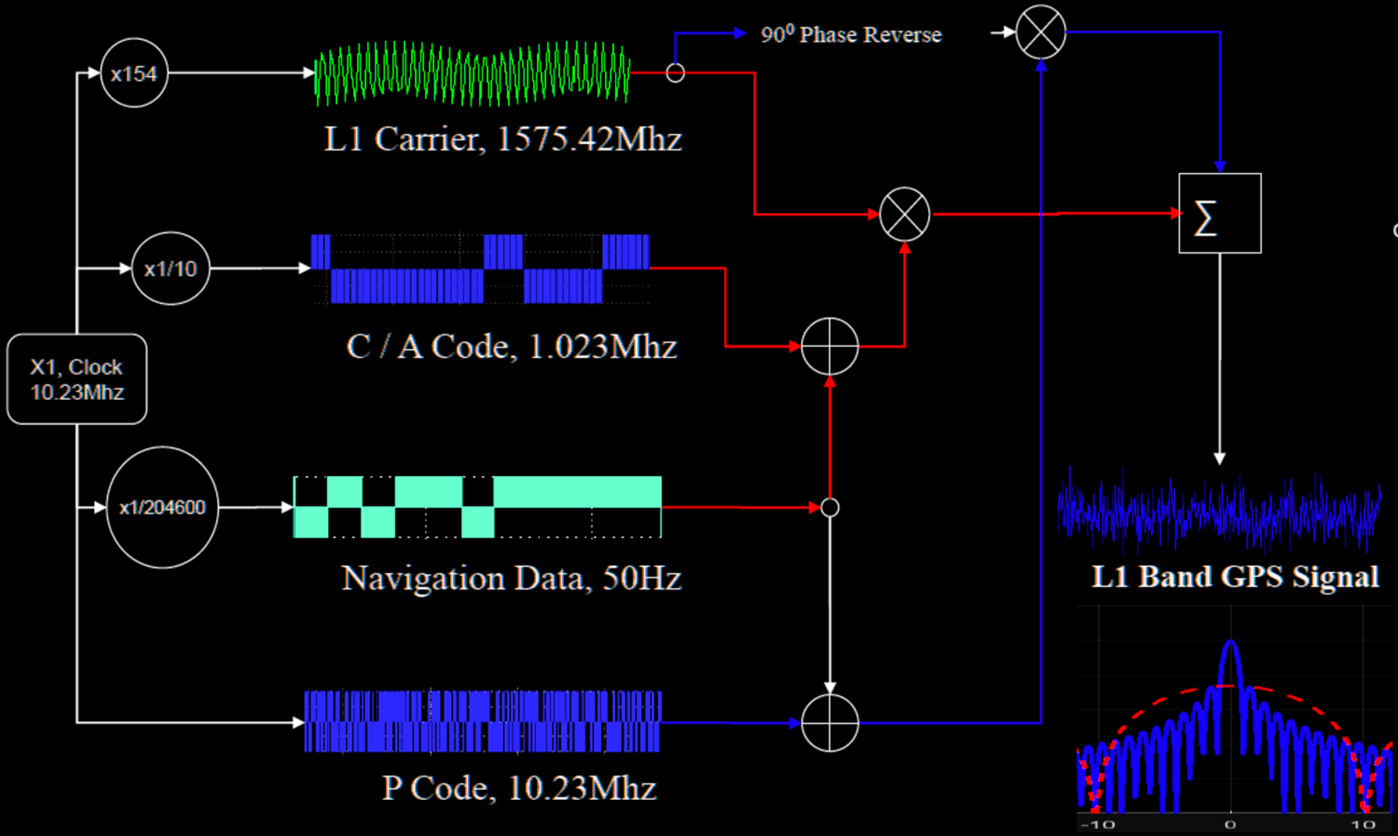
Galileo

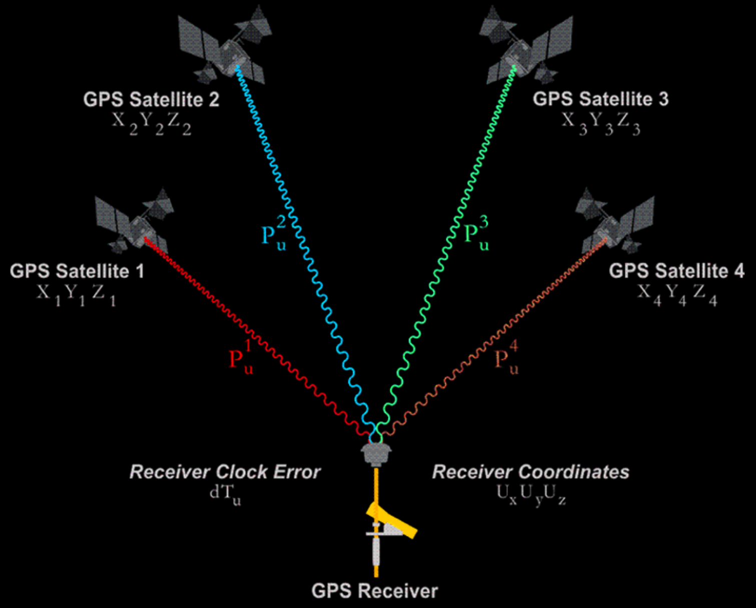
- Altitude 23,222km
- 27 Satellites + 3 Spares

