TAROGE experiment and reconstruction technique for near-horizon impulsive radio signals

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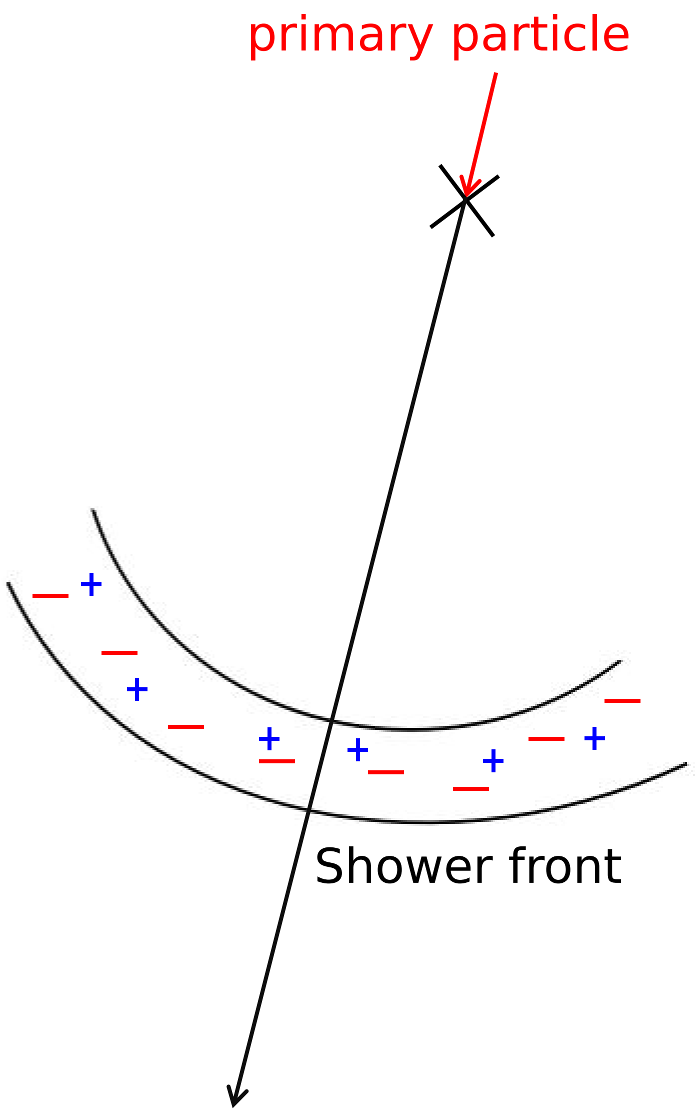
Radio detection of UHECRs



Radio emission:

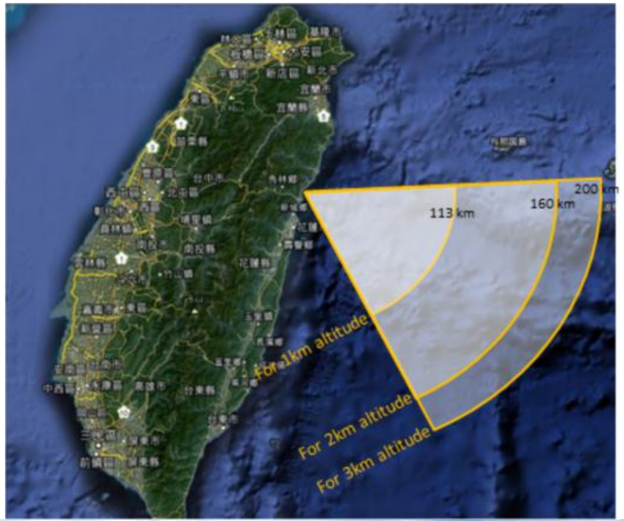
- Inelastic interaction between primary particle and atmosphere creates an extensive air shower (EAS).
- Charged particles (mainly e^+ and e^-) in the EAS are deflected by Earth's magnetic field and thus emits geomagnetic radiation polarized with Lorentz force direction.
- Coherent radiation relativistically beamed in EAS forward direction.

