TAROGE-M: TAROGE @ Mt. Melbourne
Radio Observatory on Antarctic High Mountain for Detecting Near-Horizon Ultra-High Energy Air Showers

Shih-Hao Wang

(for the TAROGE and ARIANNA collaborations)

Department of Physics and Leung Center for Cosmology and Particle Astrophysics , National Taiwan University

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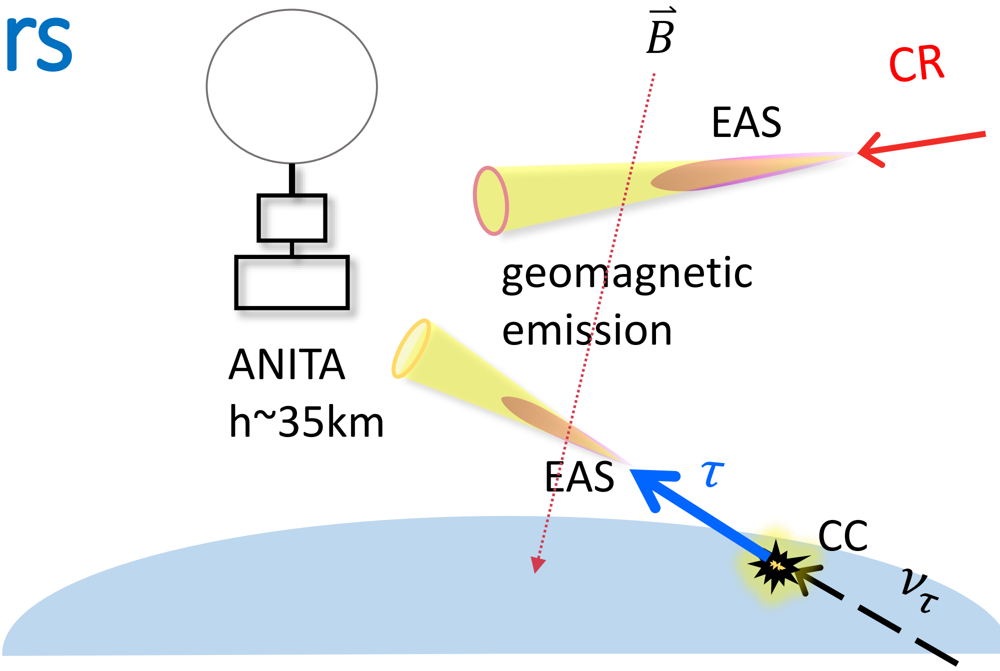
Outline

- motivation & goal
- TAROGE-M station at Mt. Melbourne
  - design and operation summary
- in-situ calibration with
  - Galactic noise
  - drone-borne pulser
- preliminary cosmic-ray search
  - expected area acceptance and angular distribution
  - event selection criteria
- summary & future works

Radio detection of UHE air showers

- Ultra high energy (UHE, E>10^{17} eV) cosmic rays (CR) & neutrinos
  - origin? characteristics?
- Radio pulse detection of air showers by UHECR & Earth-skimming tau neutrinos
  - geomagnetic emission (e^-e^+, $\vec{E} \parallel \vec{v} \times \vec{B}_g$)
  - established technique for CR
- ANITA: efficient detectors for both
  - balloon-borne, ~35 km above Antarctica,
  - 200-1000 MHz band
  - 4 flights: each has live time ~30 day / 3 year
  - dozens of UHECR events



→ found anomalous events of unknown origin?

- upward-going air showers, **E= 0.5-5 EeV**
- 2 events at -27° & -35° elevation angle [2]
- 4 events at ~-6° elevation angle [3]

UHE tau neutrinos from transient sources?
exotic or terrestrial origin?