GLONASS

- Altitude 19,100km
- 21 Satellites + 3 Spares

[6] J. Van Sickle. GPS Modernization and GNSS. [online]. [Last access: 09.09.2023]. url: https://janvansickle.com/gps-modernization-and-gnss/





$$p_u^1 = \sqrt{(X_1-U_x)^2+(Y_1-U_y)^2+(Z_1-U_z)^2}+c(dT_u)$$

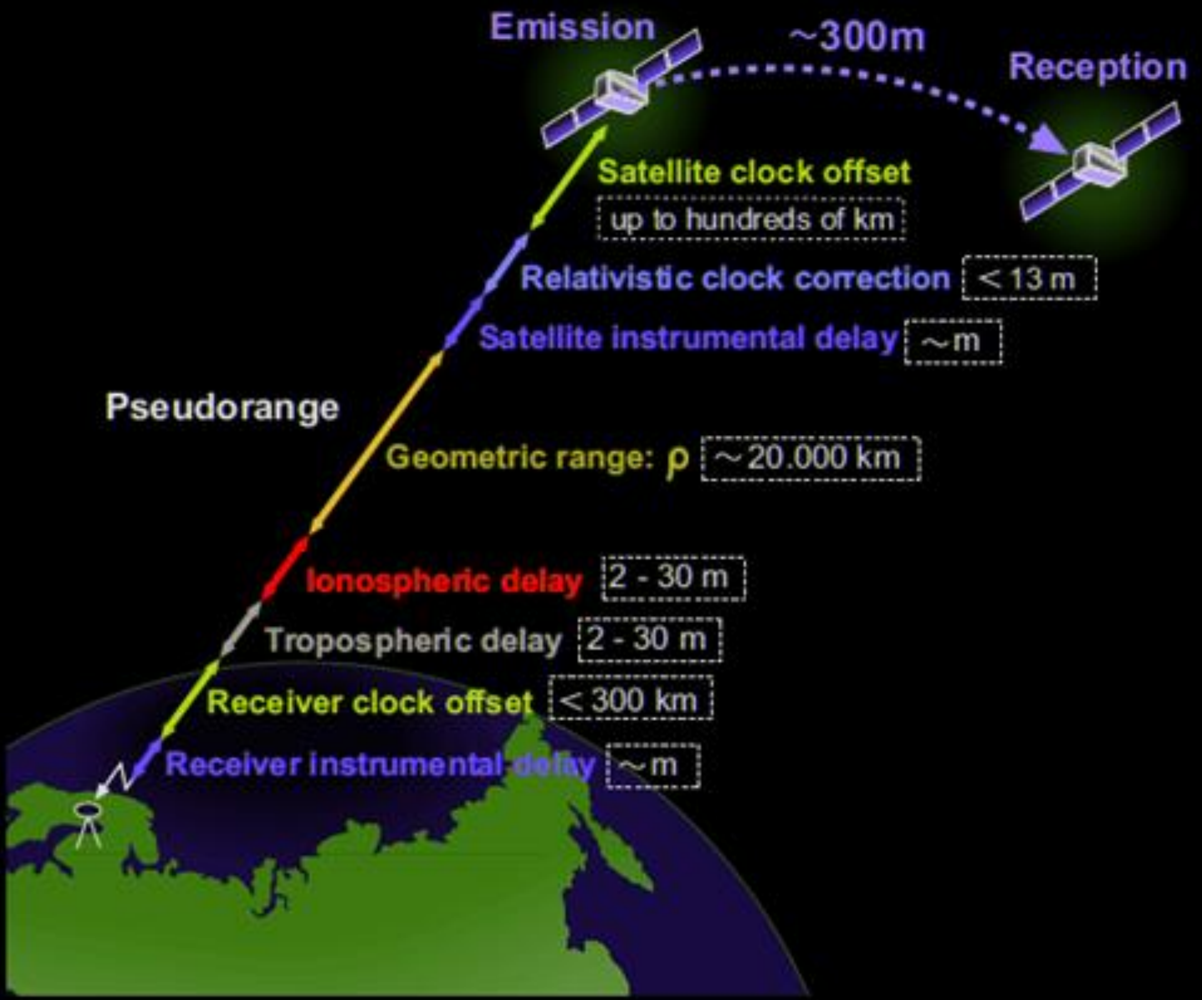
$$p_u^2 = \sqrt{(X_2-U_x)^2+(Y_2-U_y)^2+(Z_2-U_z)^2}+c(dT_u)$$

$$p_u^3 = \sqrt{(X_3-U_x)^2+(Y_3-U_y)^2+(Z_3-U_z)^2}+c(dT_u)$$

$$p_u^4 = \sqrt{(X_4-U_x)^2+(Y_4-U_y)^2+(Z_4-U_z)^2}+c(dT_u)$$

Signal and positioning principle using trilateration with at least 4 satellites

[7] from the lecture series "Global Navigation Satellite Systems" at University of Bremen, Lecturer Dennis Philip, Sommer Semester 2024



Some of the **error sources** for positioning on Earth, due to signal delay

[7] from the lecture series "Global Navigation Satellite Systems" at University of Bremen, Lecturer Dennis Philip, Sommer Semester 2024

GNSS IMPROVEMENTS WITH "RTK" RECEIVERS

- New Commercially Available **Real Time Kinematics** GPS Receivers improve Positioning to **cm-Accuracy** via Multiple Methods:
  - Differential GPS (using a close-by Refence Receiver with precisely known position)
  - Dual-Band Receivers (eliminating frequency depended Ionospheric effects)
  - Carrier Phase Measurements of Multiple Satellite Signals
- This suggests 3cm/(speed of light) = 0.1ns accuracy (since c=1ft/ns)

RADIO BEACON REFERENCE TRANSMITTER

- Signal Generator Stabilzed by a Temperature Compensated Crystal Oscillator
- Dipole Antenna emitting radio waves at 4 distinct Frequencies, such that their Superimposed Signal Repeats every 1.13 microseconds, called a Beat
- Signal is recorded in the standard CR-radio-datastream
- by analizing the phasing info of the Beacon signals in the different Detectors relative Timing Offsets of the GPS Recievers can be corrected for
- At Least 2ns accuracy already proven, but range is Limited