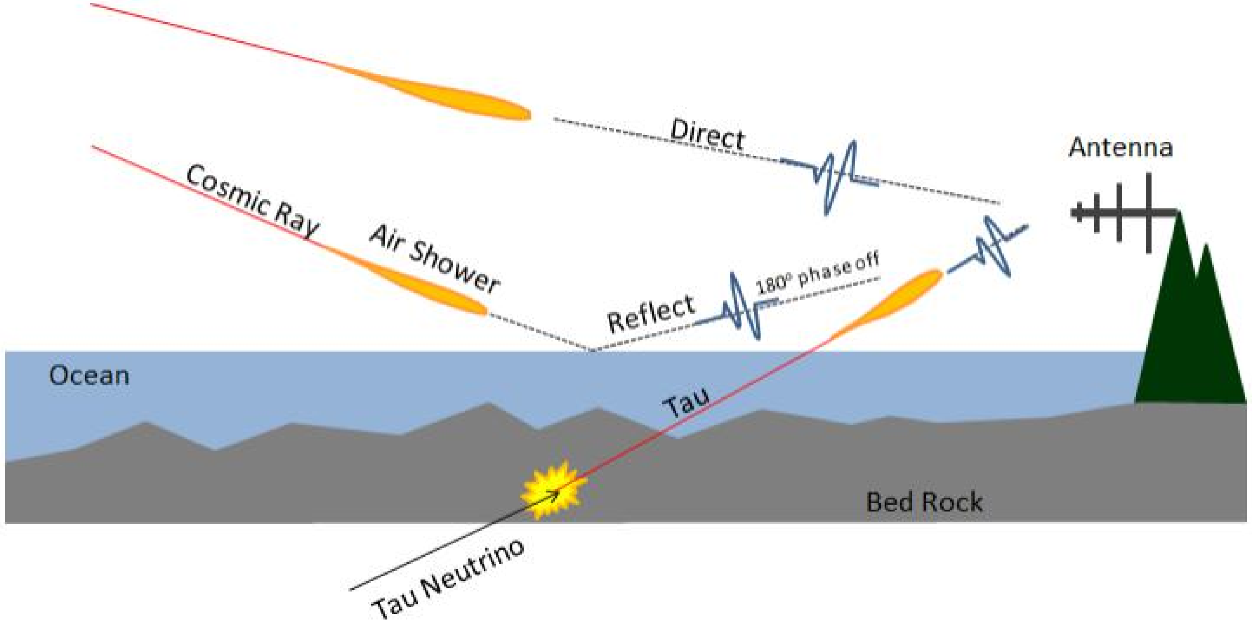
Advantages of radio detection:

- Long propagation length in air (large area coverage)
- High duty cycle (day and night)
- Cost effective instrumentation

