Time & position Calibration with known sources
Dec 05th 2024 (Xidian， Pengfei Zhang)

- Xidian
- International Scientific Event “GRAND” Collaboration Meeting, 2025, Warsaw Poland

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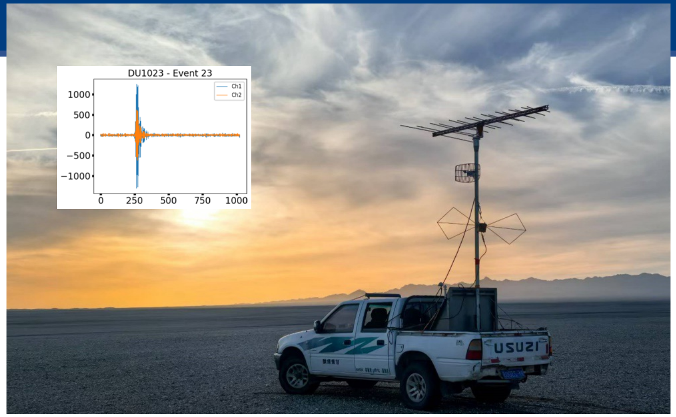
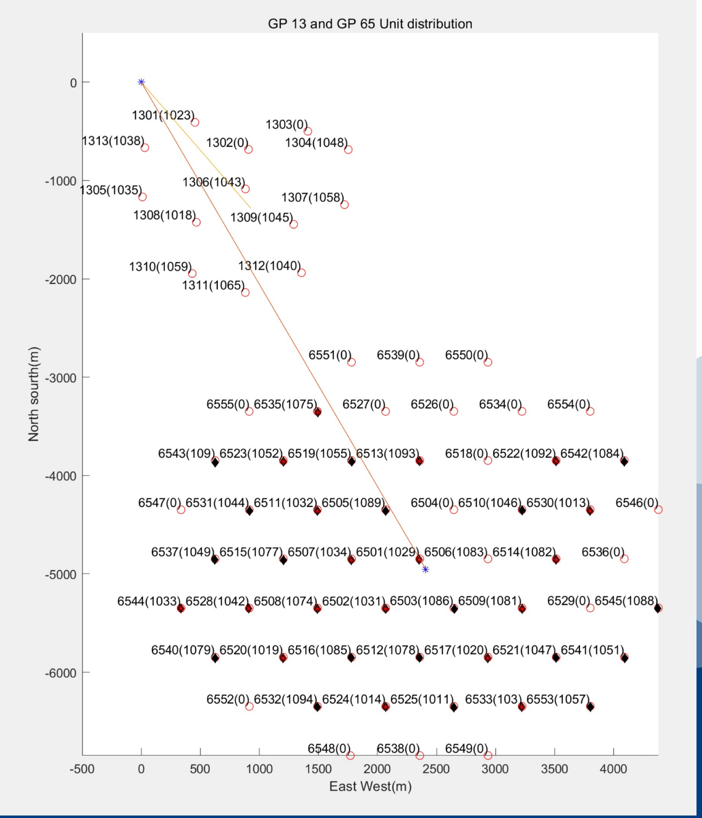




Time Calibration Background

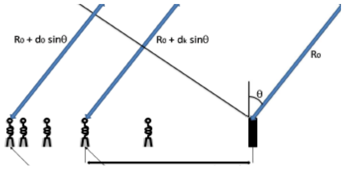
(1) For Incident direction reconstruction

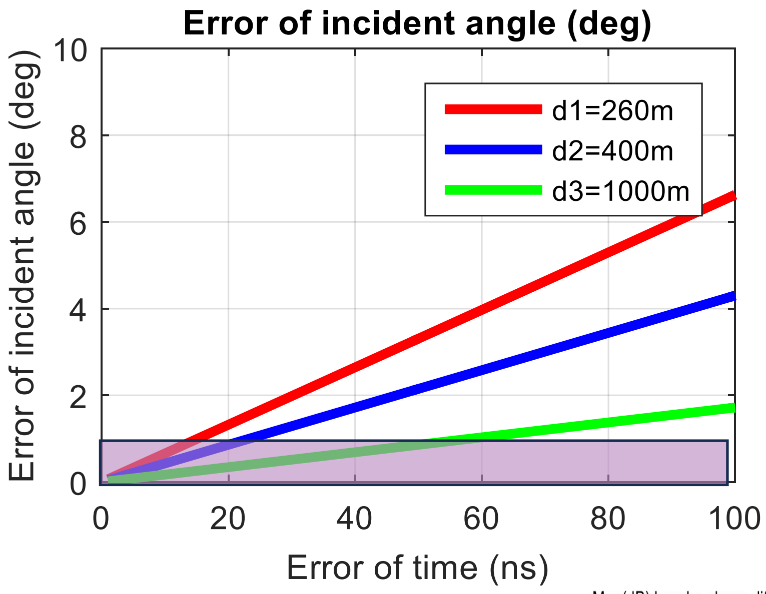
$$\begin{cases} S_1(t) = A_1 \cos(\omega t_1) \\ S_2(t) = A_2 \cos(\omega(t_1 + \Delta t)) \end{cases}$$

$$\Delta t = d \sin \theta_i / c$$

$$\theta_i = \arcsin(\Delta t c / d)$$

$$\left|\frac{d\theta_i}{d\Delta t}\right| = \left|\frac{1}{\sqrt{1-\sin(\theta_i)^2}}\frac{c}{d}\right| = \left|c / d \cos(\theta_i)\right|$$

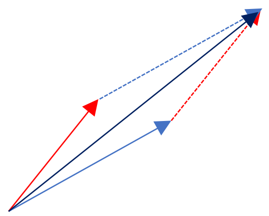


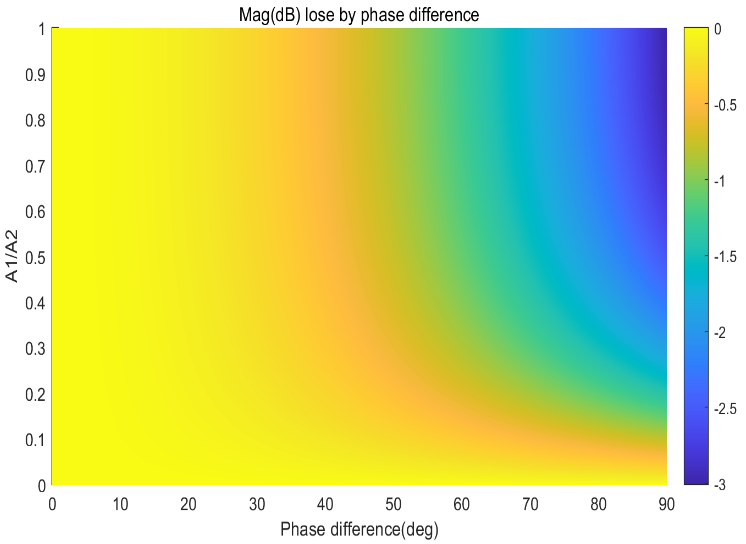


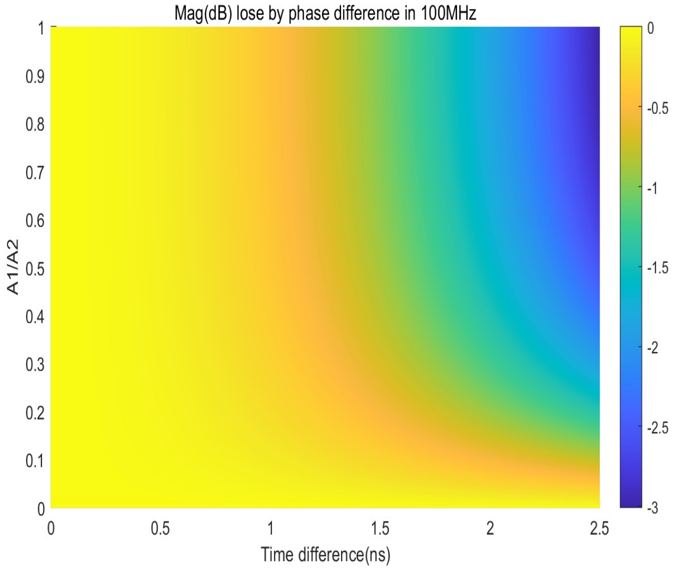
(2) For interferometric observation

$$\begin{cases} S_1(t) = A_1 \cos(\omega t + \varphi_1 + \sigma_{12}(t)) \\ S_2(t) = A_2 \cos(\omega t + \varphi_2) \end{cases}$$

$$|S_1(t) + S_2(t)| / |A_1 + A_2| = \left(A_1^2 + A_2^2 + 2A_1A_2\cos(\sigma_{12}(t))\right)^{1/2} / |A_1 + A_2|$$







Time Precision requirement

- **Ref:Nanosecond-level time synchronization of autonomous radio detector stations for extensive air showers:**

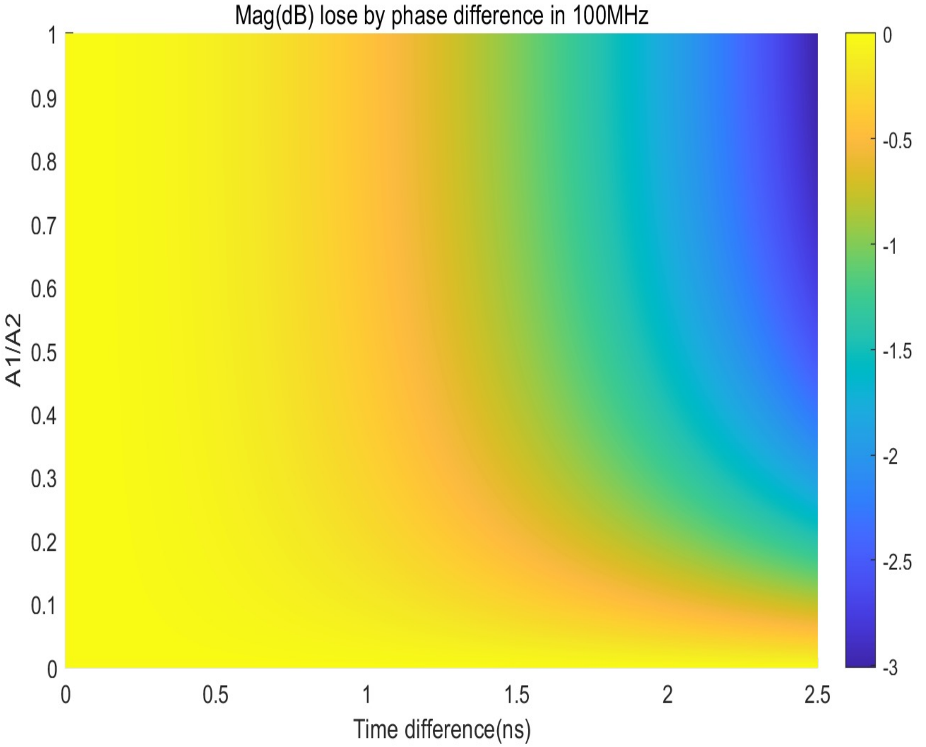
"For ns-timing precision, a maximum phase error of 20º can be tolerated. **The 20º correspond to a shift of slightly less than 1ns**, since a full period (b= 360º) is about 17ns for the lowest beacon frequency."

- **Antenna hand book**

The maximum phase error within the aperture should less than 22.5º which means that the time precision should less than 1/16 of the full period . For 200MHz and 5ns period, this lead to a very challenge time precision of **0.3125ns.**

Hence a rough requirement is 2ns

restrict requirement is 0.2~0.5ns



It should be noted that in some cased the time precision requirement can be relaxed while pay the cost of long **Coherent integration observation time.**

How to describe the error in GPS based Time synchronization system

A : The GPS time system it self have three kinds of error which have been verifier by the related work done in AERA.

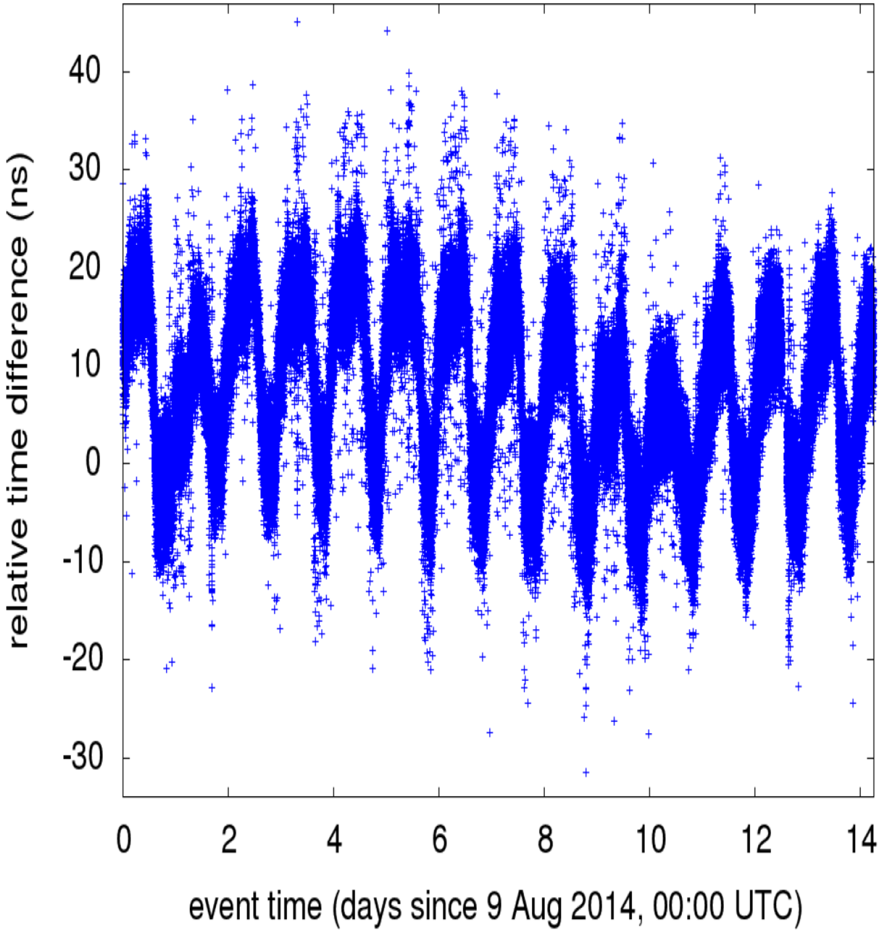
- It include the following parts:

$$\sigma_{GPS} = \sigma_{GPS\_SR}(t) + \sigma_{GPS\_LF}(t) + \sigma_{GPS\_Feb}(n)$$