IV. RESULTS FROM MY THESIS

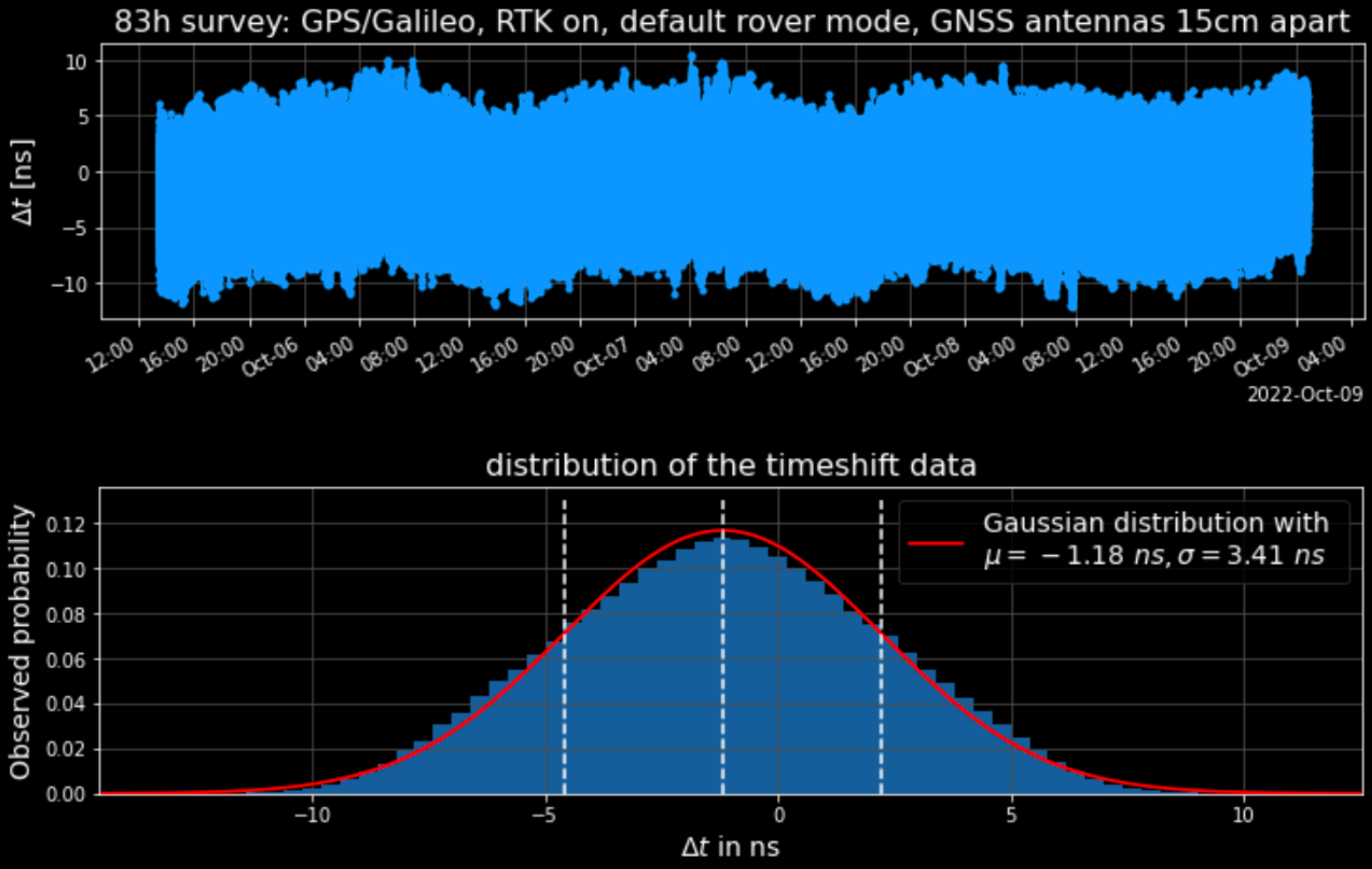
IV. Results from my thesis

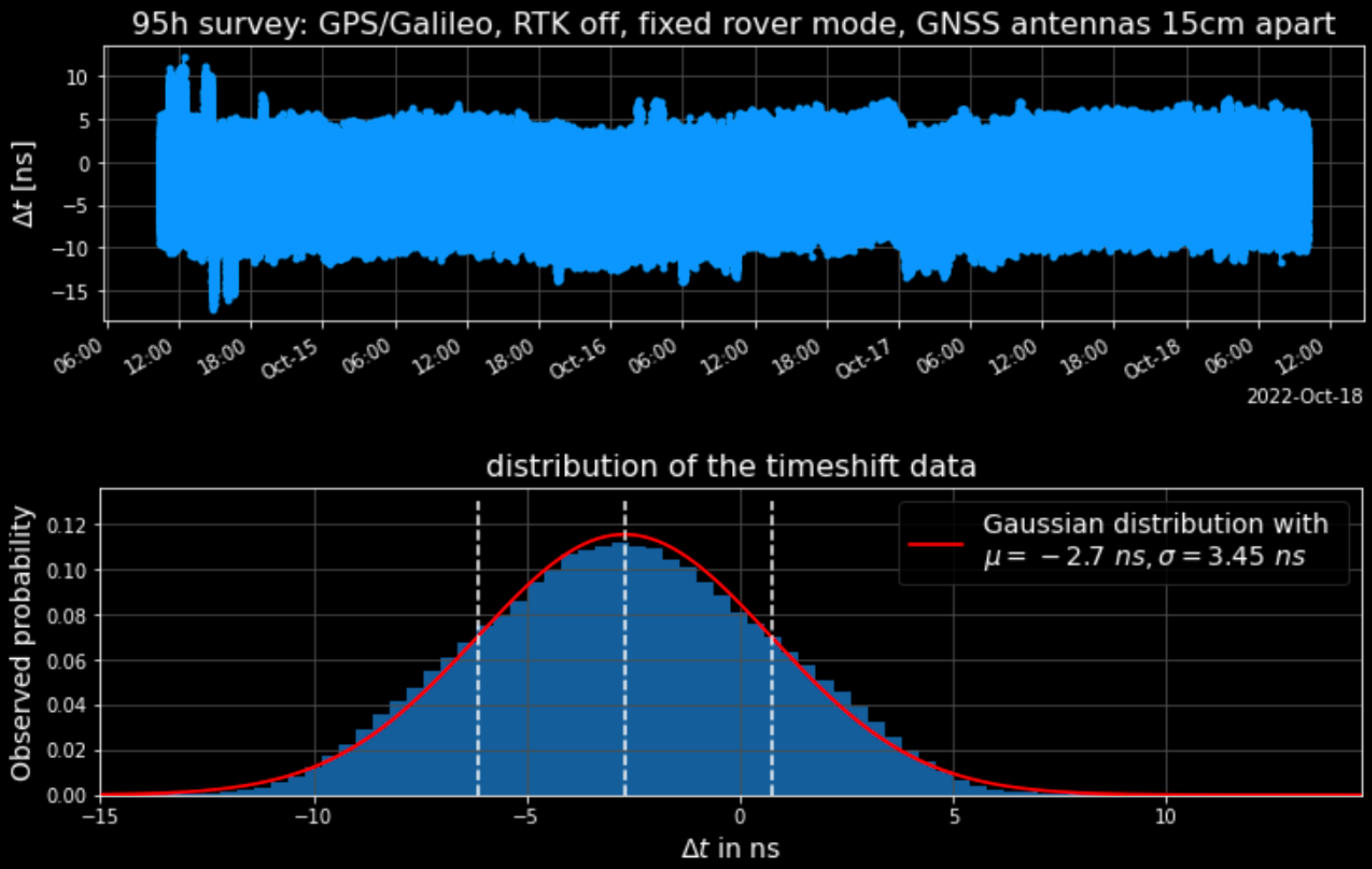
- About 1 year of procrastination
- Milkyway in Argentina (Summer and Winter) is epic
- 4 weeks high intensity writing
- Just kidding ;-)