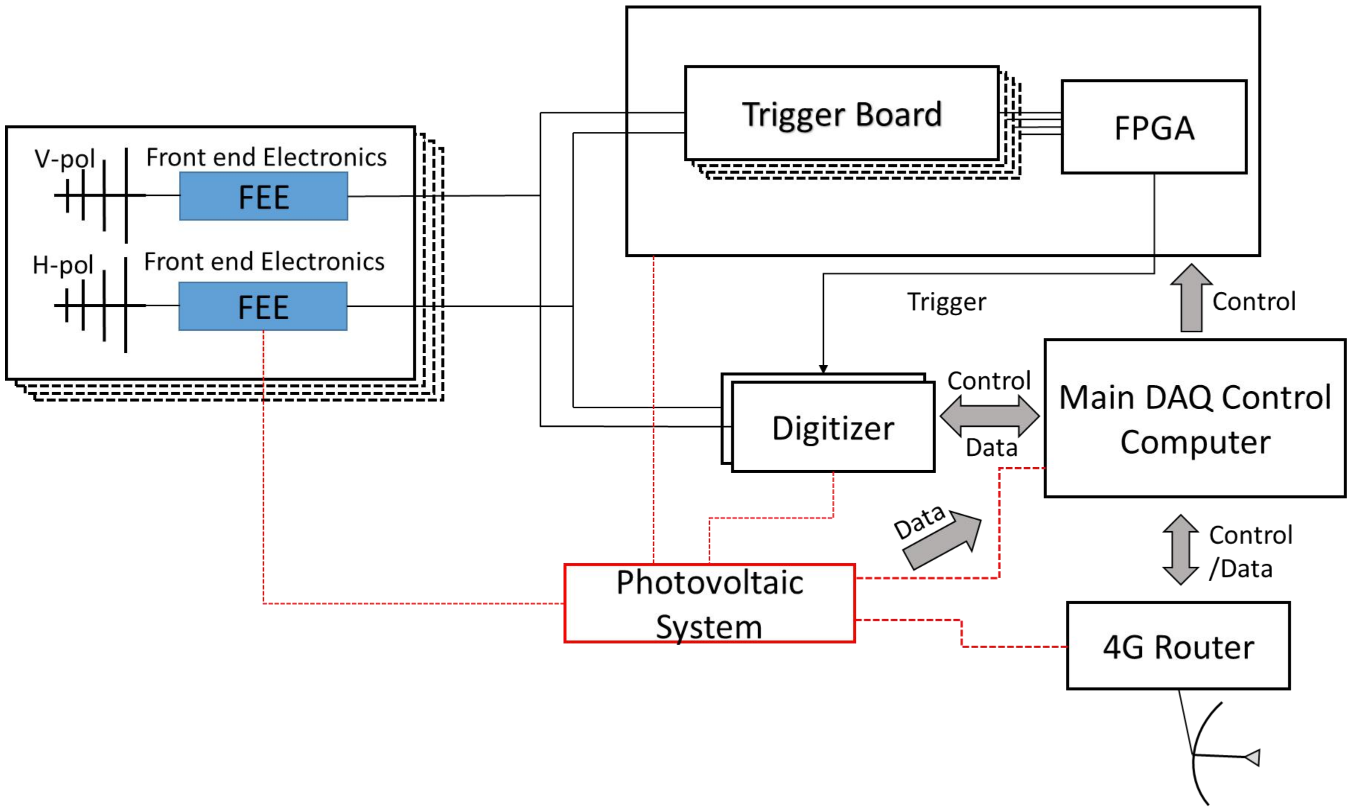
Concept of TAROGE

- TAROGE aims at radio detection of near-horizon EAS induced by UHECRs and Earth-skimming υ_τ;
- Located on high mountains of Taiwan east coast, both direct and ocean-reflected signals can be collected;
- Great advantages: high duty cycle (~90%), large acceptance and cost effective;
- Four stations deployed from 2014-2019;
- Frequency: 180 MHz to 350 MHz.