→ detectors with comparable or better sensitivity are required to confirm the origin

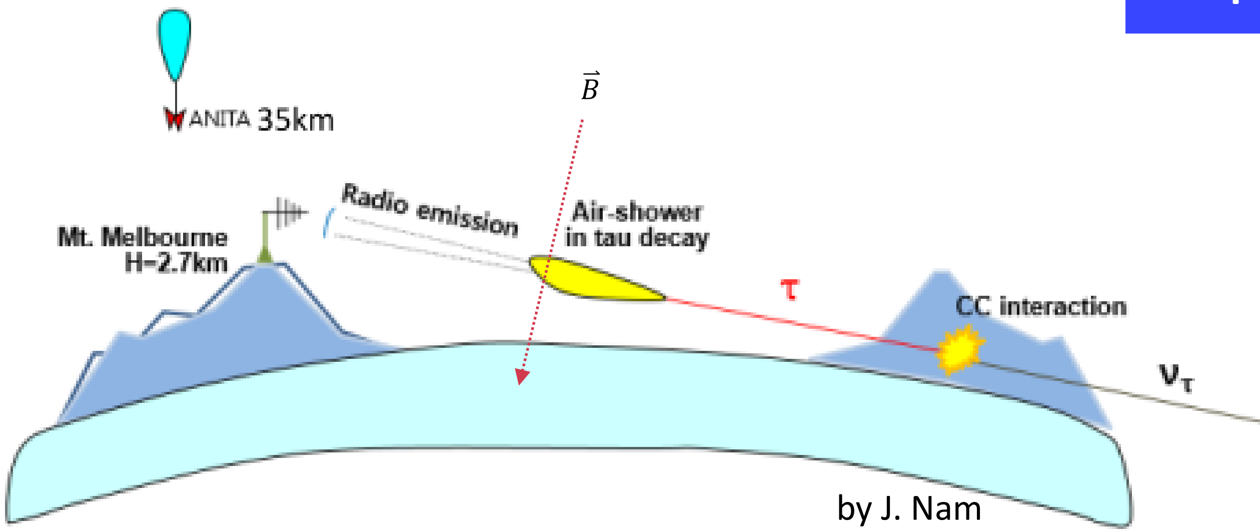
Ref:
[1] F. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1.
[2] P. Gorham et al., Phys. Rev. Lett. 121 (2018) 161102.
[3] P. Gorham et al., Phys. Rev. Lett. 126 (2021) 071103.

Radio detector on high mountain

- advantages:
  - acceptance increase with ~(height)$^{3/2}$
  - high duty cycle (>6 month/year)
  - easier to extend
  - lower energy threshold
- Antarctic mountain: ideal candidate
  - radio quiet
  - strong (>60 μT) and near vertical geomagnetic field