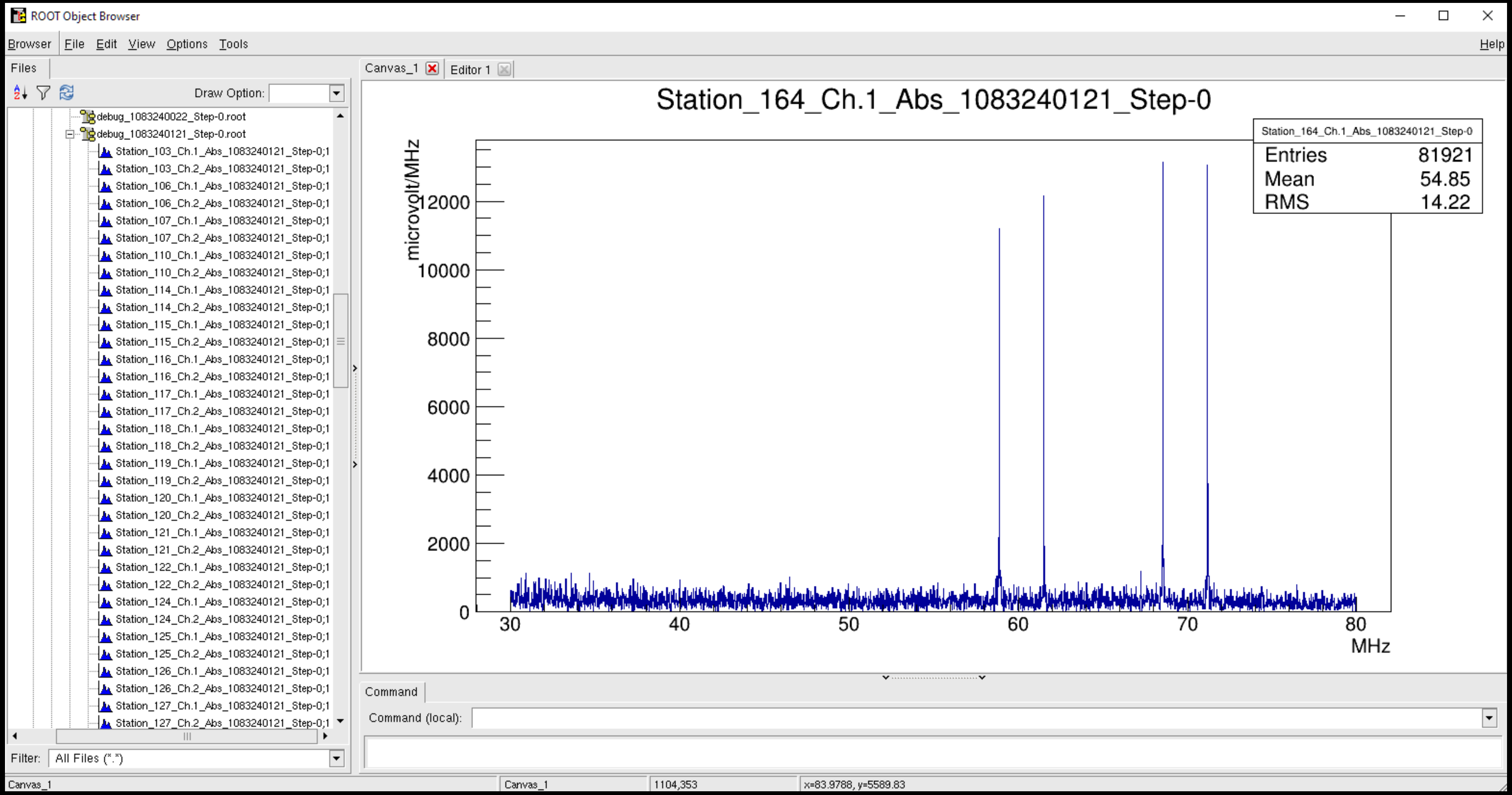
IV. RESULTS FROM MY THESIS

- Mission Statement 1)
  - Study what relative time accuracy is achieved using modern RTK GPS Receivers
  - Playing around with GPS Hardware and PC Oscilloscopes