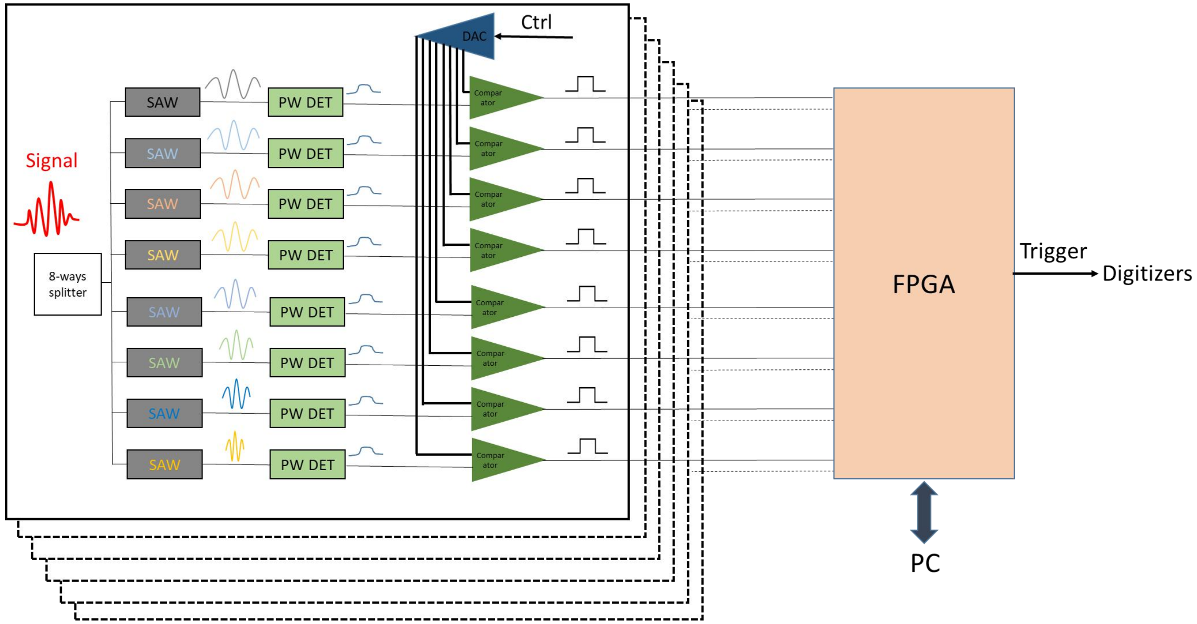


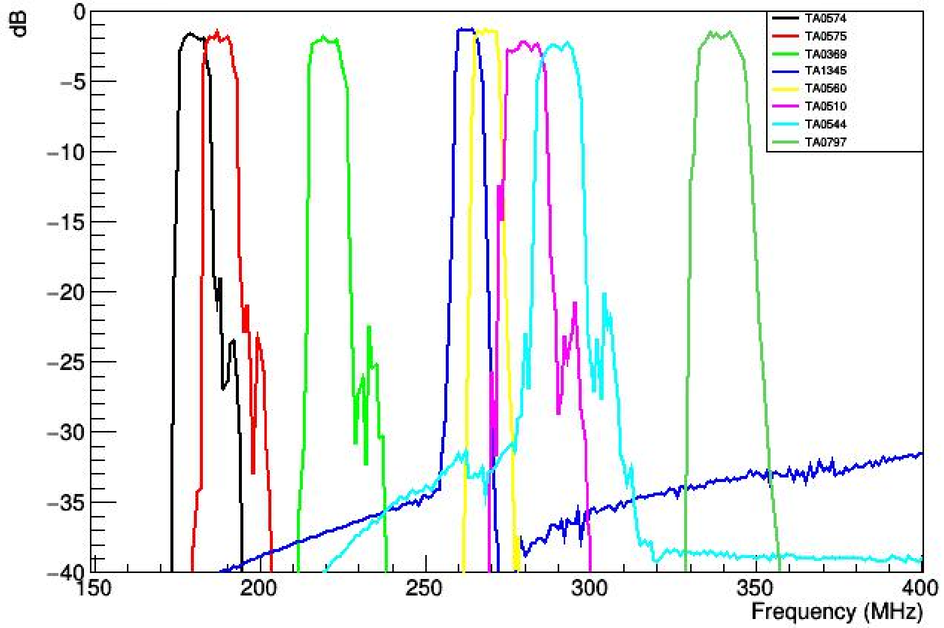
TAROGE-4 system architecture



1. 8 antennas (4 H-pol, 4 V-pol):
   - High gain: ~7 dBi
   - Broadband: 180~450 MHz
2. Front-end electronics:
   - Filter: 180~350 MHz
   - 63 dB low noise amplifier
3. Trigger system:
   - Multi-band, multi-channel coincidence technique
4. DAQ:
   - 1.25 GHz sampling rate, 1500 samples, 350 MHz bandwidth
5. Off-grid power supply (PV)
6. Real-time data transfer and control (4G network)