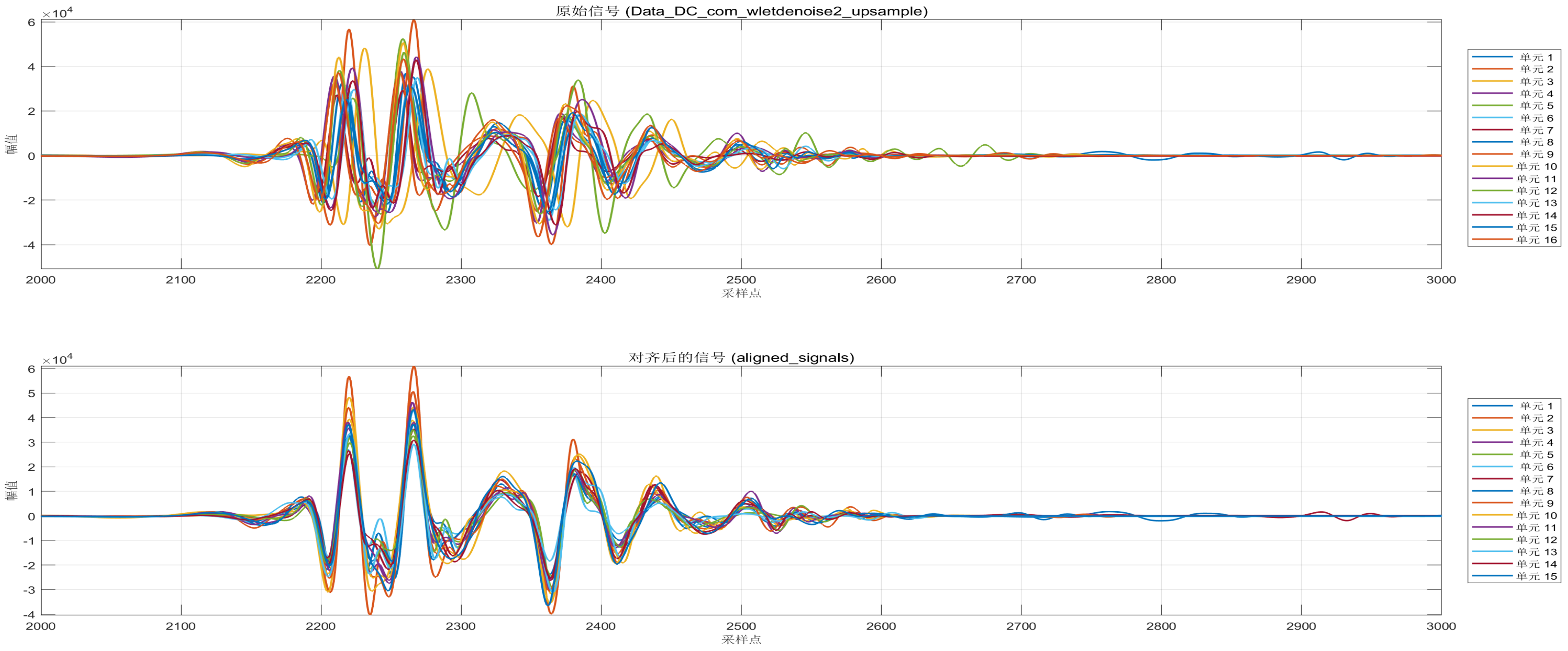
- $\sigma_{GPS\_SR}(t)$ present for short-term, rapid random error on the nanosecond scale, with a maximum variation of approximately 10 ns and a standard deviation (STD) of 5 ns.

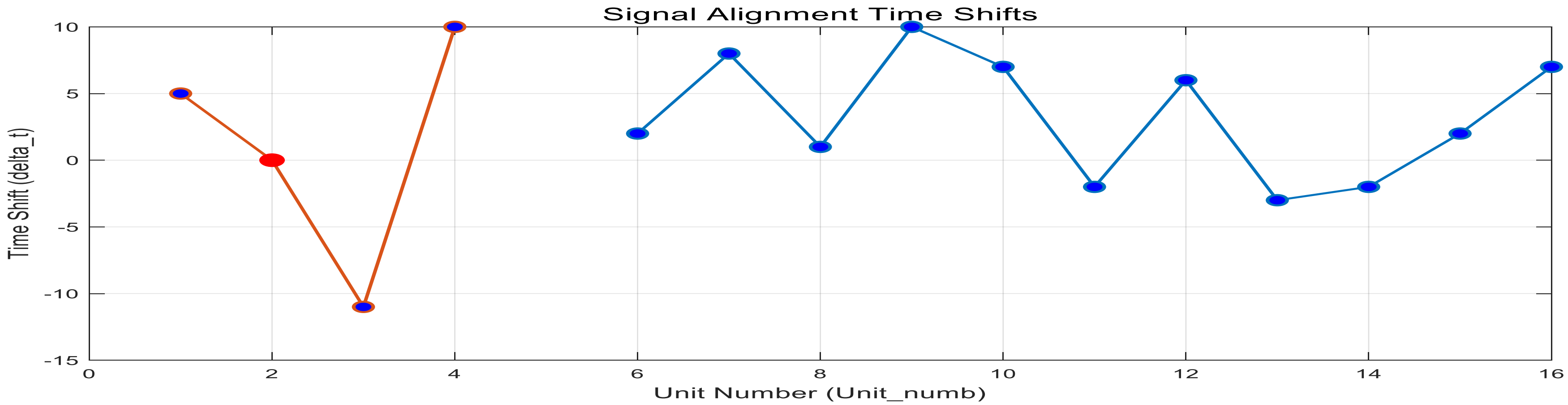
- $\sigma_{GPS\_LF}(t)$ present for the long-term fluctuation spanning several hours or even a day, with fluctuation amplitudes reaching 30-50 ns.

- The first one is acceptable for direction reconstruction for sparse array and large incident angle with 0.2^{o} precision. While both of them should be compensated by calibration for interferometric observation



Trigger algorithm based time shift will not take into consideration any more （as mentioned yesterday it can be solved based on wavelet and correlation ship ）



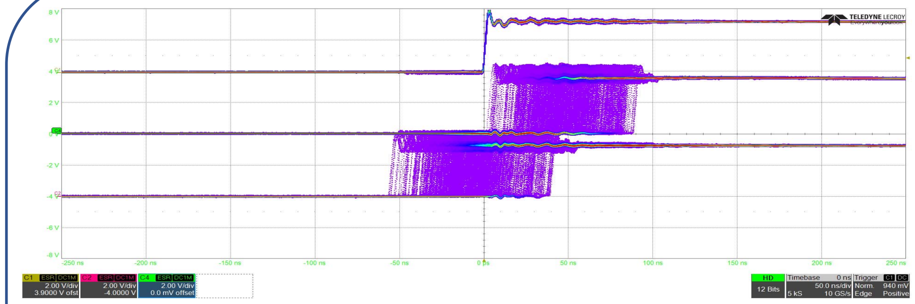


How to describe the Time error in GPS based system

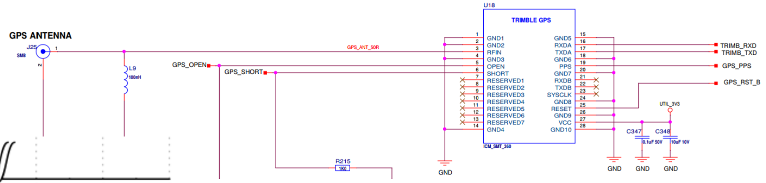
The Feb hardware system cause shift of Units time.

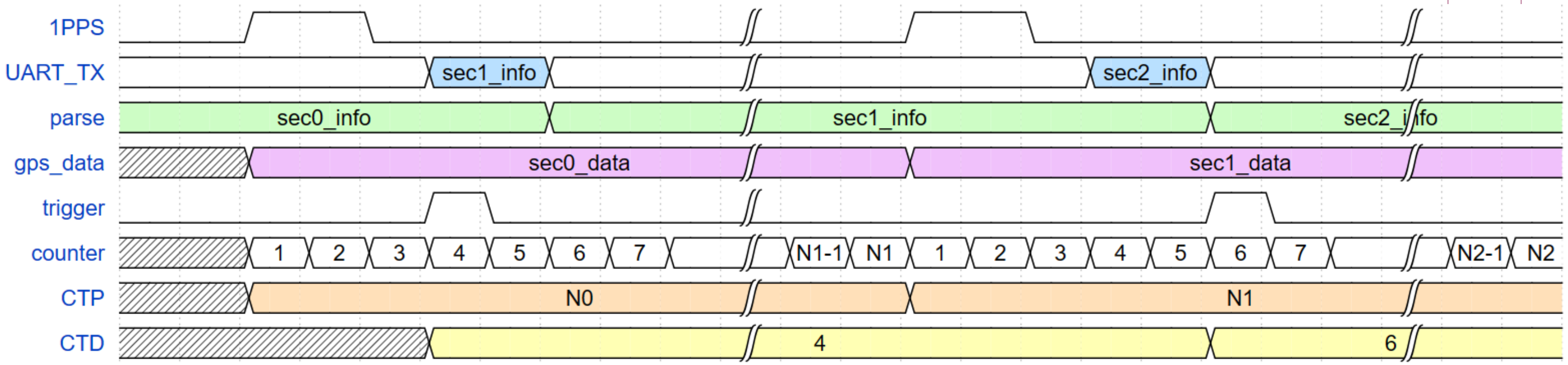
$$\sigma_{GPS\_Feb}(n)$$

- $\sigma_{Feb}(n)$ present for the stable system shift of GPS time system (which have not be reported in AERA) and for GRAND. It is firstly be observed by Xing xu within laboratory test.



Xing Xu2024.04.01 HW report

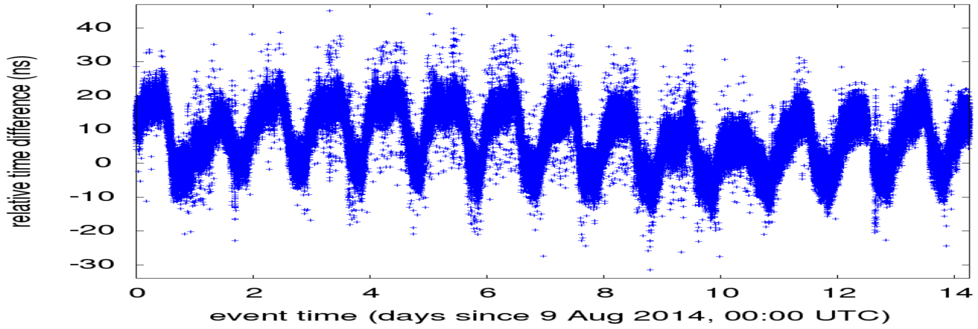


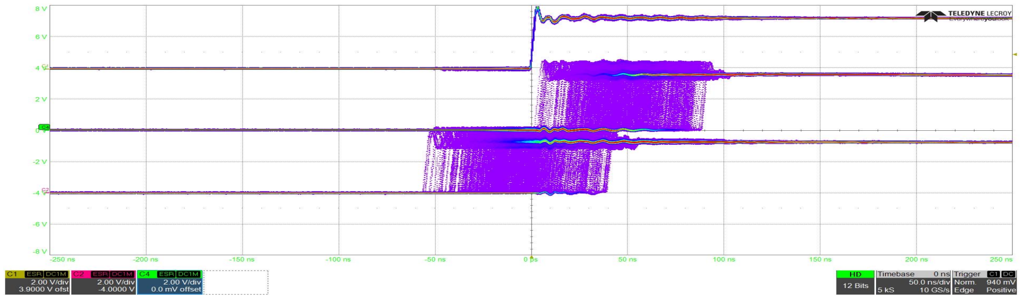


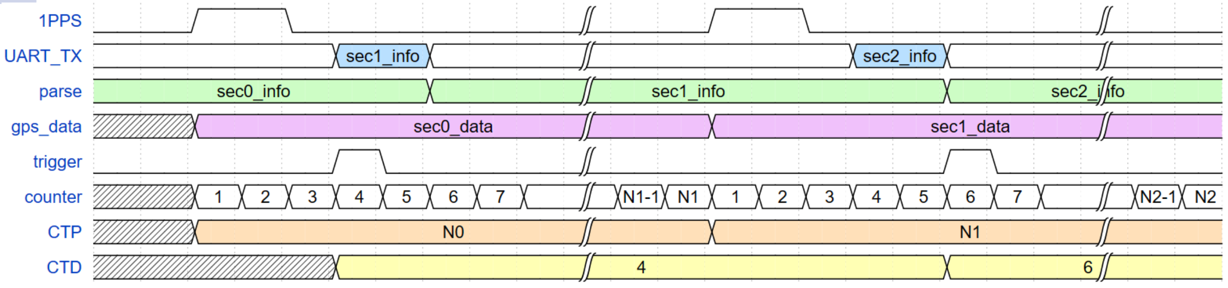
Time error in GPS based system

$$\sigma_{GPS} = \sigma_{GPS\_SR}(t) + \sigma_{GPS\_LF}(t) + \sigma_{GPS\_Feb}(n)$$

	Typical value(ns)	time-dependent features	Incident angle-dependent
σ_{GPS_SR}	5~10	Short time random	No
σ_{GPS_LS}	0~50	Long time Fluctuation	No
σ_{GPS_Feb}	0~50	Stable	No







Beacon based calibration and it’s limitation

Hardware (Ref AERA) :

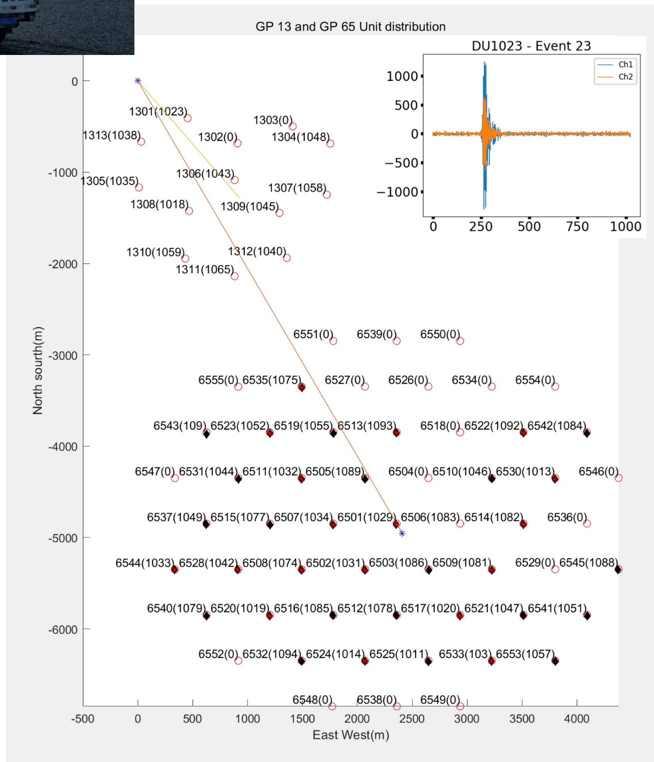
- Signal generator
- Attenuators, filters and amplifiers
- Transmitter antenna

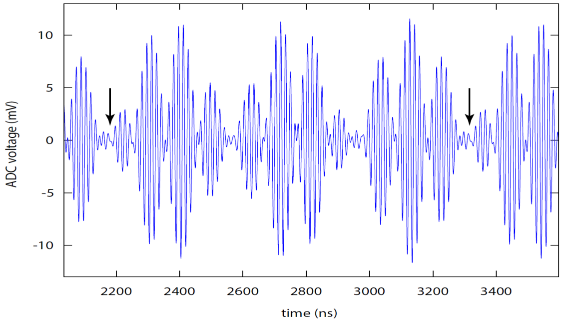
Frequency choice:

- Time calibration precision/sample rate/Antenna beam pattern;
- High order suppress/Environment interfere