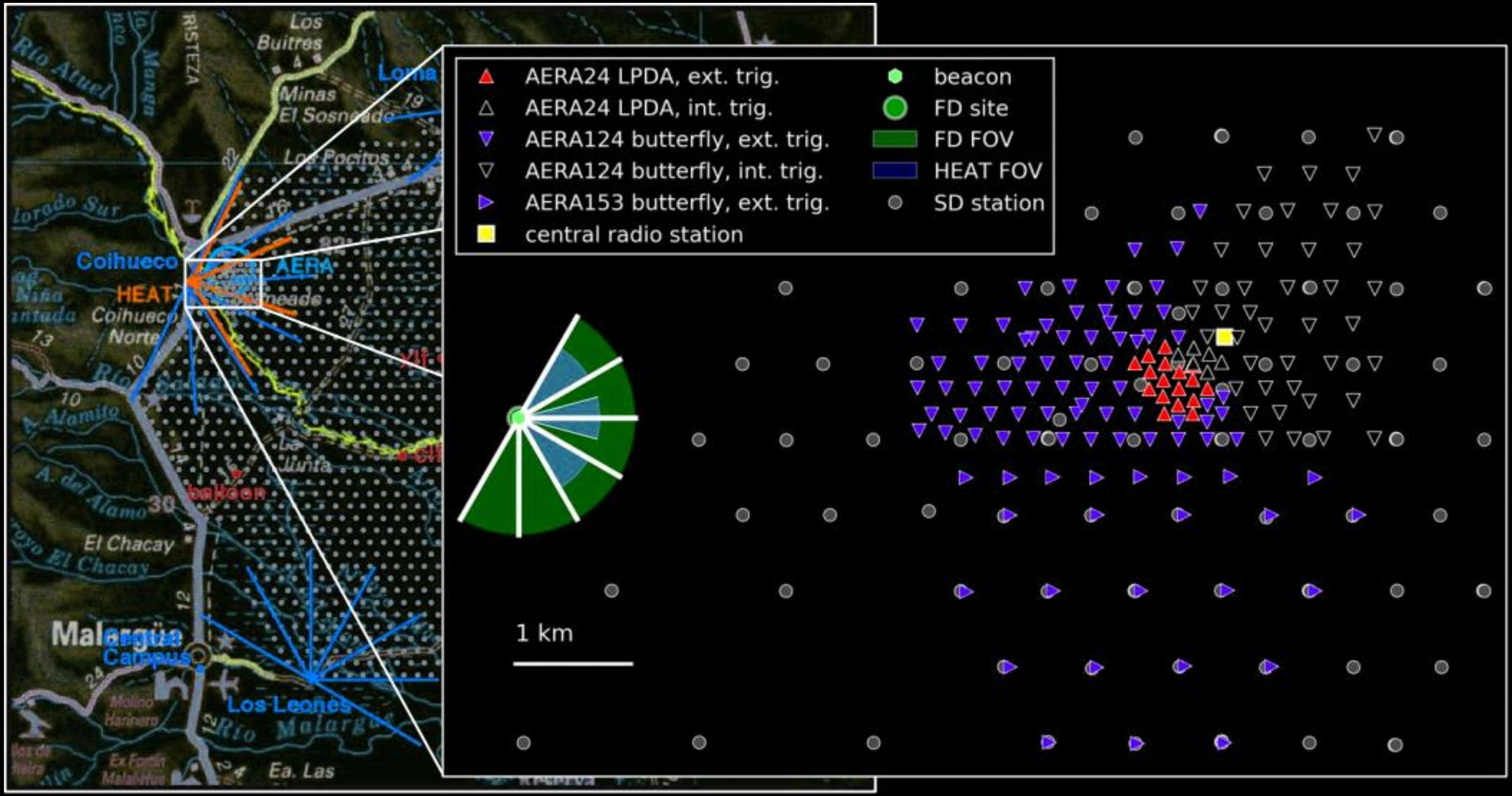
- Mission Statement 2)
  - Analyze Pierre Auger Radio Engineering Array data
    to find Beacon Signal Strength Distance Dependance
  - and thus, explore the feasibility of a potential future expansion of the beacon