Advanced trigger system for suburban environment



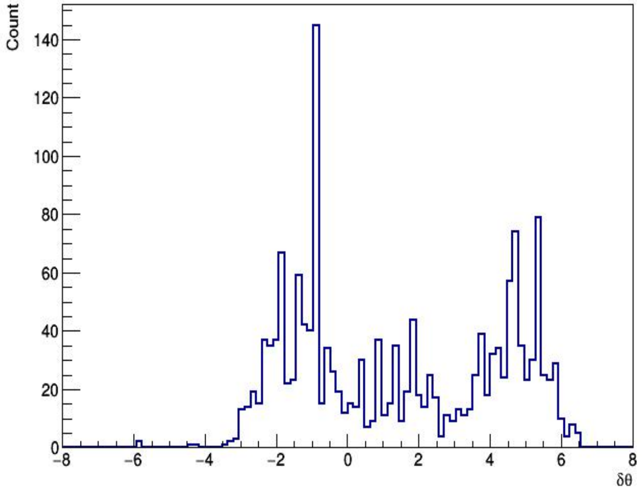


- Multi-band coincidence technique:
  - Effective discriminating power for impulsive signals (wide-band) against CW noise
- 8 surface acoustic wave (SAW) filters are used to divide each channel:
  - Narrow bandwidth as well as steep cut-off
- Multi-channel coincidence technique:
  - Further reduces thermal noise effect
  - Independent in H-pol and V-pol.

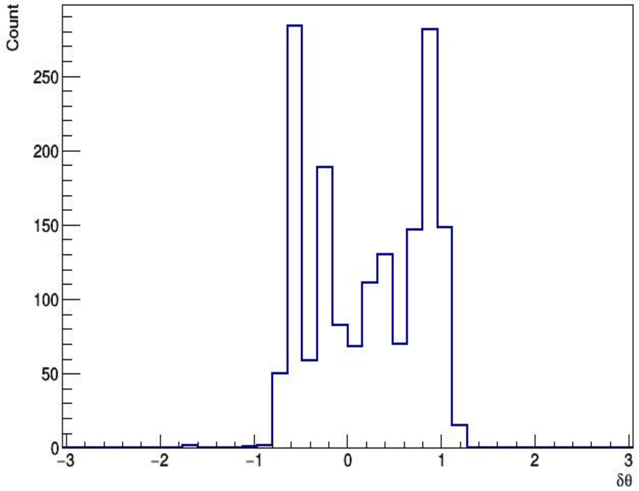
Interference from ground reflected signal

- Angular reconstruction is crucial in data analysis:
  - Primary particle direction;
  - Energy reconstruction;
  - Distinguish up-going and down-going signals;
- Reconstruction performance in low elevation angle is degraded by interference from ground.
- Methods:
  - Raise the height of antenna towers
    => Practically limited
  - Deconvolution of reflection
    => Systematic error: Non-uniform terrain, model-dependent electromagnetic properties of ground
  - Differential method
    => Manage to cancel out response between channels