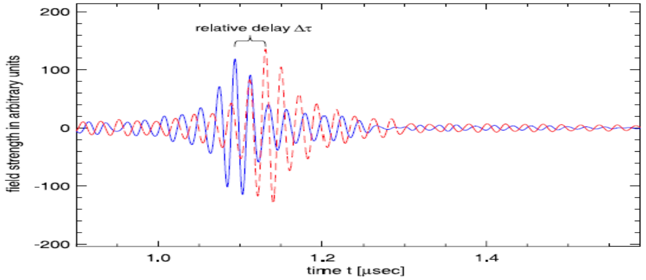
Note:

- Sample frequency;(500MHz)
- Record length; (8192)
- Port choice ; （Y/Z）
- Mixing and high order suppress （-40dB）
- Arriving time define and acquisition algorithm





Nanosecond-level time synchronization of autonomous radio detector stations for extensive air showers

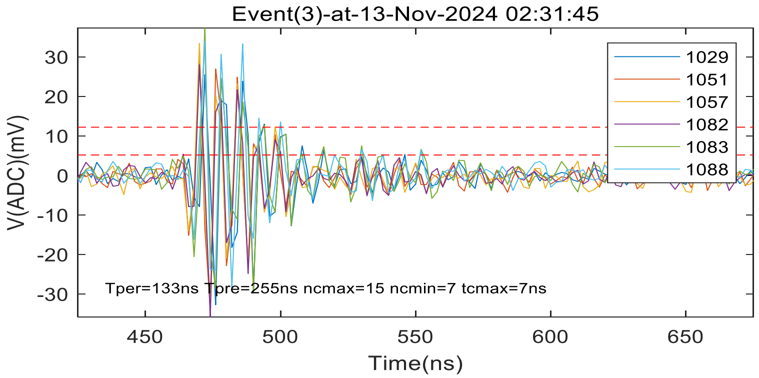


New method for the time calibration of an interferometric radio antenna array

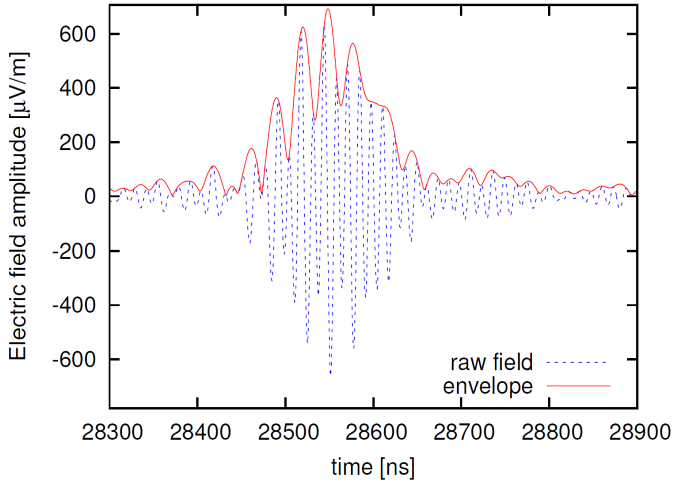
Beacon based TR process-- relative time delay

A： The time delay include:

$$T_{TR\_beacon} = T_{T\_transmiter} + T_{P\_process} + T_{R\_antenna} + T_{R\_RF\_Chain} + T_{Feb\_sample}$$



- $T_{T\_transmiter}$ present for the transmitter process, what we should pay attention is the distortion caused by dispersion, which may lead error in arriving time determine.
- $T_{P\_process} = l_n / (c / n_{air})$ present for the Radio wave travel time, The problem is that we should confirm that the whether radio waves travel as free space plan wave at the speed of light in the atmosphere or possibly as surface of ground as crawl waves. There is a big difference between the time delay between them. The test results now available show that the former one is correct, but if we using the Z channel , we should check it again. Another problem is the precision of n_air will lead problem in long distance test such as 10km.



Beacon based TR relative time delay

- $T_{R\_antenna}$ present for the Respond time of antenna, the problem is that if pulse is used, for the **grazing** incident case , the disperse of antenna in different frequency together with the reflection of ground will leads to the aliasing of the pulse and the arriving time based on peak value detection. while this is always the cased for beacon based calibration

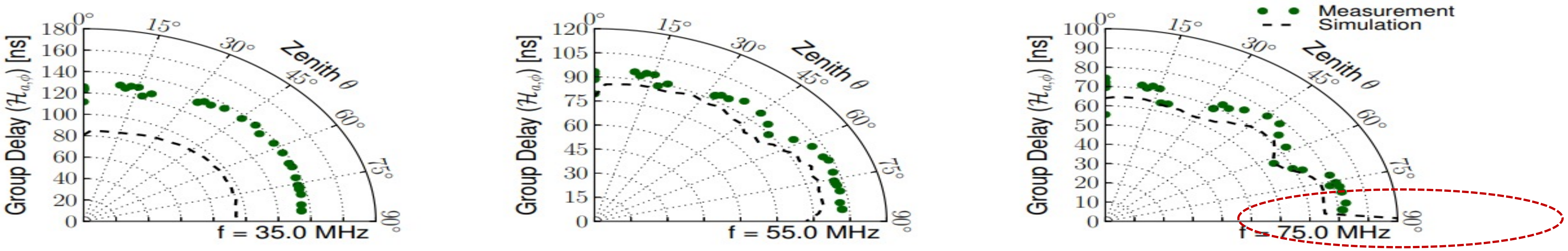


Figure 12: The group delay of the Small Black Spider LPDA as a function of zenith angle for three different frequencies in the measurements and the simulations.

See in : Antennas for the Detection of Radio Emission Pulses from Cosmic-Ray induced Air Showers at the Pierre Auger Observatory

- $T_{R\_RF\_Chain} + T_{Feb\_sample}$ present for the remain RF respond time and the Feb sample time , which always uniform and stable.

The time delay data during test include the GPS _Time as recording reference:

$$T_{TR\_beacon}^{Test}(n) = T_{T\_transmiter} + T_{P\_process}(n) + T_{R\_antenna}(n,\theta,\varphi) + T_{R\_RF\_Chain} + T_{Feb\_sample} + \sigma_{GPS\_SR}(n) + \sigma_{GPS\_LF}(n) + \sigma_{GPS\_Feb}(n)$$

The relative time delay difference:

$$T_{TR\_beacon}^{Test}(n) - T_{TR\_beacon}^{Test}(n_{ref}) = T_{P\_process}(n) + T_{R\_antenna}(n,\theta,\varphi) + \sigma_{GPS\_SR}(n,t) + \sigma_{GPS\_LF}(n,t) + \sigma_{GPS\_Feb}(n)$$

The calibrated parts:

$$\Delta T_n^{ref} = T_{TR\_beacon}^{Test}(n) - T_{TR\_beacon}^{Test}(n_{ref}) = \Delta l(n)/(c/n_{air}) + T_{R\_antenna}(n,\theta,\varphi) + \sigma_{GPS\_SR}(n,t) + \sigma_{GPS\_LF}(n,t) + \sigma_{GPS\_Feb}(n)$$

Based on a RTK test of the location of all units , this can be obtained with a 1cm error, and results in 0.03ns

This is a challenge parts, while we can using a repeat test of data as AERA done or a test based on cable cross check to obtain it at 0.5ns precision

This is the part that should be obtain during calibration

Discuss

$$\Delta T_n^{ref} = T_{TR\_beacon}^{Test}(n) - T_{TR\_beacon}^{Test}(n_{ref}) = \Delta l(n)/(c/n_{air}) + T_{R\_antenna}(n,\theta,\varphi) + \sigma_{GPS\_SR}(n,t) + \sigma_{GPS\_LF}(n,t) + \sigma_{GPS\_Feb}(n)$$

Based on a RTK test of the location of all units , this can be obtained with a 1cm error, and results in 0.03ns

This is a challenge parts, while we can using a repeat test of data as AERA done or a test based on cable cross check to obtain it at 0.5ns precision

This is the part that should be obtain during calibration

- $\sigma_{GPS\_SR}(n, t) + \sigma_{GPS\_LF}(n, t)$ ask for a real time calibration, which mean that the beacon signal will always in the spectrur data(As AERA), which lead limited influence to the event detection;
- $l(n) - l(ref)$)should be tested in the precision of 0.03m, if we hope to obtain 0.2ns precision in time domain;
- The remain question is how to obtain the $T_{TR\_beacon}(n) - T_{TR\_beacon}(n_{ref})$
- This will based on the strategy of the choice of wave shape and the related trigger algorithm.

AERA using 4 sin wave and the related FFT phase information of $\Delta\phi_j$ to obtain the Best time delay τ :

$$C(\Delta\tau) = \sum_j \int A_{1,j} A_{2,j} \sin(\omega_j t)\sin(\omega_j (t-\Delta\tau) + \Delta\phi_j)dt$$
$$\propto \sum_j A_{1,j} A_{2,j} \cos(\Delta\phi_j - \omega_j \Delta\tau)$$

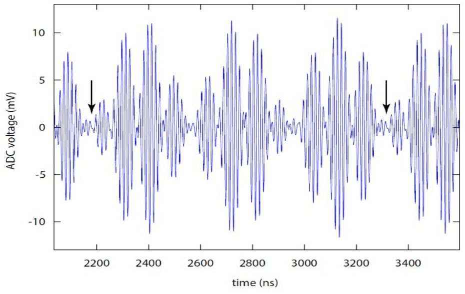
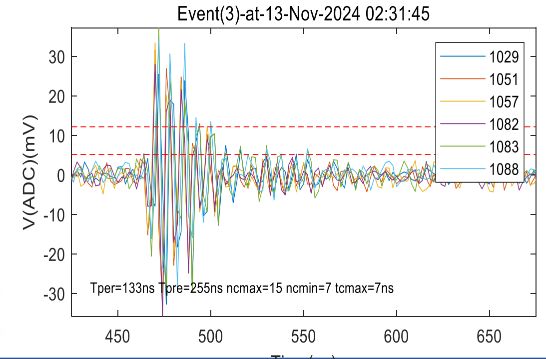


Figure 2. Beacon beat: a voltage-time trace recorded with the analog-to-digital converters (ADCs) of the north-south channel of an AERA station is digitally filtered such that it contains only the four beacon frequencies. The signal shape of the beacon beat has a periodicity of approximately 1100ns, as indicated by

GP13 using pulse



Calibration source and what we can do based on them?

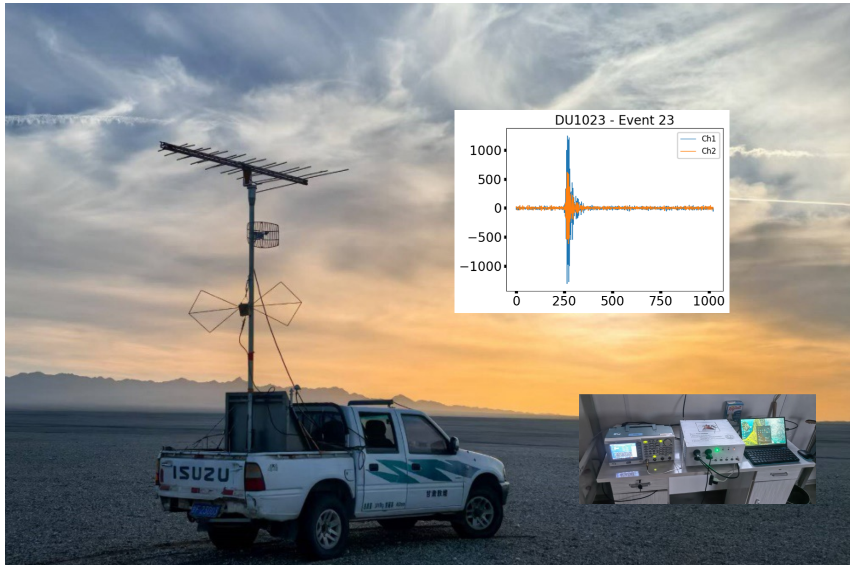
(1) Fixed Beacon (long running)

Time calibration: (How to separate the contribution:)

GPS +group-delay + firmware record

- (weather +cloudy + GPSantenna + GPS chain+GPS _Chip)
- Antenna+RF Chain +AD;
- Firmware confirm within laboratory

Those part will be done in laboratory



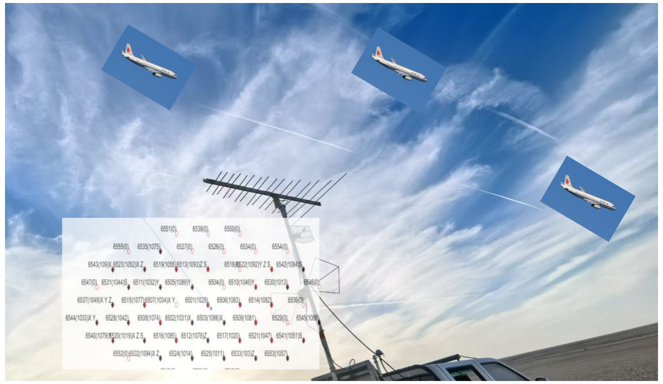
(2) Moving beacon on truck (Co-plan calibration)

Time calibration; (2000second fix time?)

Location calibration;

(3)Moving beacon in UAV(drone)

Pattern; Polarization(limitation)



(4)Airplane

Pattern; Polarization?