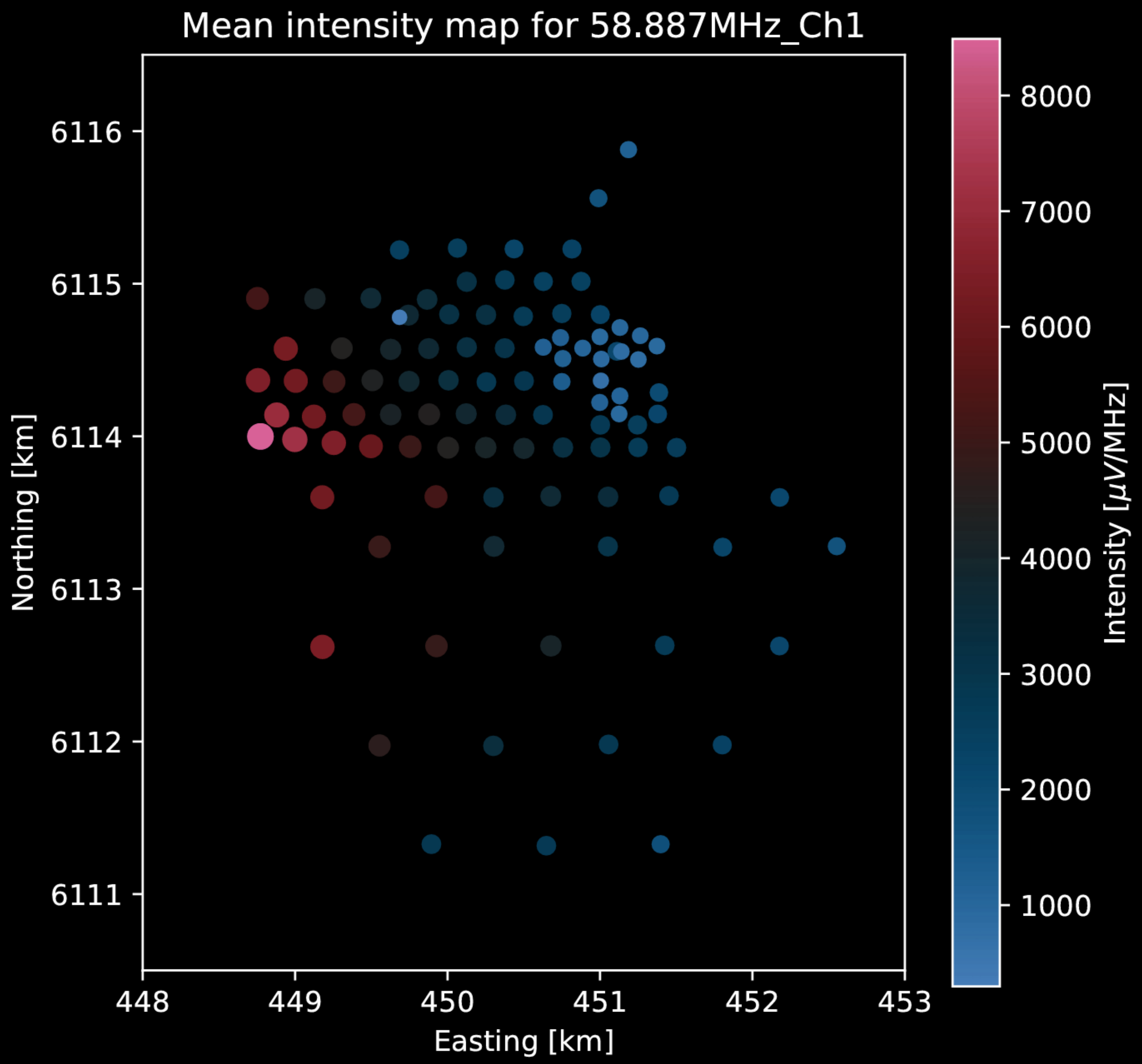

83h survey: GPS/Galileo, RTK on, default rover mode, GNSS antennas 15cm apart
Δt [ns]
10
5
0
−5
−10
12:00
16:00
20:00
Oct-06
04:00
08:00
12:00
16:00
20:00
Oct-07
04:00
08:00
12:00
16:00
20:00
Oct-08
04:00
08:00
12:00
16:00
20:00
Oct-09
04:00
2022-Oct-09
distribution of the timeshift data
Observed probability
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Gaussian distribution with
$\mu = -1.18\ ns, \sigma = 3.41\ ns$
−10
−5
0
5
10
Δt in ns


95h survey: GPS/Galileo, RTK off, fixed rover mode, GNSS antennas 15cm apart
Δt [ns]
2022-Oct-18
distribution of the timeshift data
Gaussian distribution with
μ = −2.7 ns, σ = 3.45 ns
Observed probability
Δt in ns



Raw data from the the Auger Radio Engeering Array, where the **beacon** transmitter is deployed


AERA24 LPDA, ext. trig.
AERA24 LPDA, int. trig.
AERA124 butterfly, ext. trig.
AERA124 butterfly, int. trig.
AERA153 butterfly, ext. trig.
central radio station
beacon
FD site
FD FOV
HEAT FOV
SD station
1 km
Coihueco
HEAT
AERA
Los Leones
Los Buitres
Minas El Sosneado
Los Pocitos
Río Atuel
El Chacay
La Junta
Campus


Mean intensity map for 58.887MHz_Ch1
Northing [km]
6116
6115
6114
6113
6112
6111
Easting [km]
448
449
450
451
452
453
Intensity [μV/MHz]
8000
7000
6000
5000
4000
3000
2000
1000

To find the relationship between amplitude and distance to the beacon, we assume the Power Law function $y = a \cdot x^b$