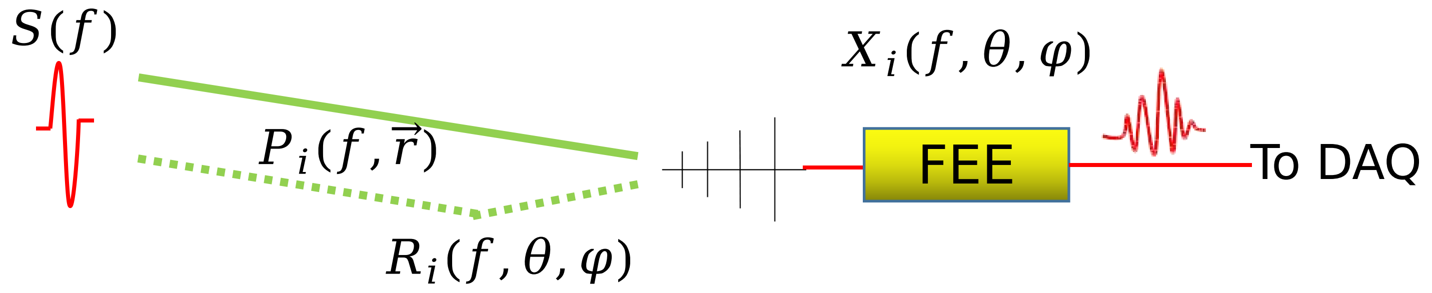
δθ distribution



δφ distribution



Differential method



- The received signal is modeled as:
  $W_i(f,\theta,\varphi) = S(f) * P_i(f,\vec{r}) * R_i(f,\theta,\varphi) * X_i(f,\theta,\varphi) + N_i(f)$
  S: source signal; P_i: phase shift due to propagation; R_i: reflection; X_i: system responses, including antenna, filters, LNA, cables; N_i: noise; i: channel number.
- Define differential response: $\alpha_{ij} = \frac{R_i * X_i}{R_j * X_j}$.
- Apply α_{ij} to W_j: $W'_j = \alpha_{ij} * W_j = S * P_j * R_i * X_i + O(N_j)$, then, W'_j and W_i have common systematic effects ($R_i * X_i$).
- Cross-correlating W'_j and W_i, the common systematic effects are cancelled out.
- Grid search interferometric method to reconstruct the angles.

==> How to obtain α_{ij}?

Obtain α_{ij} by drone-borne pulser

- For each cal-pulser event, we can have:

$$\alpha_{ij}^{m} = \frac{W_i^m}{W_j^m} * \frac{P_j^m}{P_i^m} = \frac{R_i^{m*} X_i^m}{R_j^{m*} X_j^m} + O(N_i^m) + O(N_j^m),$$

m denotes event number.

- α_{ij} is obtained by averaging α_{ij}^{m}.
- All angles scanning cal-pulser with good positioning is needed.

==> Drone-borne cal-pulser system:

- Strong impulse (high SNR)
- DGPS (centimeter-level positioning accuracy)
- Easy control (scan all angles).

For details of drone pulser,please see: C. Kuo et al., PoS(ICRC2021) 283.

Advantages

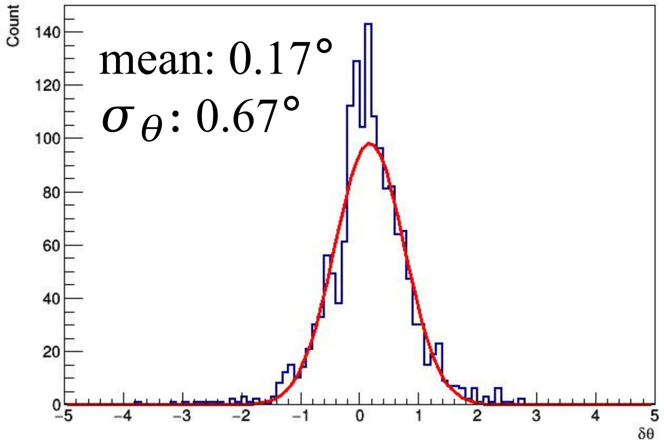
- Software solution:
  - Solve the problem in analysis level, don't need to change hardware part.
- Low systematic error:
  - No assumptions on terrain and ground electromagnetic properties
- Accurate pulser spectrum $S(f)$ is not needed.
- Other system responses are also calibrated.