The first site test：Preparation for beacon test

Many thanks to： Yanhuang， Wang， xiao，   Yizhang，
Oliver， Palbolo， Fred， Bohao， Pengxiong

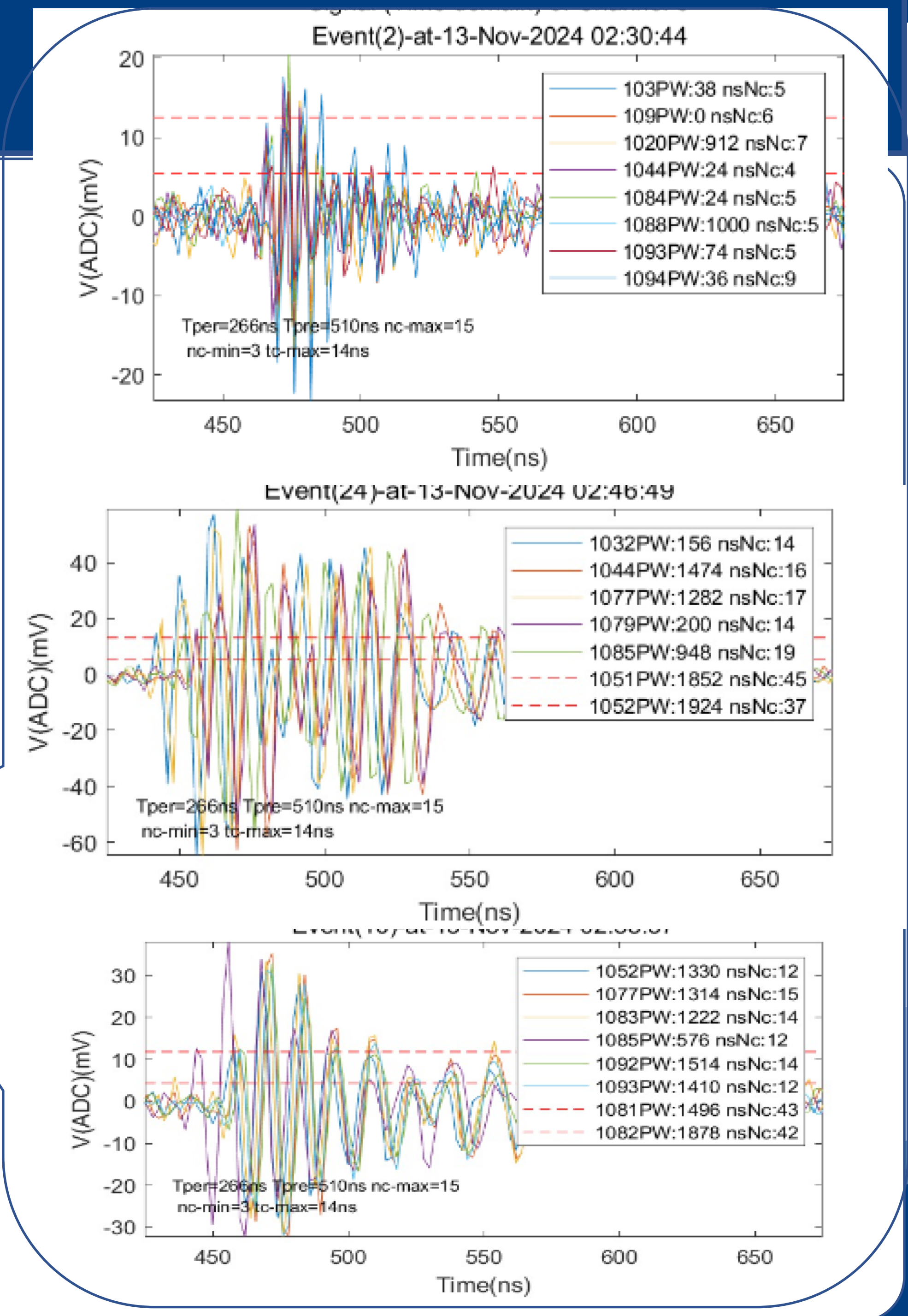
(1) Position information

(2) Beacon system hardware

- LPDA antenna
- PL
- Source
- Truck

(3) Trigger algorithm and pulse choice

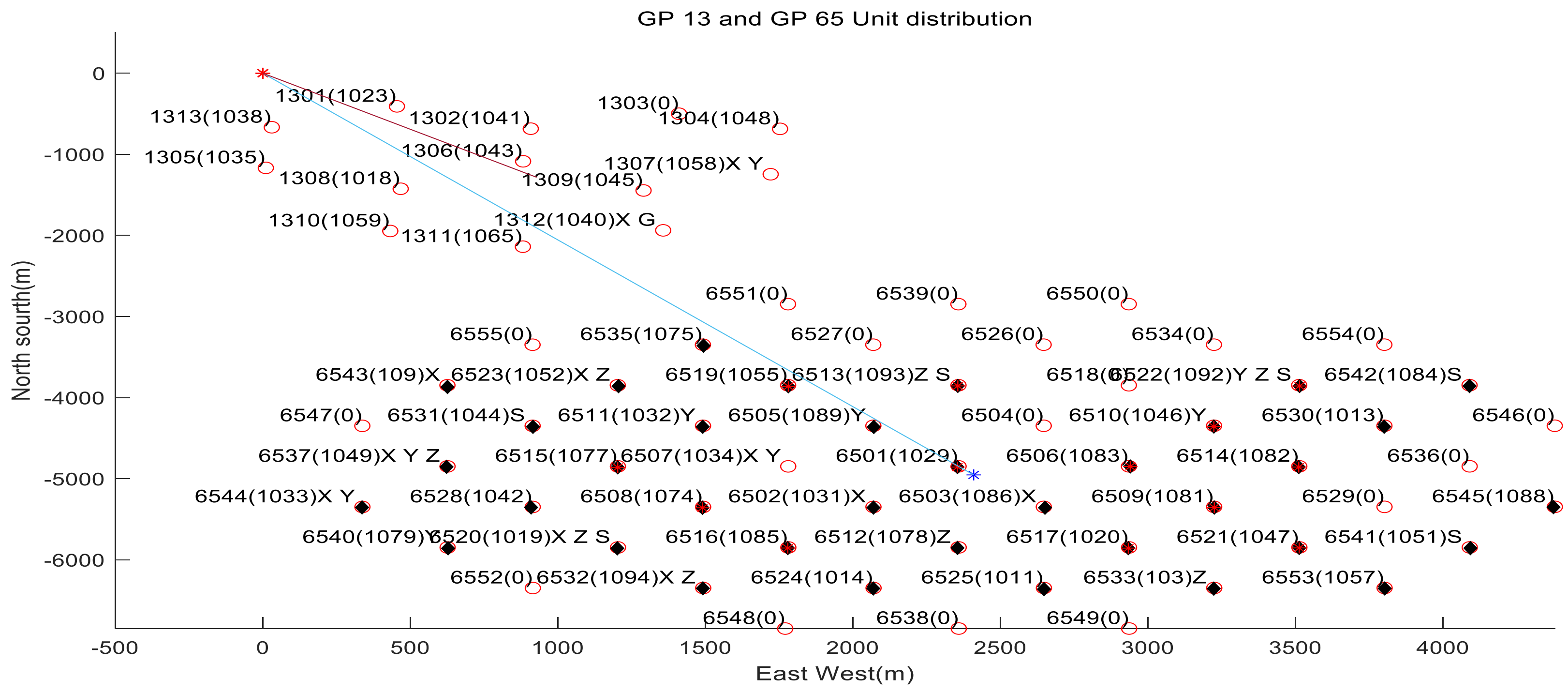
(4) Gain/ radiation pattern calibration



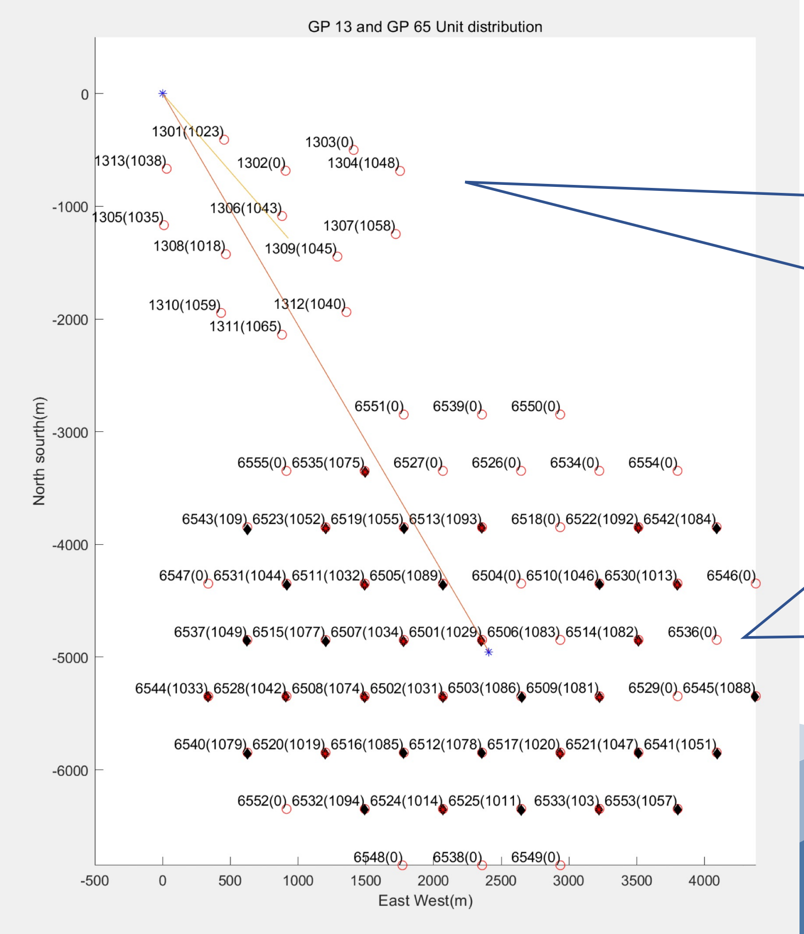
Statues of Units in GP13~ GP65

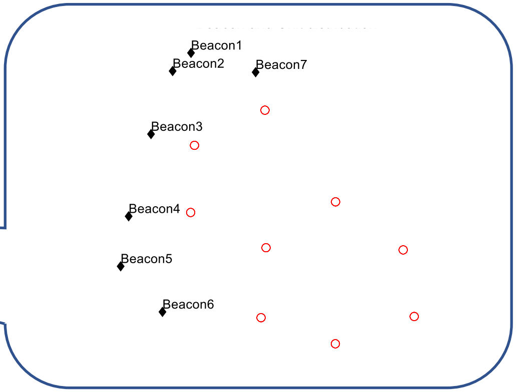
Mechanical + solar panel： 13
Charge controller： 13
Antenna： 13
LNA： 13，
Full function FEB： 11， Missing （2,3）
Now Work： 11(8)

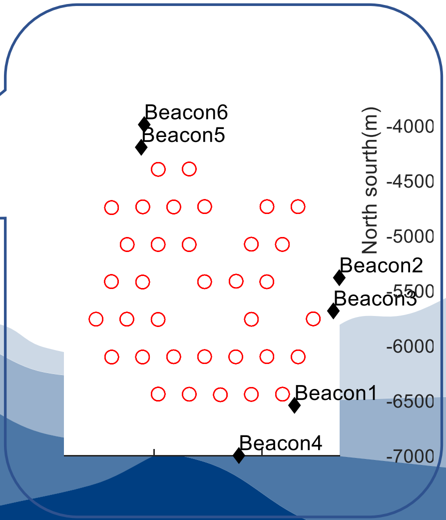
Mechanical + solar panel： 65
Charge controller： 63； Missing： 119， 106
Antenna： 54； Missing 4 and others
LNA： 54， not work： 36, 29, 26, 34, 54, 50, 18
Full function FEB： 38
Good statuses: 36， 12 （1078） ,33 （103） Z channel not good
Now work： 35 （inclue 13&33） (Run 127:33Units)
Loss: 3 （1086） ， 30 （1013） , 7 （1034）