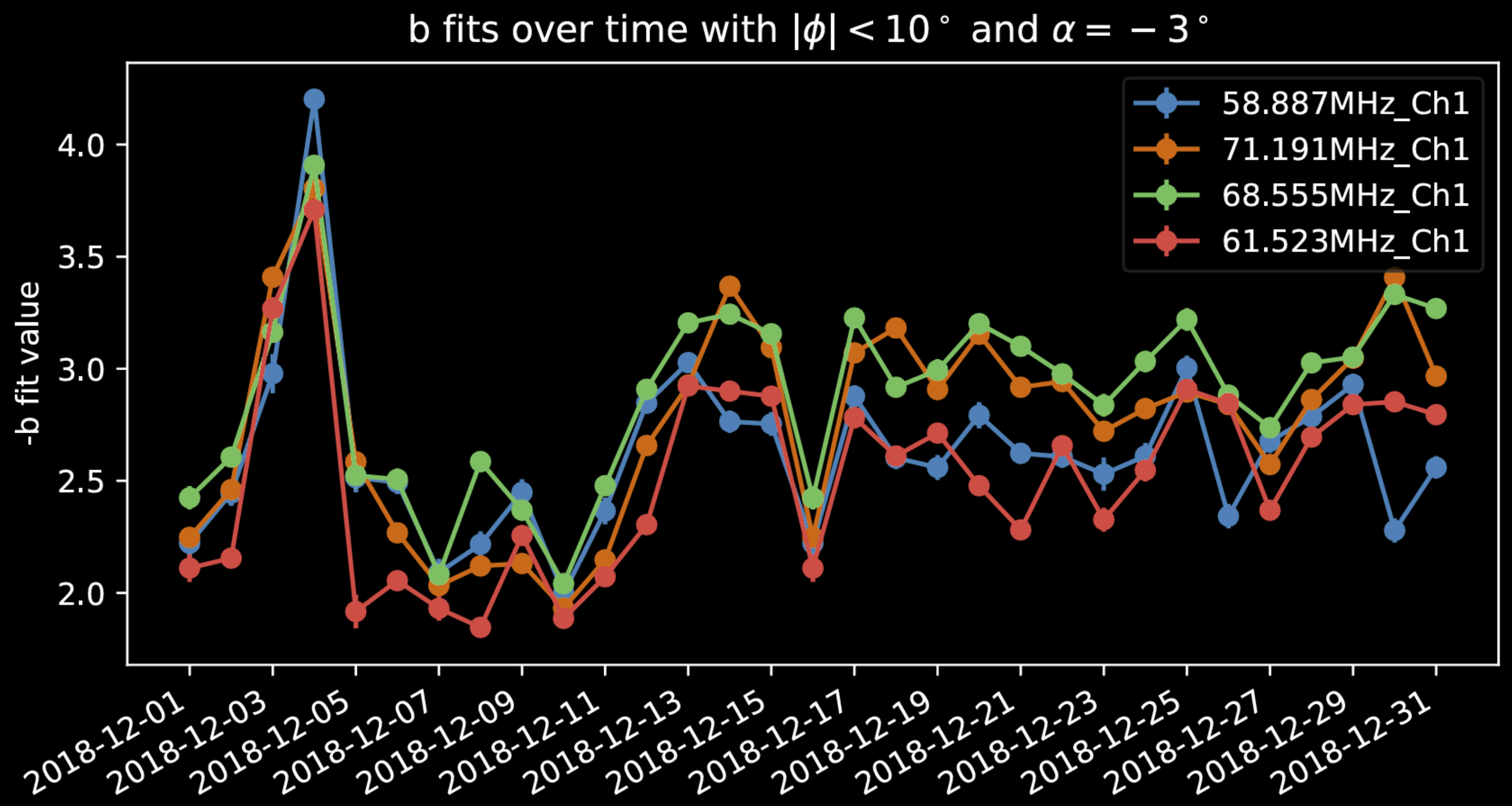


Figure 5.16: Evolution of the spectral index b over the course of December 2018.

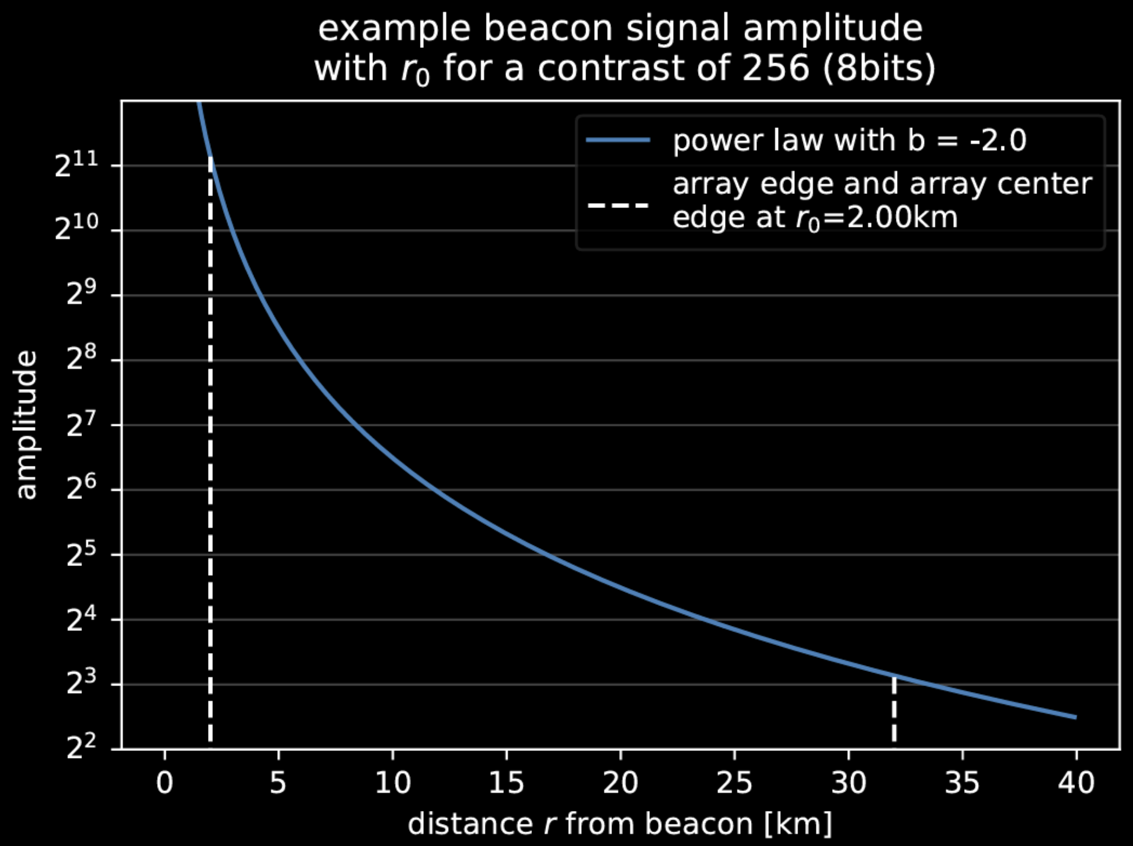
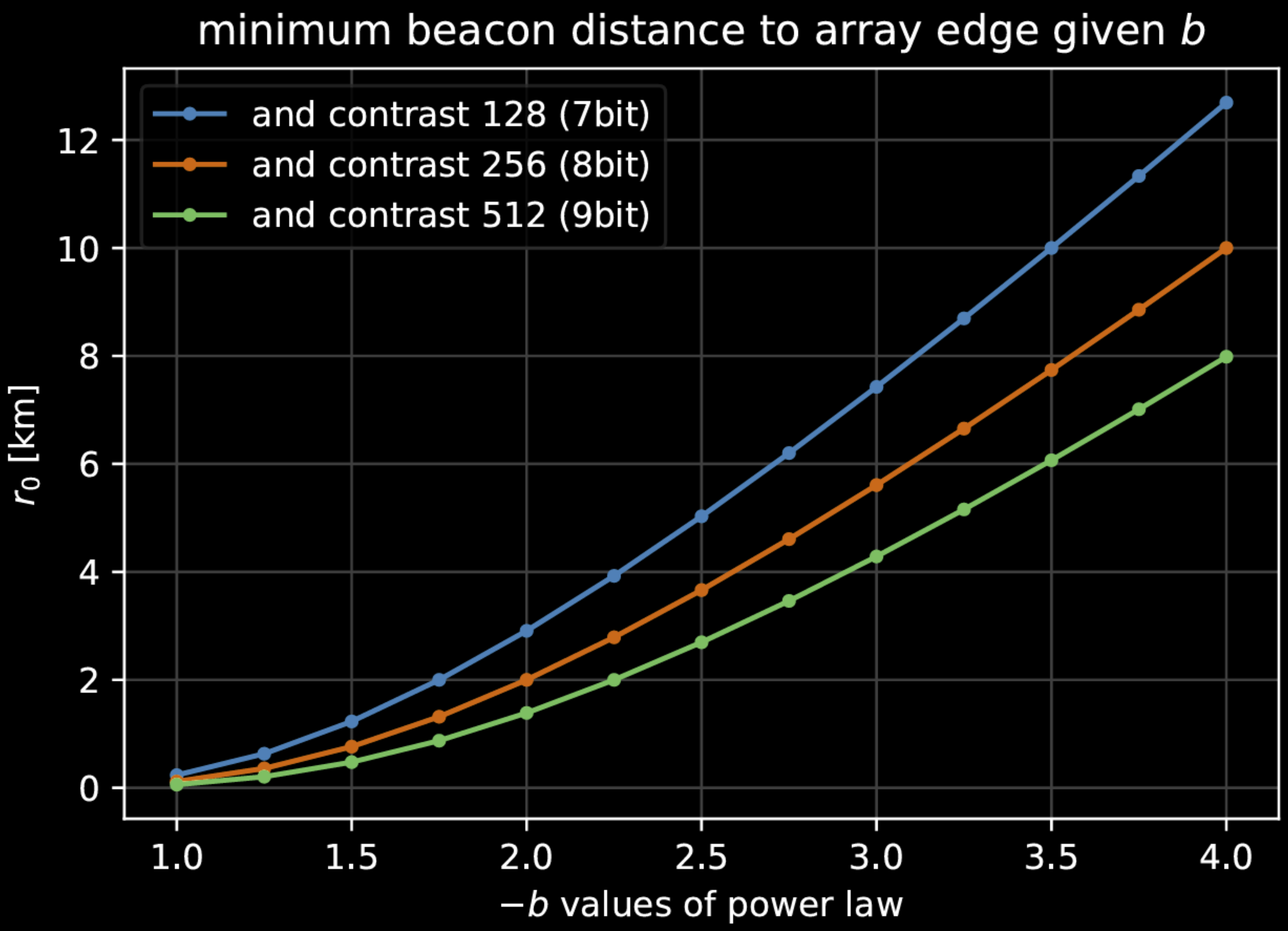