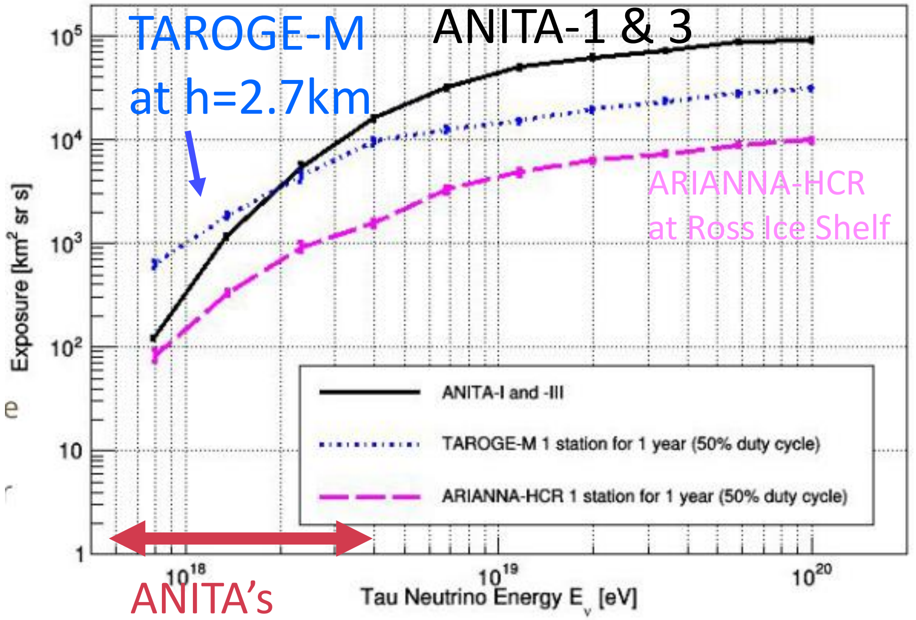
  →sensitive to near-horizontal showers

  →horizontally polarized (Hpol, clear signature)
- detector at ~3 km has comparable υ_τ sensitivity as ANITA's around 1 EeV with a few station x year