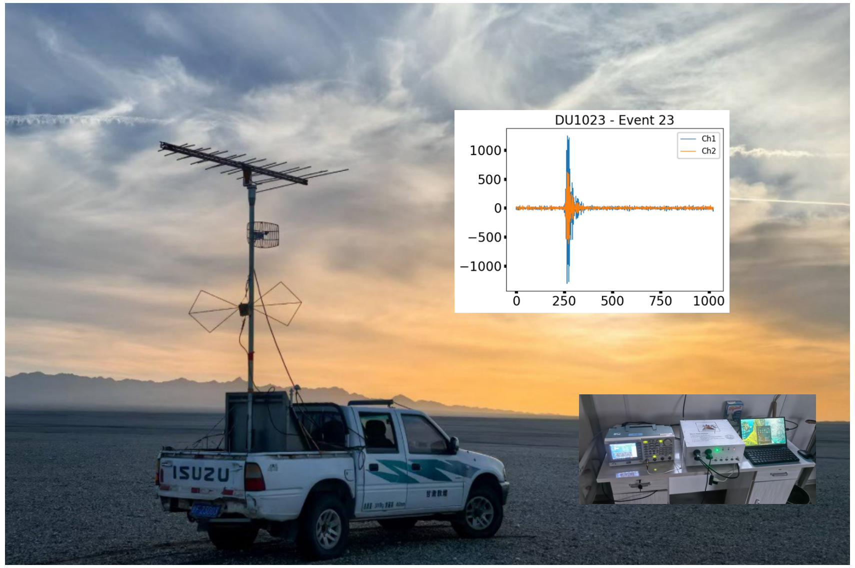


GPS time calibration based on Beacon test







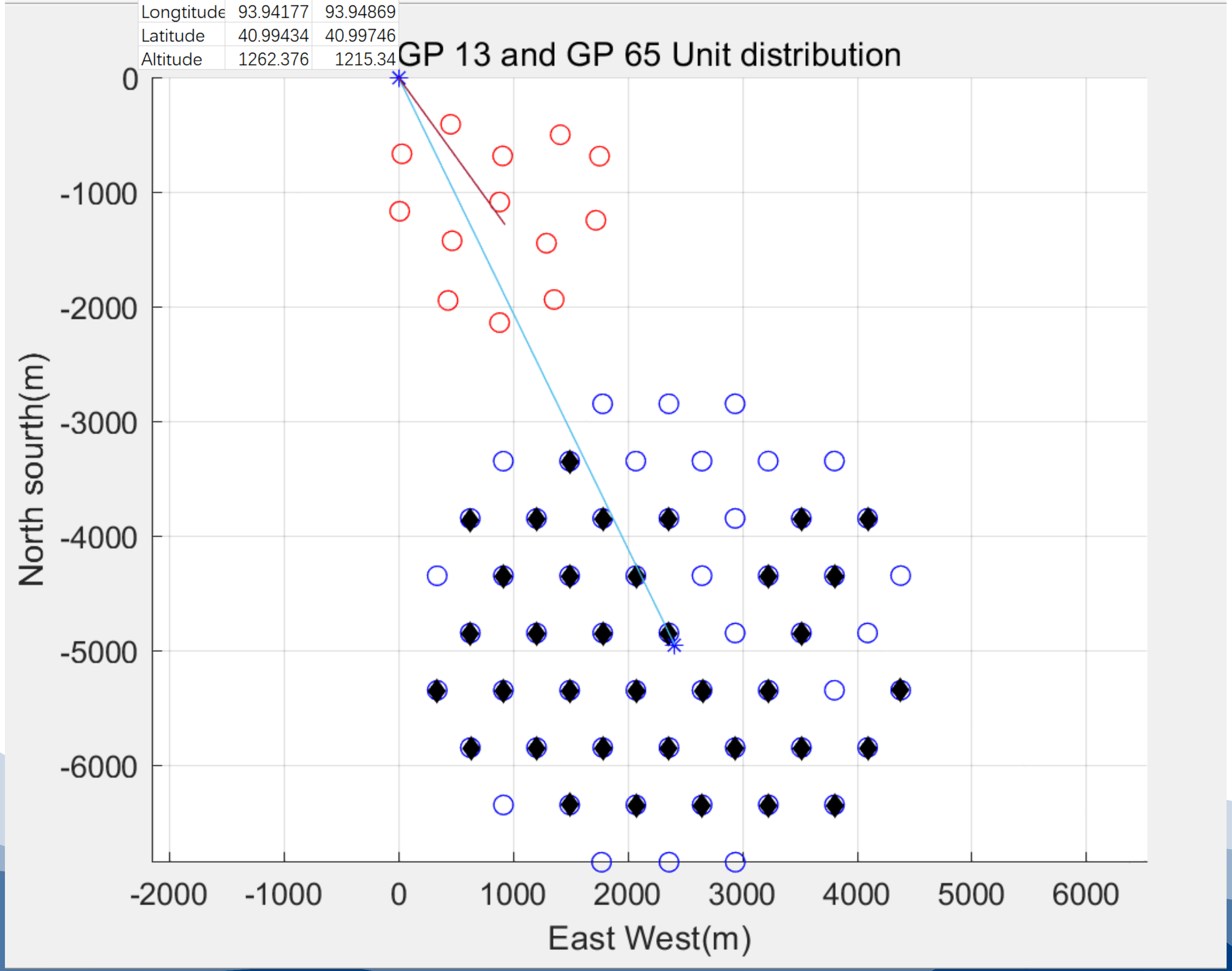


- Beacon (115MHz)
  3pulse
  100ms
  5V
  3minites

- DU
  1034+GP13/GP65
  No LNA
  L1 trigger
  X or Y trigger

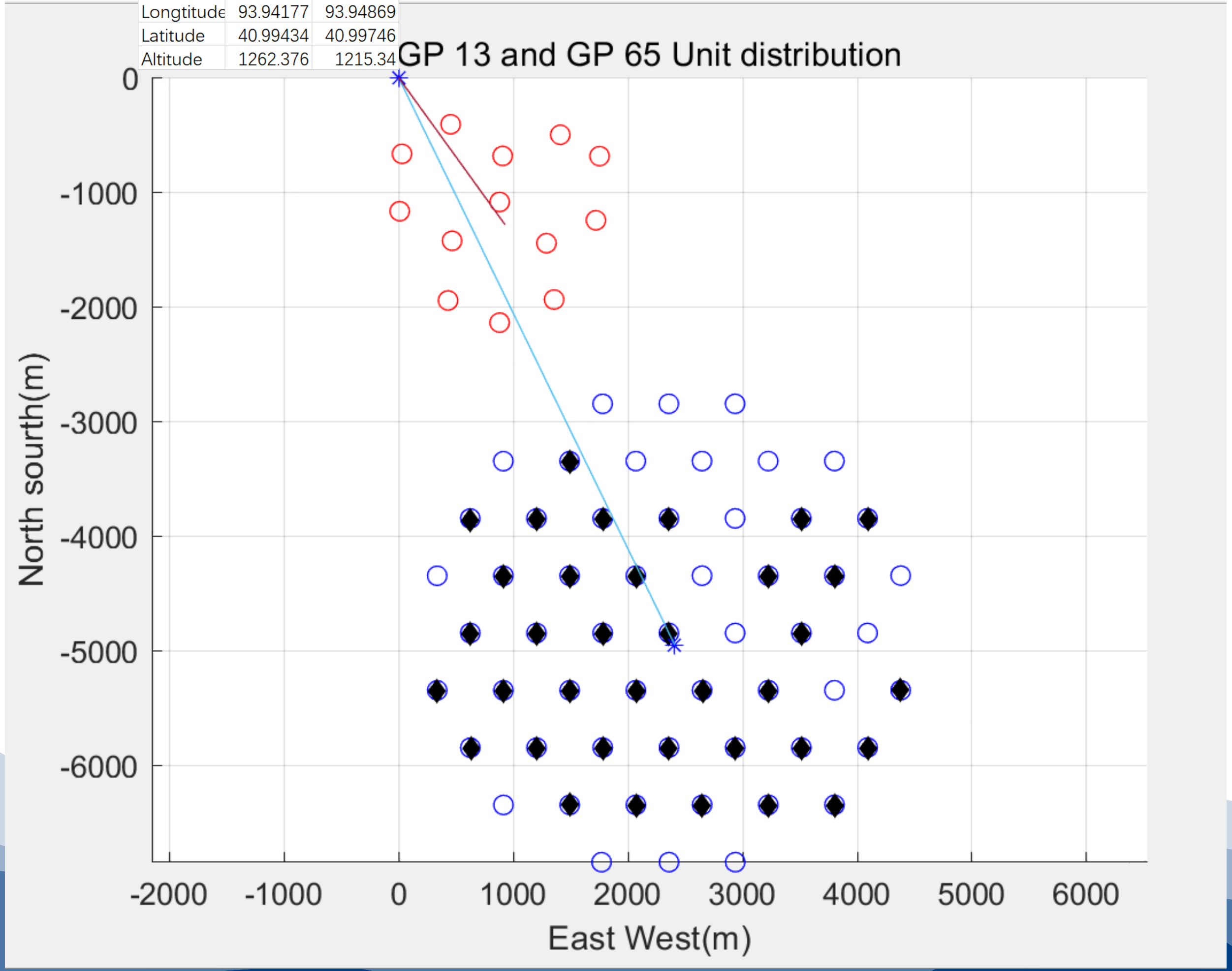
Statues confirm （GPS under test work well）

ref	Authorizec	test
Longtitude	93.94177	93.94869
Latitude	40.99434	40.99746
Altitude	1262.376	1215.34



The starting GPS time of ID-103(Latitude=40.9402 Longtitude=93.987 Altitude=1270.9638) is: 2024:10:23:22:2:20
The starting GPS time of ID-109(Latitude=40.9626 Longtitude=93.9561 Altitude=1234.7943) is: 2024:10:23:22:2:20
The starting GPS time of ID-1011(Latitude=40.9402 Longtitude=93.9801 Altitude=1267.2851) is: 2024:10:23:22:2:20
The starting GPS time of ID-1013(Latitude=40.9582 Longtitude=93.9938 Altitude=1228.6681) is: 2024:10:23:22:2:20
The starting GPS time of ID-1014(Latitude=40.9402 Longtitude=93.9733 Altitude=1267.8271) is: 2024:10:23:22:2:20
The starting GPS time of ID-1019(Latitude=40.9447 Longtitude=93.963 Altitude=1267.8574) is: 2024:10:23:22:2:20
The starting GPS time of ID-1020(Latitude=40.9447 Longtitude=93.9835 Altitude=1263.2349) is: 2024:10:23:22:2:20
The starting GPS time of ID-1029(Latitude=40.9537 Longtitude=93.9766 Altitude=1246.0239) is: 2024:10:23:22:2:20
The starting GPS time of ID-1031(Latitude=40.9492 Longtitude=93.9733 Altitude=1255.5966) is: 2024:10:23:22:2:20
The starting GPS time of ID-1032(Latitude=40.9582 Longtitude=93.9664 Altitude=1236.3247) is: 2024:10:23:22:2:20
The starting GPS time of ID-1033(Latitude=40.9493 Longtitude=93.9527 Altitude=1261.3226) is: 2024:10:23:22:2:20
The starting GPS time of ID-1034(Latitude=40.9537 Longtitude=93.9698 Altitude=1242.1395) is: 2024:10:23:22:2:20
The starting GPS time of ID-1042(Latitude=40.9492 Longtitude=93.9595 Altitude=1260.9882) is: 2024:10:23:22:2:20
The starting GPS time of ID-1044(Latitude=40.9582 Longtitude=93.9596 Altitude=1251.4855) is: 2024:10:23:22:2:20
The starting GPS time of ID-1046(Latitude=40.9582 Longtitude=93.987 Altitude=1231.5985) is: 2024:10:23:22:2:20
The starting GPS time of ID-1047(Latitude=40.9447 Longtitude=93.9904 Altitude=1259.4381) is: 2024:10:23:22:2:20
The starting GPS time of ID-1049(Latitude=40.9538 Longtitude=93.9561 Altitude=1252.4754) is: 2024:10:23:22:2:20
The starting GPS time of ID-1051(Latitude=40.9447 Longtitude=93.9973 Altitude=1268.3875) is: 2024:10:23:22:2:20
The starting GPS time of ID-1052(Latitude=40.9627 Longtitude=93.963 Altitude=1249.7938) is: 2024:10:23:22:2:20
The starting GPS time of ID-1055(Latitude=40.9627 Longtitude=93.9698 Altitude=1232.6568) is: 2024:10:23:22:2:20
The starting GPS time of ID-1057(Latitude=40.9402 Longtitude=93.9938 Altitude=1269.9668) is: 2024:10:23:22:2:20
The starting GPS time of ID-1074(Latitude=40.9492 Longtitude=93.9664 Altitude=1259.1177) is: 2024:10:23:22:2:20
The starting GPS time of ID-1075(Latitude=40.9672 Longtitude=93.9664 Altitude=1231.4105) is: 2024:10:23:22:2:20
The starting GPS time of ID-1077(Latitude=40.9537 Longtitude=93.963 Altitude=1249.3626) is: 2024:10:23:22:2:20
The starting GPS time of ID-1078(Latitude=40.9448 Longtitude=93.9766 Altitude=1265.7503) is: 2024:10:23:22:2:20
The starting GPS time of ID-1079(Latitude=40.9447 Longtitude=93.9561 Altitude=1275.3077) is: 2024:10:23:22:2:20
The starting GPS time of ID-1081(Latitude=40.9492 Longtitude=93.987 Altitude=1254.6058) is: 2024:10:23:22:2:20
The starting GPS time of ID-1082(Latitude=40.9537 Longtitude=93.9904 Altitude=1244.0918) is: 2024:10:23:22:2:20
The starting GPS time of ID-1084(Latitude=40.9627 Longtitude=93.9973 Altitude=1220.9782) is: 2024:10:23:22:2:20
The starting GPS time of ID-1085(Latitude=40.9447 Longtitude=93.9698 Altitude=1253.4985) is: 2024:10:23:22:2:20
The starting GPS time of ID-1086(Latitude=40.9492 Longtitude=93.9802 Altitude=1247.3204) is: 2024:10:23:22:2:20
The starting GPS time of ID-1088(Latitude=40.9493 Longtitude=94.0006 Altitude=1246.4776) is: 2024:10:23:22:2:20
The starting GPS time of ID-1089(Latitude=40.9582 Longtitude=93.9733 Altitude=1235.9529) is: 2024:10:23:22:2:20
The starting GPS time of ID-1092(Latitude=40.9627 Longtitude=93.9904 Altitude=1231.9989) is: 2024:10:23:22:2:20
The starting GPS time of ID-1093(Latitude=40.9627 Longtitude=93.9767 Altitude=1228.4018) is: 2024:10:23:22:2:20
The starting GPS time of ID-1094(Latitude=40.9403 Longtitude=93.9664 Altitude=1268.7551) is: 2024:10:23:22:2:20

Calibration of Time based on given GPS location



ref	Authorizec	test
Longtitude	93.94177	93.94869
Latitude	40.99434	40.99746
Altitude	1262.376	1215.34

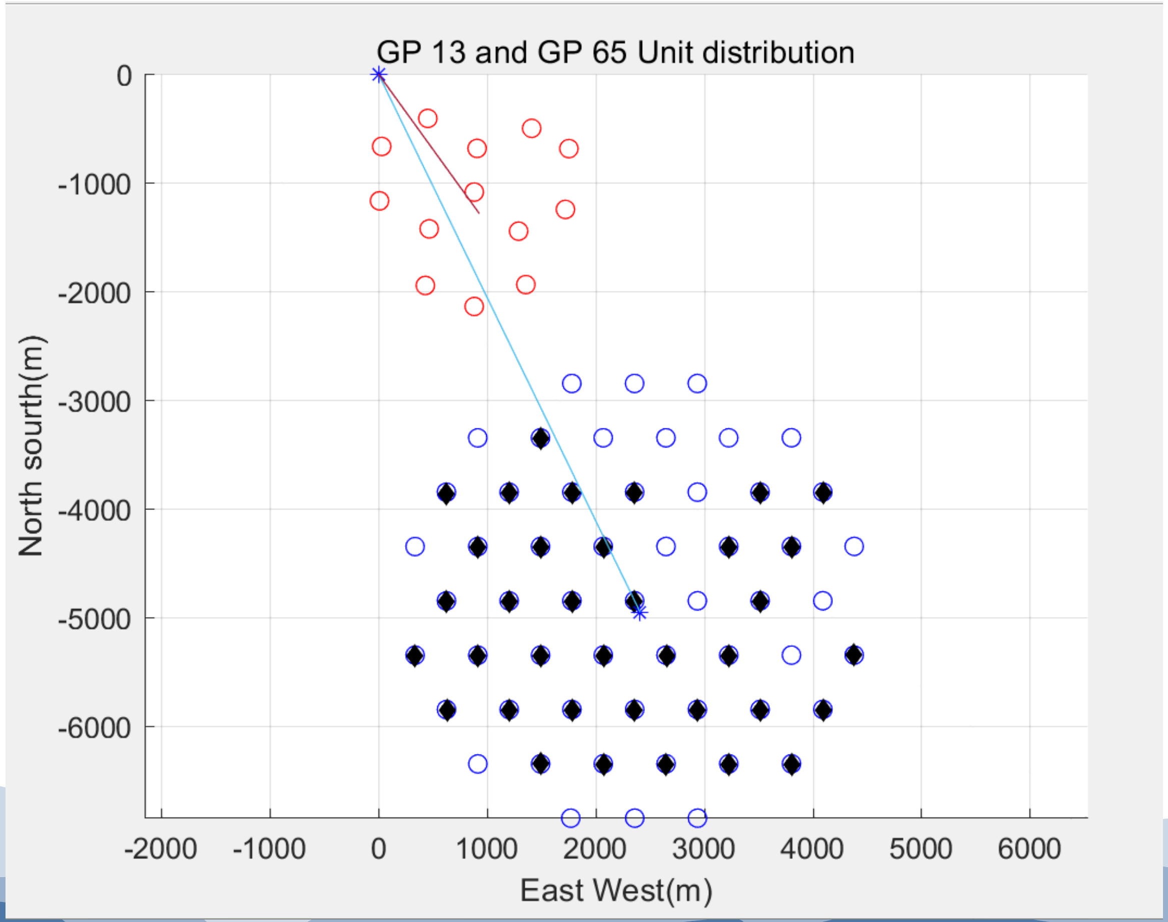
$$t_n^i(k) = t_{1034}^{\textbf{Beacon}} + \frac{l_n^i}{c} + \Delta t_n$$

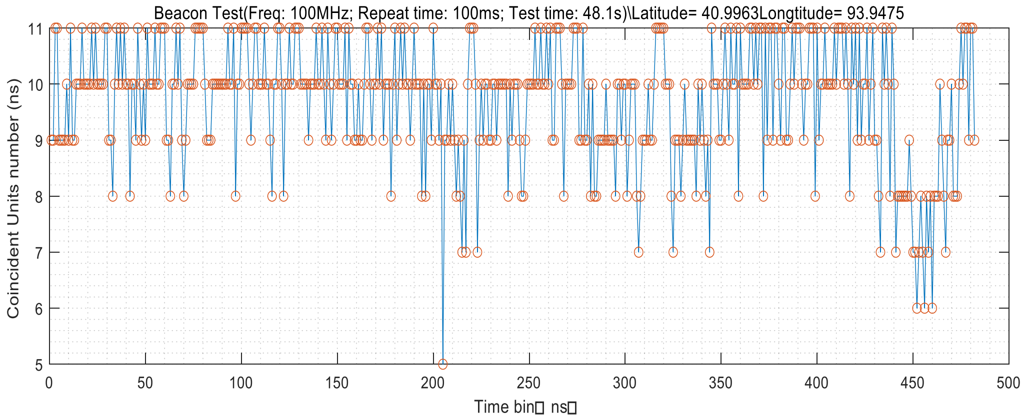
$$t_n^i = \frac{1}{K}\sum_{k=1}^{K} t_n^i(k)$$

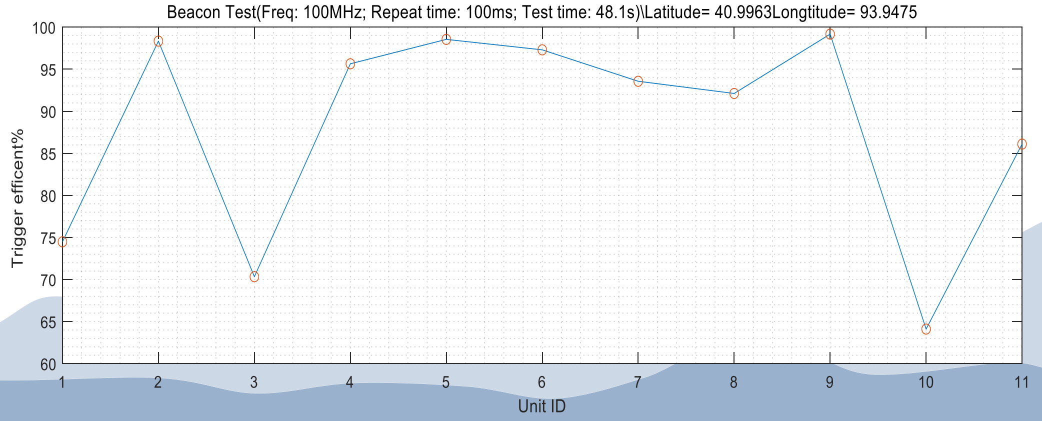
$$\Delta t_n = t_n^i - (t_{1034}^{\textbf{Beacon}} + \frac{l_n^i}{c})$$

For each Beacon position i=1~I(I=8, The number of different beacon locations)， we send k pulse, and the collect the arriving time for all units (include the reference DU1034), the arriving time for all units n=1~N, hence the time delay difference can be calibrate based on the average value in test.