Figure 5.17: Illustration showing the locations of r_0 and r_1. Both points are marked with vertical dashed lines and represent the array edge and array center respectively. The beacon is located at $r = 0$. The amplitude profile for $b = -2.0$ is also shown on a logarithmic scale. For this example, the difference between r_1 and r_0 is assumed to be 30 km. This leads to a beacon located 2.0 km away from the array edge. A contrast of $2^8 = 256$ between edge and center is observed.

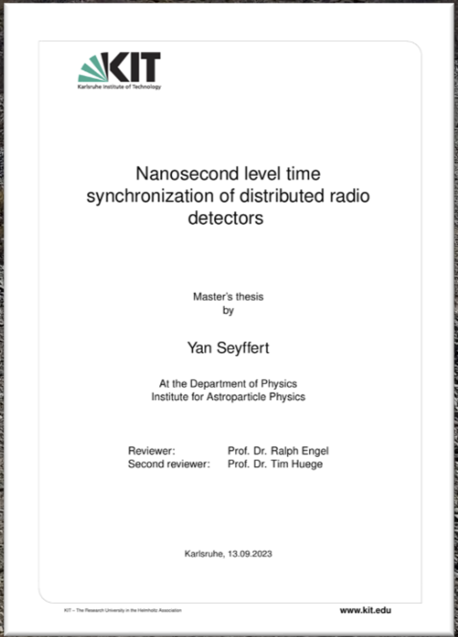


minimum beacon distance to array edge given b
and contrast 128 (7bit)
and contrast 256 (8bit)
and contrast 512 (9bit)
r0 [km]
0
2
4
6
8
10
12
1.0
1.5
2.0
2.5
3.0
3.5
4.0
−b values of power law

V. CONCLUSIONS

- THE FINDINGS REVEALED THAT EMPLOYING RTK CORRECTIONS DID NOT IMPROVE TIME SYNCHRONIZATION BEYOND 3.4NS – AT LEAST WITH THE GIVEN HARDWARE
- WE FOUND THAT THE RECEIVED POWER DROPS VERY QUICKLY, WITHIN A TYPICAL RANGE OF $P \propto 1/R^4$ AND $P \propto 1/R^6$, DEVIATING A LOT FROM THE IDEAL $P \propto 1/R^2$
- DEPLOYING A SIMILAR SYSTEM FOR THE WHOLE ARRAY WOULD NECESSITATE BEACONS BE LOCATED AT AROUND 2 TO 8KM DISTANCE TO THE ARRAYS PERIMETER. ALTHOUGH THIS APPEARS NOT EASILY REALIZABLE (DUE TO TOPOGRAPHY), IT COULD BE WITHIN THE REALM OF POSSIBILITY
- **RADIO INTERFEROMETRY WHICH NEEDS ≤1NS SYNCHRONIZATION, STILL MUST WAIT FOR MORE TECHNOLOGICAL ADVANCEMENT**

THANK YOU FOR YOUR ATTENTION!



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