Angular resolution by differential method

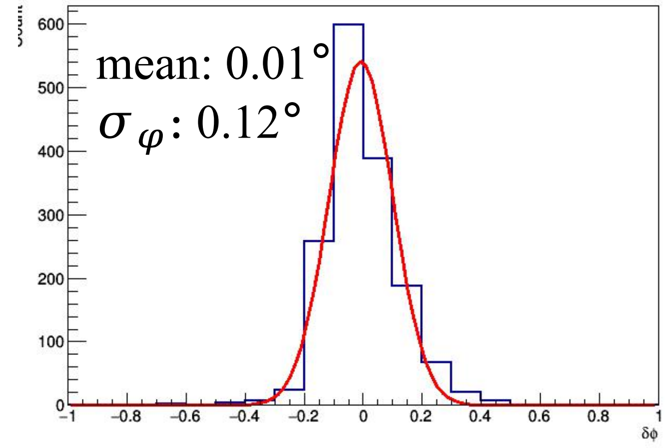
Data set:

- Small angles range around antennas' boresight is scanned for obtaining α_{ij}.
- 1500 cal-pulser events inside scanned range are collected for validation from another flight.

δθ distribution

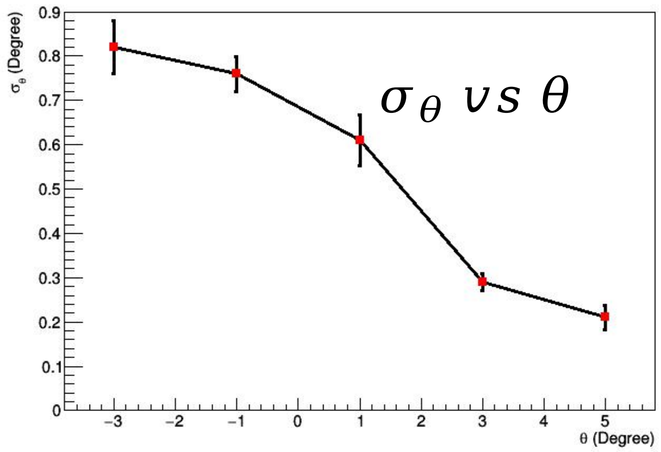


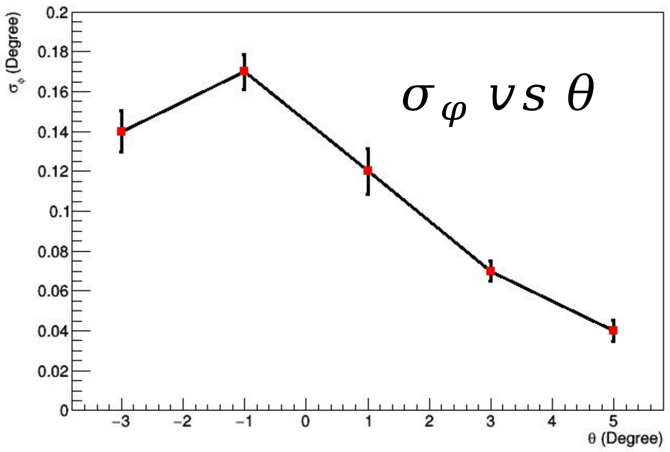
δφ distribution



Result:

- Angular resolution:
  - 0.67° in elevation
  - 0.12° in azimuth
- Even down into -3°, we still have sub-degree resolution.





FYI: Horizon of TAROGE-4 is -0.85°

Summary & Future work

Summary:

1. TAROGE has advantages in: high duty cycle, large acceptance and cost effective instrumentation.
2. New trigger system at TAROGE-4 improves its performance.
3. Differential method for event angular reconstruction is feasible by using drone borne cal-pulser system.
4. Sub-degree level resolution is achieved for near-horizon events.

Future work:

1. Scan all angles in TAROGE-4 field of view.
2. Apply this method to other TAROGE stations.

Thanks for listening!