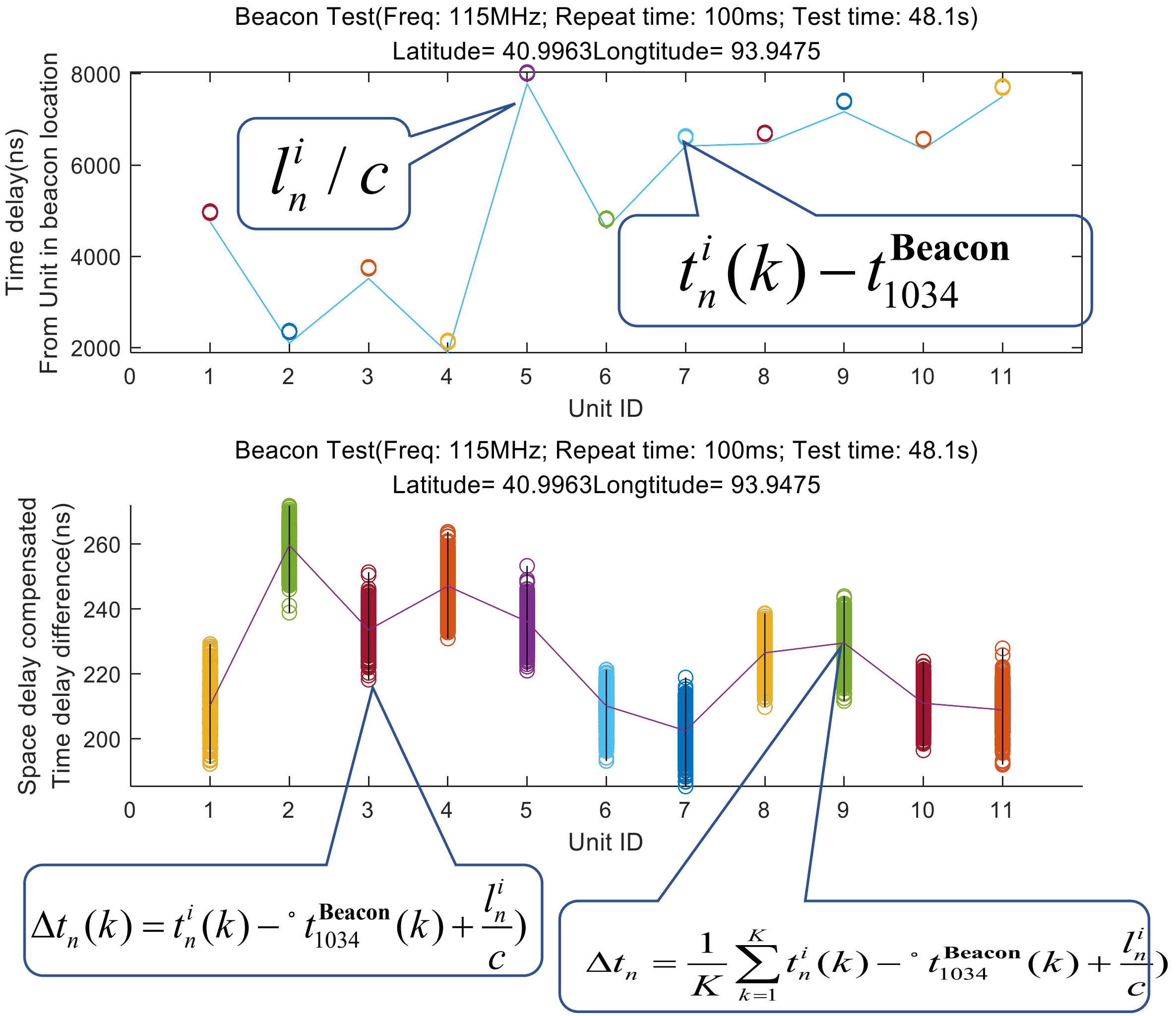
Data selection: time window=200ns, N_trigger_min=5

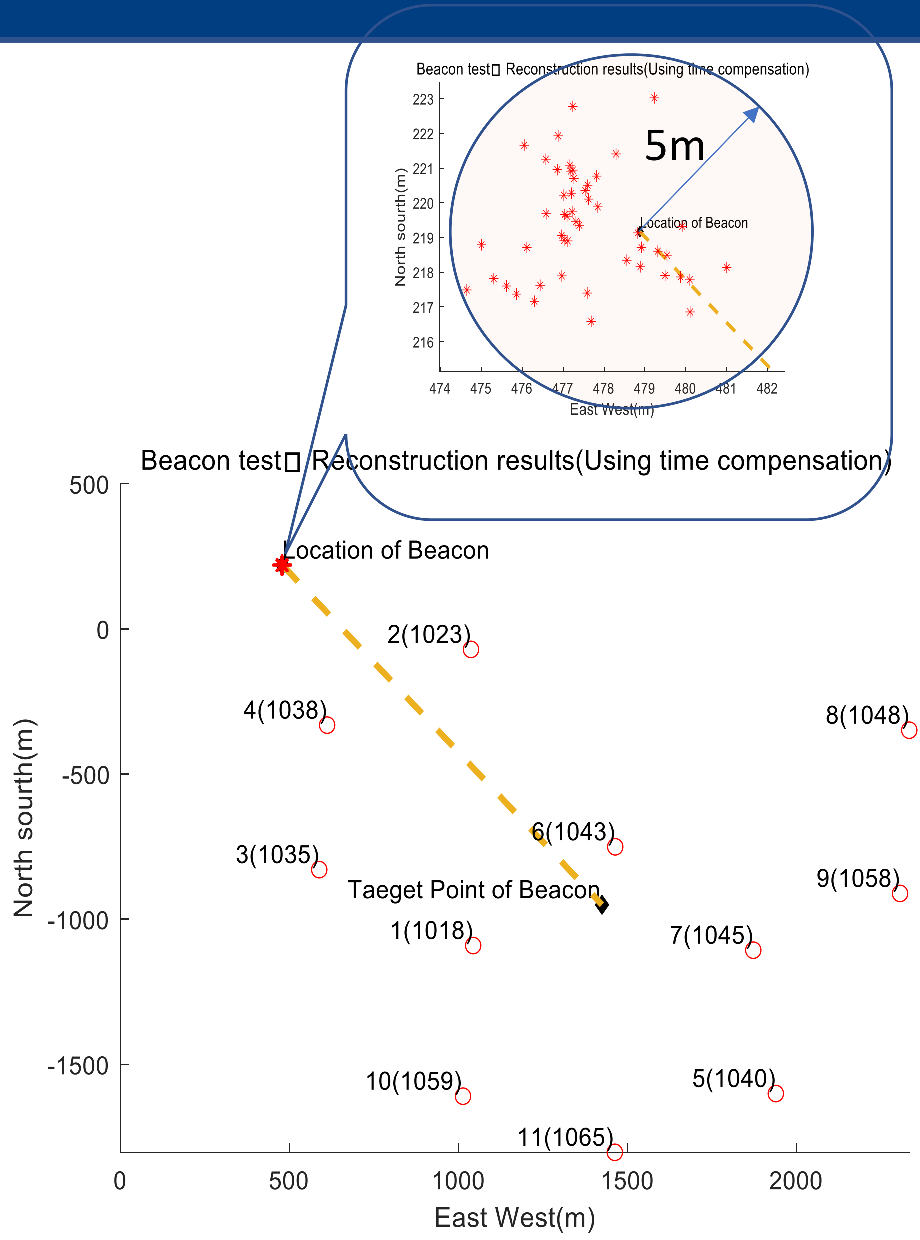




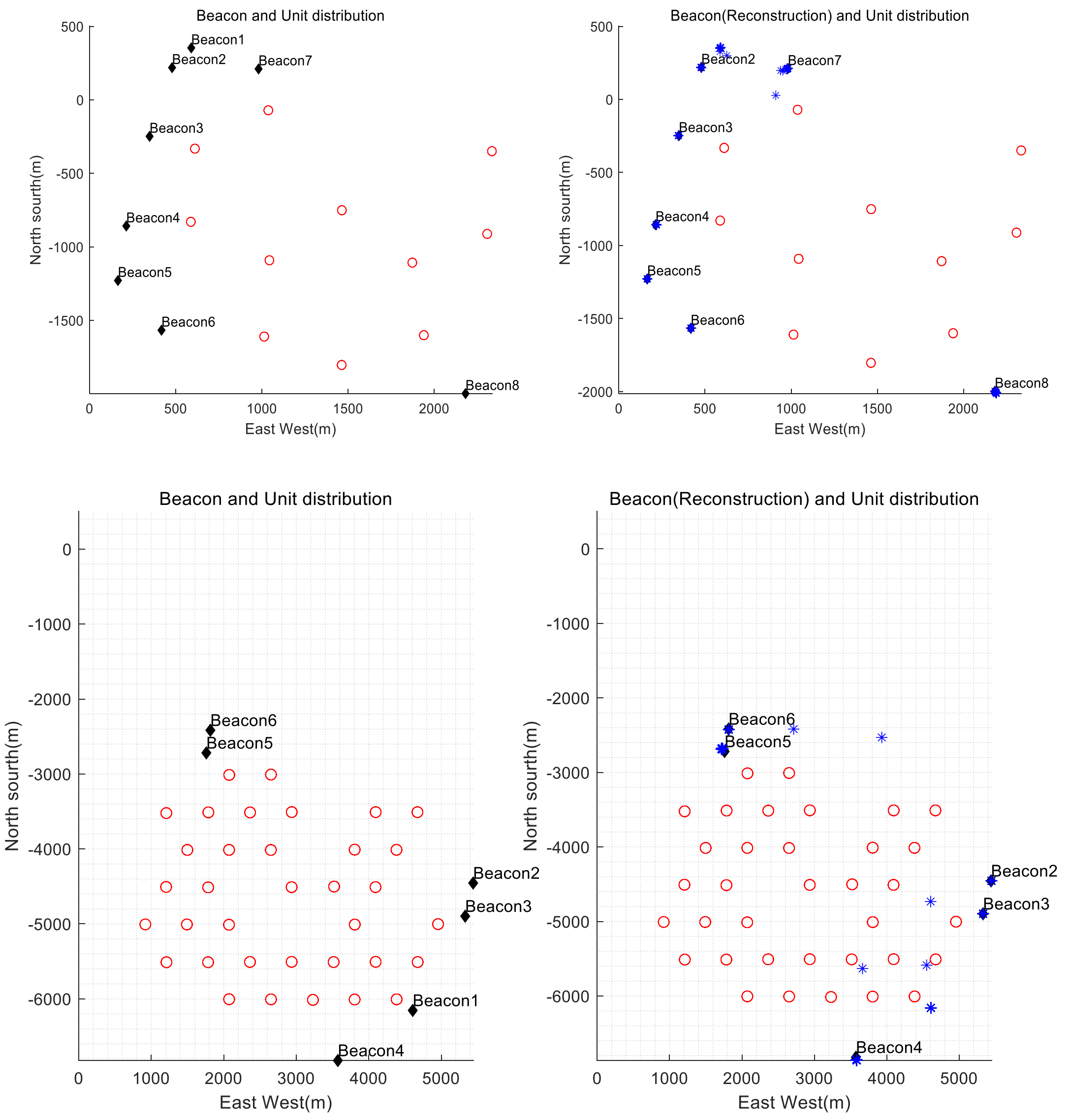


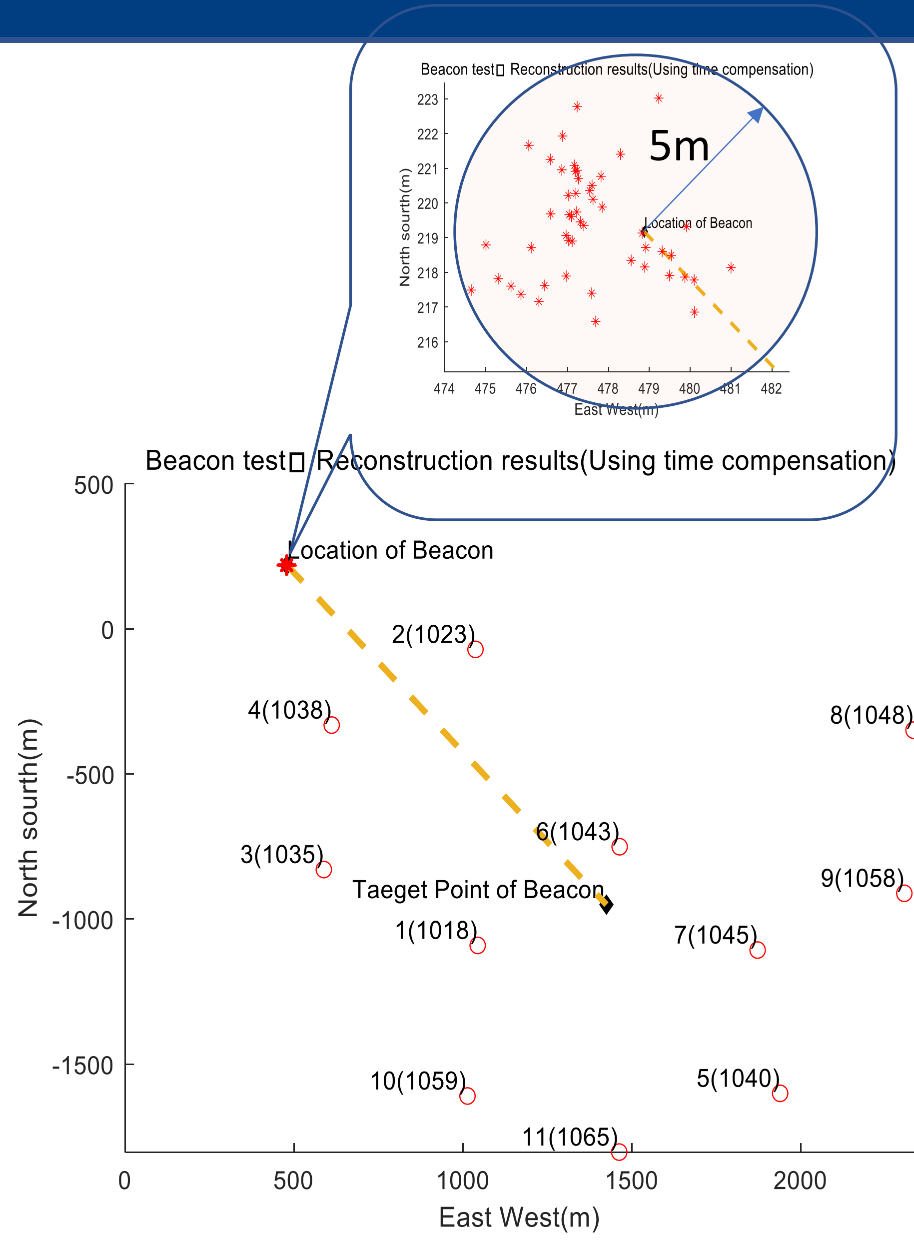
Typical results





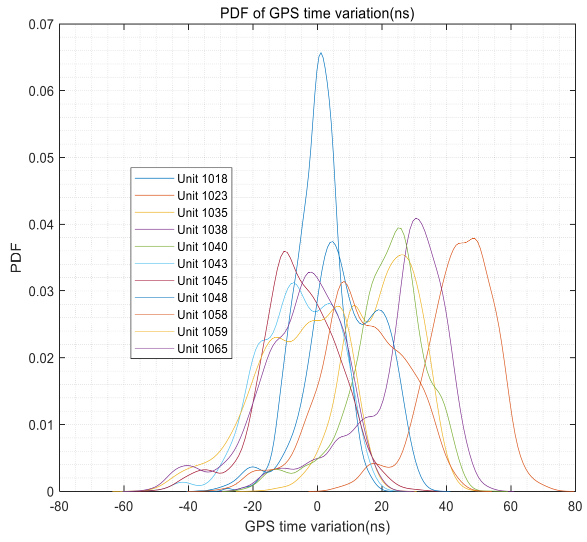
Reconstruct results

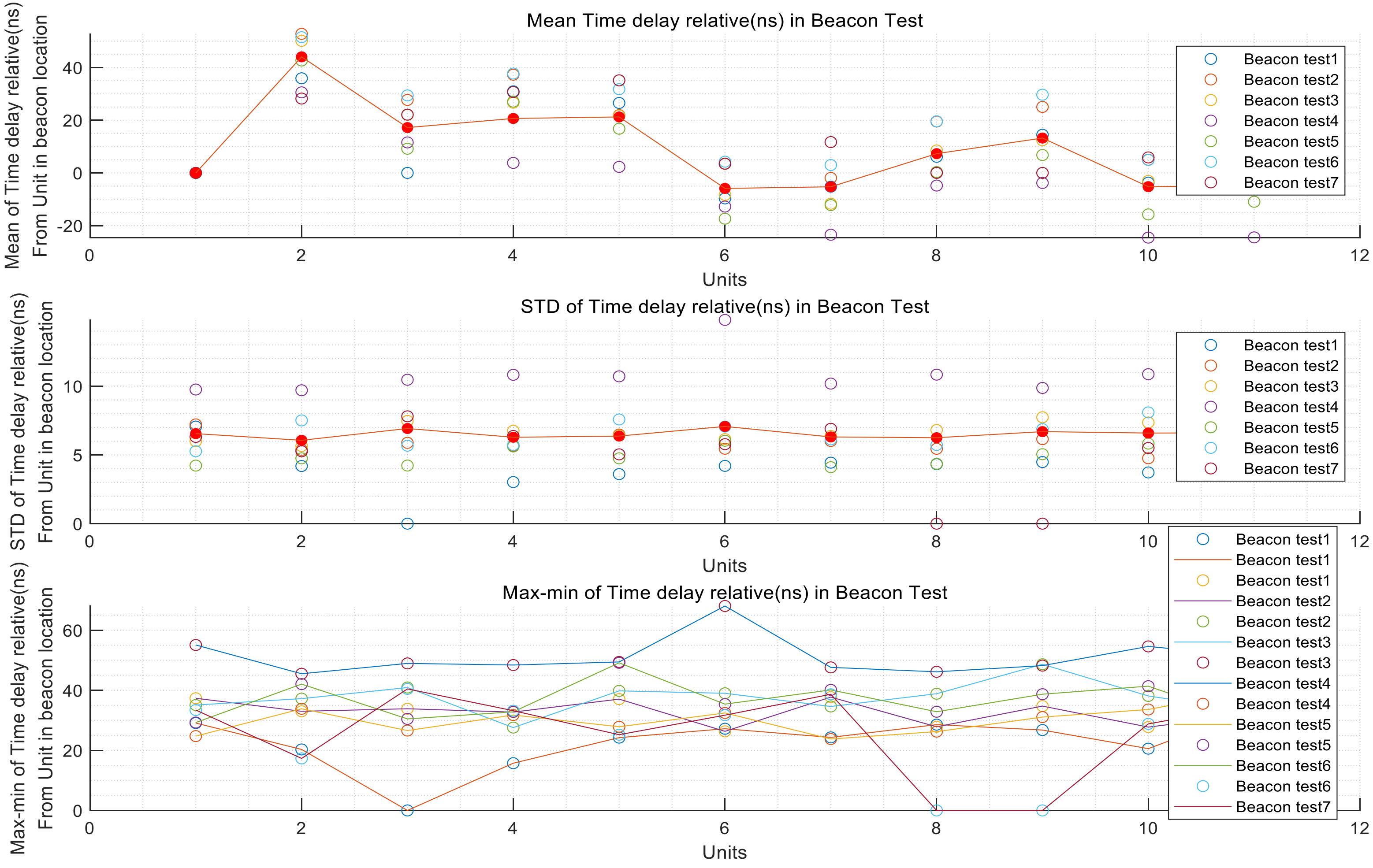




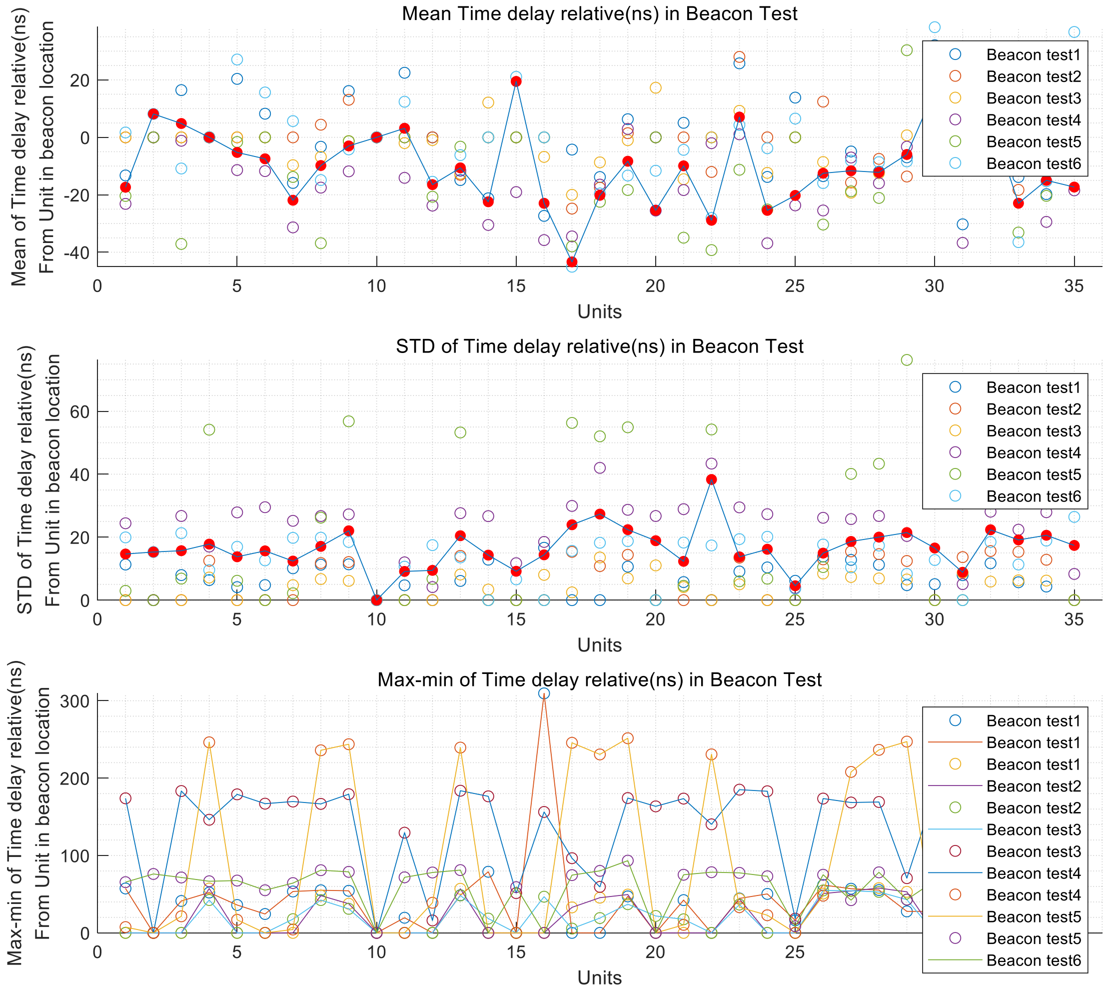
Muti_beacon test results

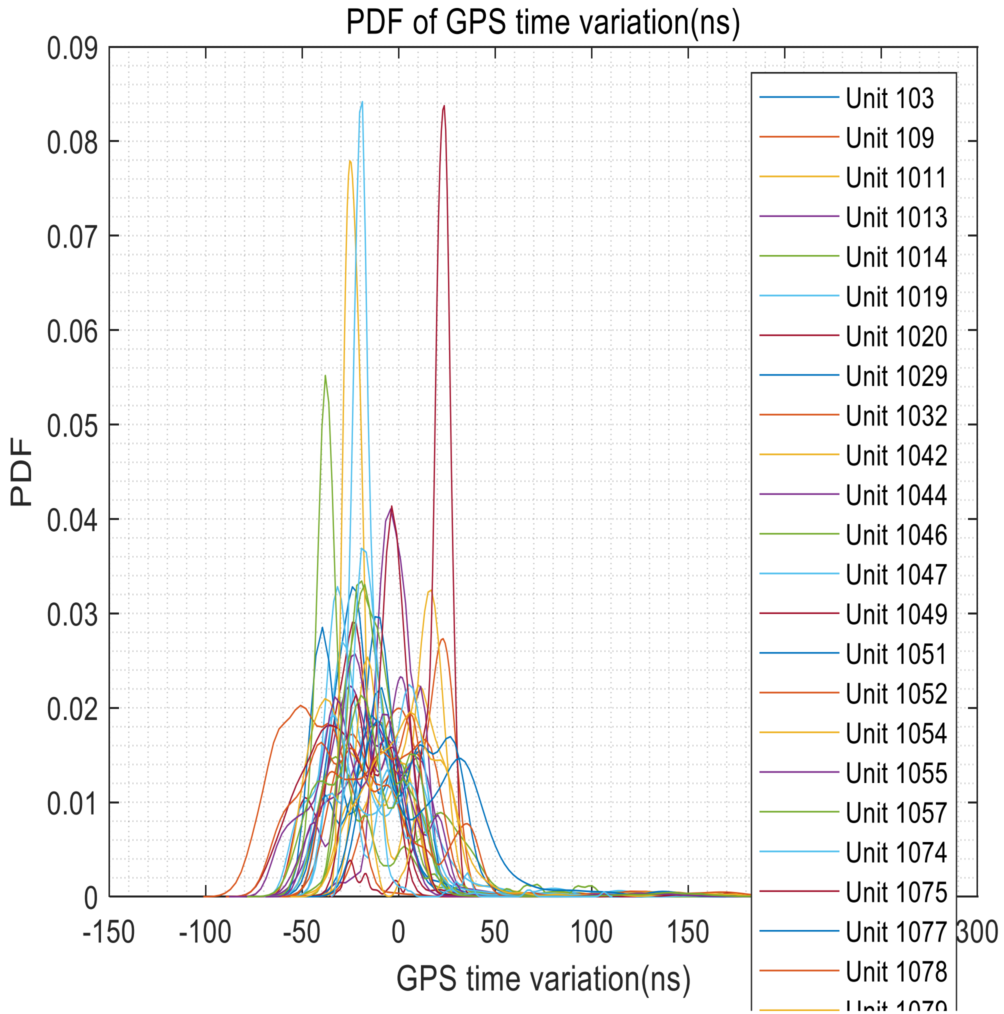
- GPS time for different Units has a relatively stable difference of up to 50ns.(Represented by systematic differences in system response times)
- The 1 sigma accuracy of GPS is about 7ns;
- Some GPS time distribution is double peaks.





GP65

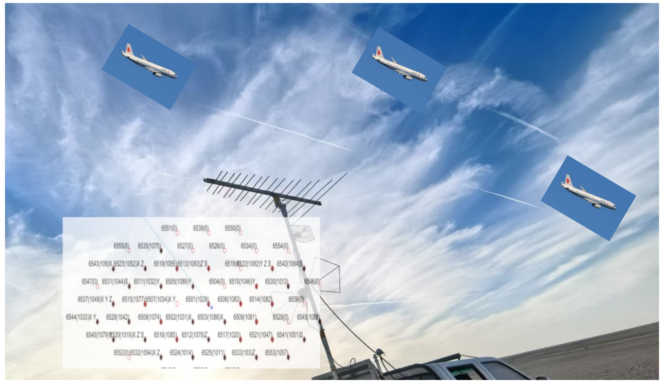

Mean Time delay relative(ns) in Beacon Test
Mean of Time delay relative(ns) From Unit in beacon location
Units
STD of Time delay relative(ns) in Beacon Test
STD of Time delay relative(ns) From Unit in beacon location
Max-min of Time delay relative(ns) in Beacon Test
Max-min of Time delay relative(ns) From Unit in beacon location
Beacon test1
Beacon test2
Beacon test3
Beacon test4
Beacon test5
Beacon test6

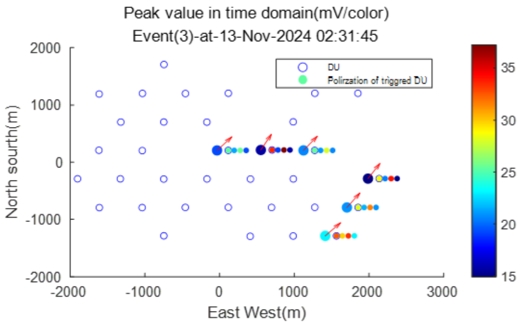

PDF of GPS time variation(ns)
PDF
GPS time variation(ns)
Unit 103
Unit 109
Unit 1011
Unit 1013
Unit 1014
Unit 1019
Unit 1020
Unit 1029
Unit 1032
Unit 1042
Unit 1044
Unit 1046
Unit 1047
Unit 1049
Unit 1051
Unit 1052
Unit 1054
Unit 1055
Unit 1057
Unit 1074
Unit 1075
Unit 1077
Unit 1078

Air plane-base calibration

Advantage of Airplane:

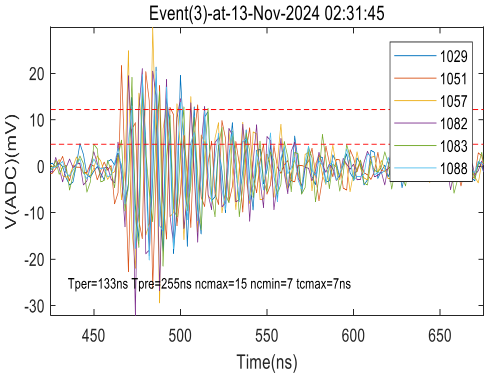
- (1)Free (almost for all time and All-weather work);
- (2) Moving (generate a trace that can used in different direction);
- (3)Relative stable (Magnitude\ spectrum and polarization);

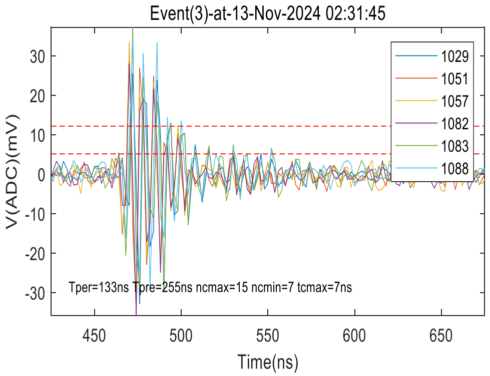


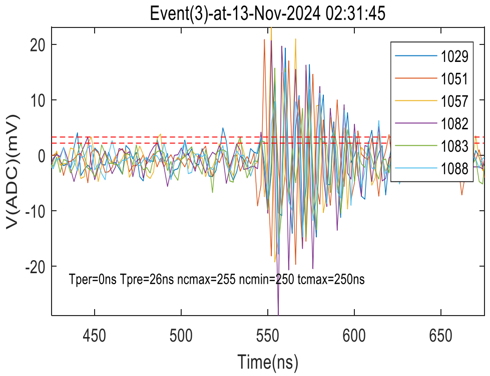


Uncertainty of Airplane:

- Location(Direction, distance)
- Signal magnitude;
- Polarization
- Trace







Another choice : Calibration Based on Wifi RF Chain

- 1: High frequency and time resolution
- 2: off-the-shelf hardware

  based on rocket and bullet
- 3: No ground reflection and

  $T_{R\_antenna}$ is stable and uniform

Signal generator

200M up-conversion->5G

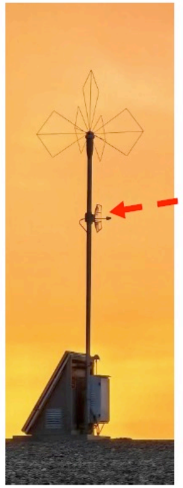
5G down-conversion->200M

Time calibration

GRAND wifi system

Brand: UBIQUITI
Station: BULLET
Access Point: ROCKET
Mode: PtMP
1 rocket: PtMP max. 330+ Mbps(Datasheet)

330>> 50Mbps
PACKAGE LOSS IN DUNHUANG !!! Why?



**Question :is it necessary to keep the GPS system for all units in next generation ?
Or a Local crystal oscillator clock is enough.**

Discuss

$$\Delta T_n^{ref} = T_{TR\_beacon}^{Test}(n) - T_{TR\_beacon}^{Test}(n_{ref}) = \Delta l(n)/(c/n_{air}) + T_{R\_antenna}(n,\theta,\varphi) + \sigma_{GPS\_SR}(n,t) + \sigma_{GPS\_LF}(n,t) + \sigma_{GPS\_Feb}(n)$$

Based on a RTK test of the location of all units , this can be obtained with a 1cm error, and results in 0.03ns

This is a challenge parts, while we can using a repeat test of data as AERA done or a test based on cable cross check to obtain it at 0.5ns precision

This is the part that should be obtain during calibration

- $\sigma_{GPS\_SR}(n,t) + \sigma_{GPS\_LF}(n,t)$ ask for a real time calibration, which mean that the beacon signal will always in the spectrum data(As AERA), which lead limited influence to the event detection;
- $l(n) - l(ref)$)should be tested in the precision of 0.03m, if we hope to obtain 0.2ns precision in time domain;
- The remain question is how to obtain the $T_{TR\_beacon}(n) - T_{TR\_beacon}(n_{ref})$
- This will based on the strategy of the choice of wave shape and the related trigger algorithm.

AERA using 4 sin wave and the related FFT phase information of $\Delta\phi_j$ to obtain the Best time delay τ :

GP13 using pulse

$$C(\Delta\tau) = \sum_j \int A_{1,j} A_{2,j} \sin(\omega_j t)\sin(\omega_j(t-\Delta\tau)+\Delta\phi_j)dt$$

$$\propto \sum_j A_{1,j} A_{2,j} \cos(\Delta\phi_j - \omega_j\Delta\tau)$$

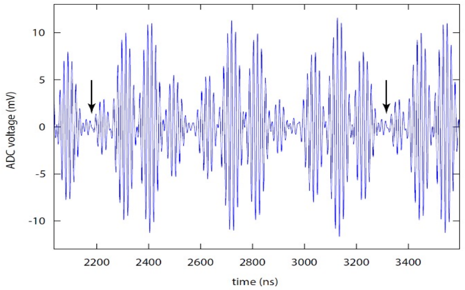
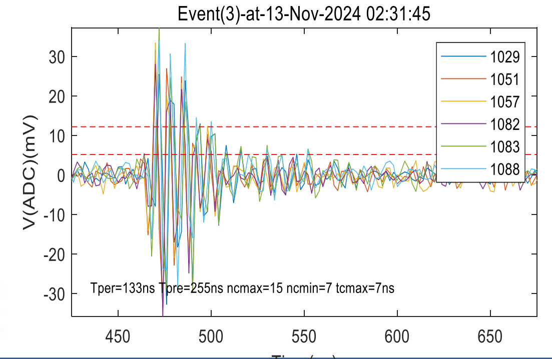


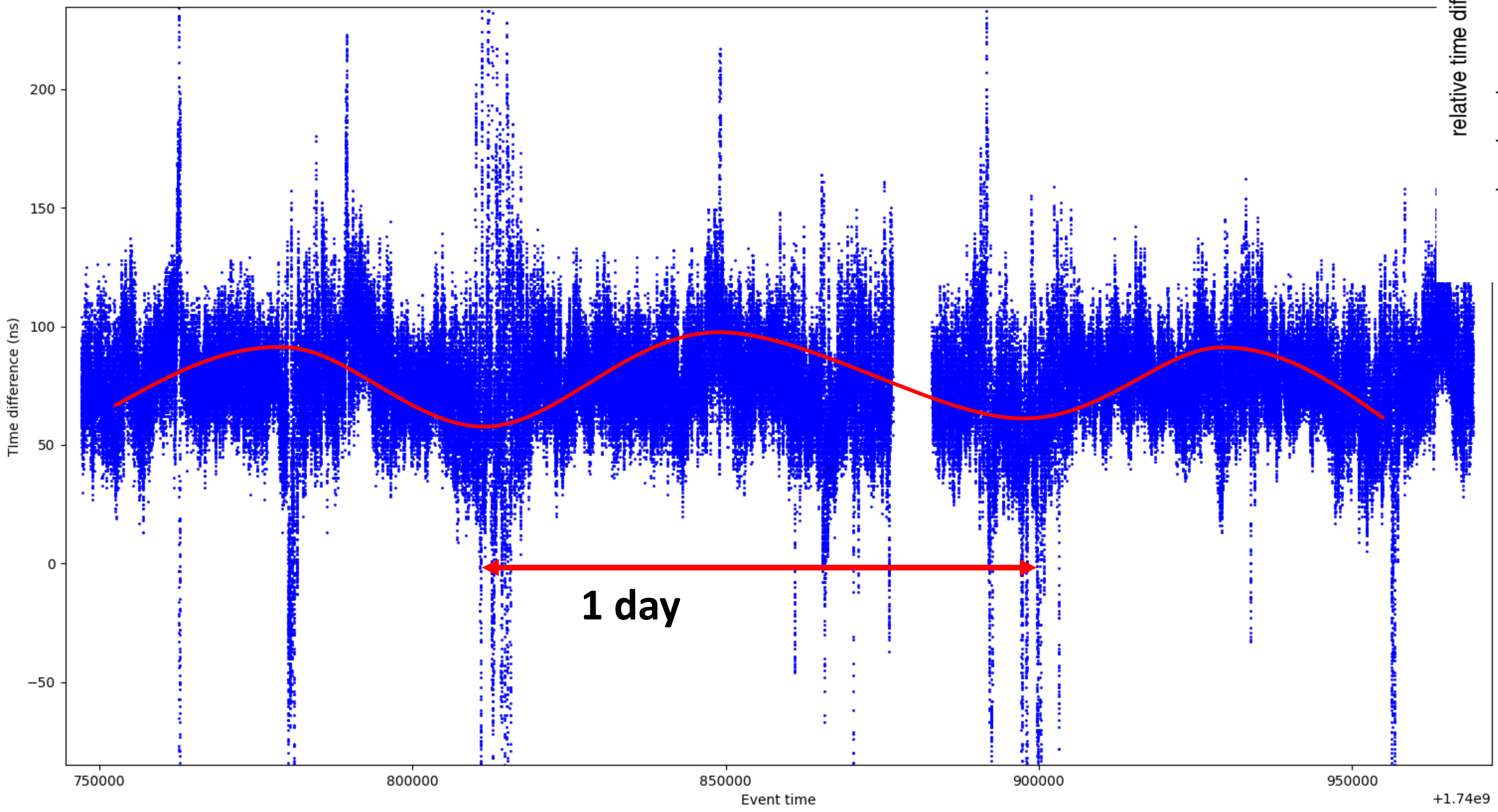
Figure 2. Beacon beat: a voltage-time trace recorded with the analog-to-digital converters (ADCs) of the north-south channel of an AERA station is digitally filtered such that it contains only the four beacon frequencies. The signal shape of the beacon beat has a periodicity of approximately 1100 ns, as indicated by

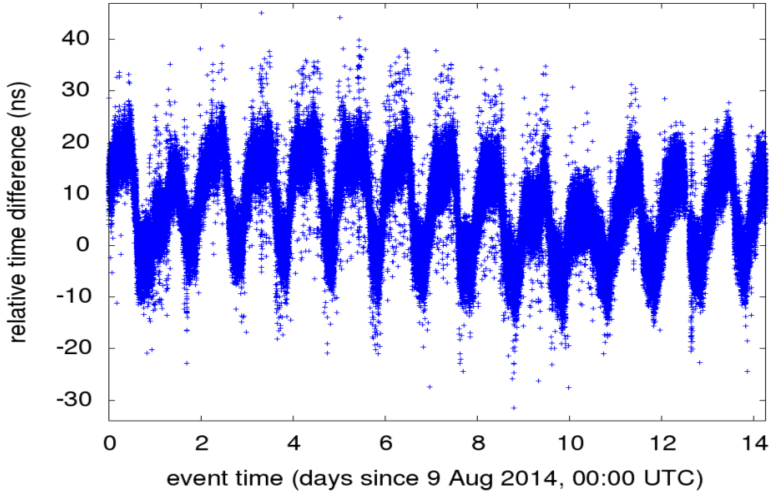


Summary

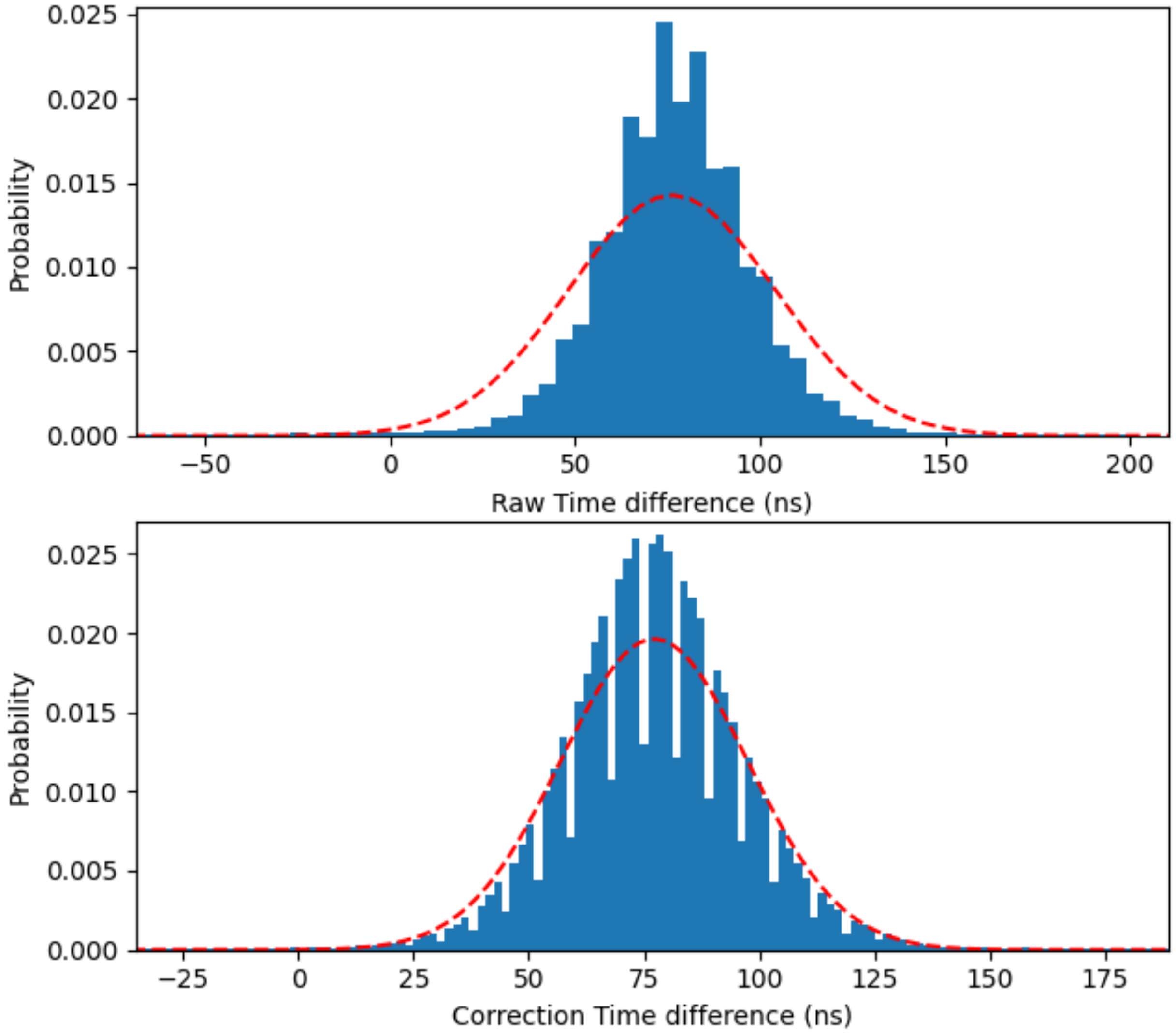
- (1) We have figured out the factors that can caused error in GPS time， and we do the related calibration based on moving beacon in Dunhuang.
- (2)Calibration of position and antenna need improved based on RTK;
- (3) Calibration of time with 2 ns is very challenge；
- (4)Need cross check from other tests.

（PMO Xingxu） Time Difference Periodical Change





PMO Xing xu： Time Difference Distribution



σ(time diff) = 27.98ns
→ σ(single board) = 19.78ns

σ(time diff) = 20.32ns
→ σ(single board) = 14.37ns