by J. Nam

Earth-skimming tau neutrino acceptance

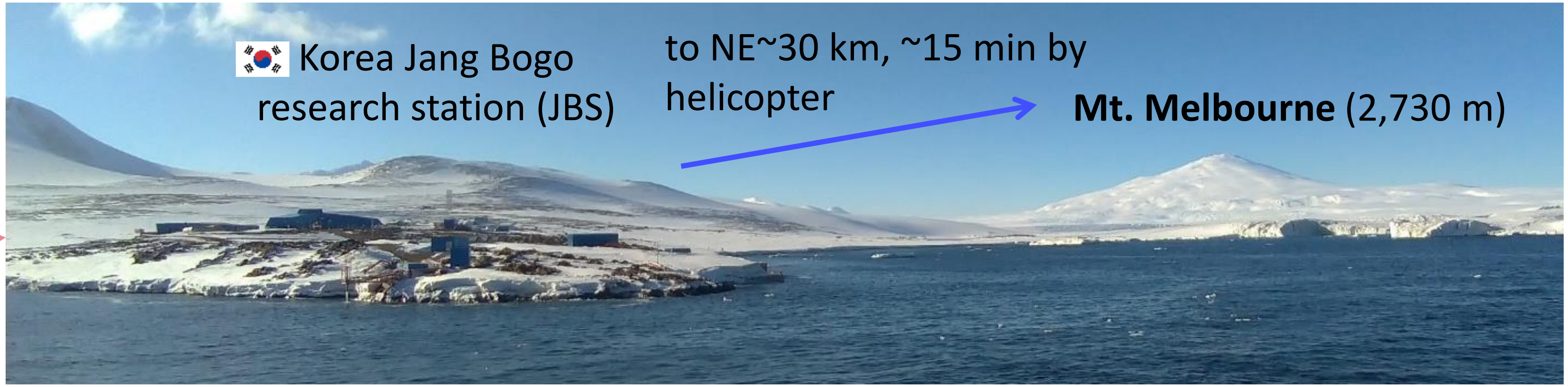


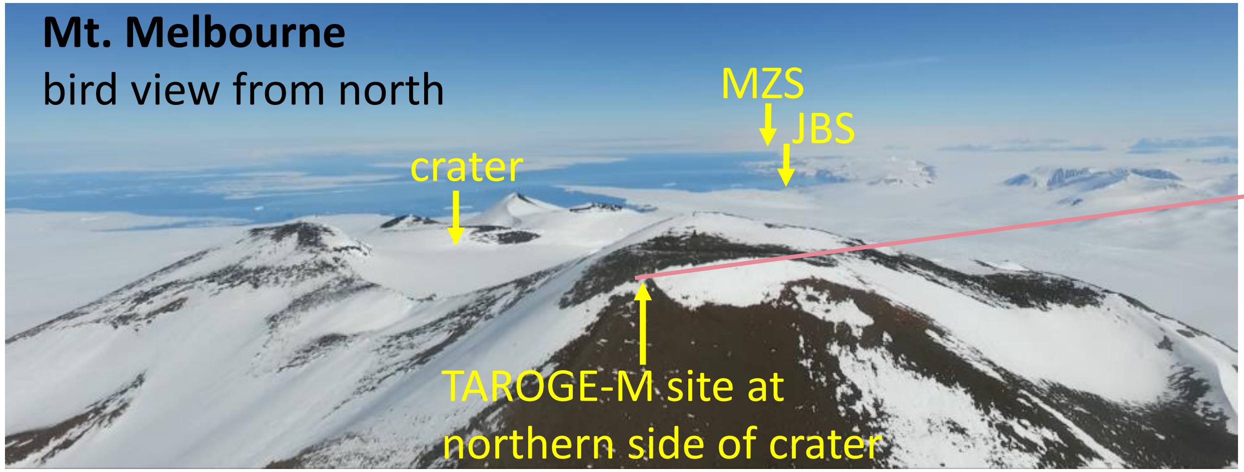
ANITA's anomalous event E_{sh}

J. Nam et al., PoS(ICRC2019)967
C.H. Leung, master thesis, NTU, 2020

[4] J. Nam et al., PoS(ICRC2019)967.
[5] S. Wissel et al., JCAP 11 (2020) 065.

TAROGE at Mt. Melbourne, Antarctica





redeployed and upgraded from the prototype (2019)
2020/01/15 & 25 (4 people x 9 hours)

- 2,730 m high volcano at 74°20′55.88″S,164°41′35.38″
- strong (63μT) & near vertical (-82^{o} inclination) geomagnetic field

Ref: World Magnetic Model 2020; [4] J. Nam et al., PoS(ICRC2019)967

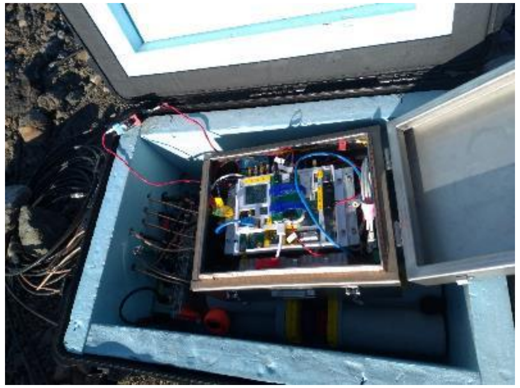
TAROGE-M

design based on experiences of TAROGE & ARIANNA-HCR stations
(Taiwan mountain & Ross Ice Shelf)

8x 30W PV panels
for summer operation (Aug-Apr)

- Rx: 6 LPDA antennas
  - gain ~7 dBi at 180-500 MHz
  - 4 Hpol: // geomagnetic emission
  - 1 Vpol: measure polarization
  - 1 backward Hpol: veto noise behind
  - installed on 3 m towers
  - max baseline ~19 m
- survey antenna position with photogrammetry
  - 3mm accuracy is achieved
  - for event reconstruction

Main system
- in EMI shielding boxes in thermally insulated enclosure
- power consumption < 20 W



Inmarsat antenna
satellite communication

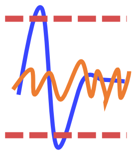
wind turbine
test winter operation

Ref: [4] J. Nam et al., PoS(ICRC2019)967. [7] S. Wang et al., PoS(ICRC2019)462

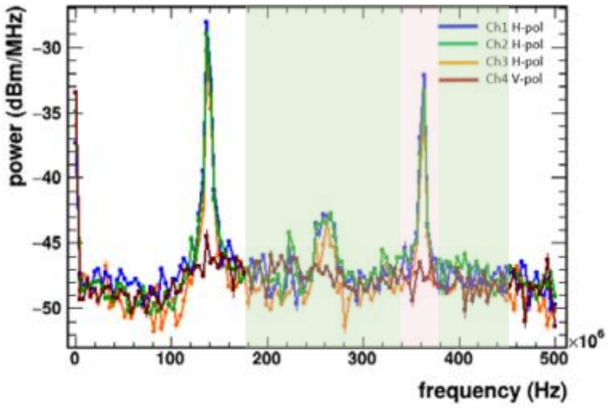
Data acquisition system

- RF front-end module
  - **180-450** MHz bandpass + 360 MHz notch
  - 2-stage low noise amplifiers
  - overall gain ~57 dB

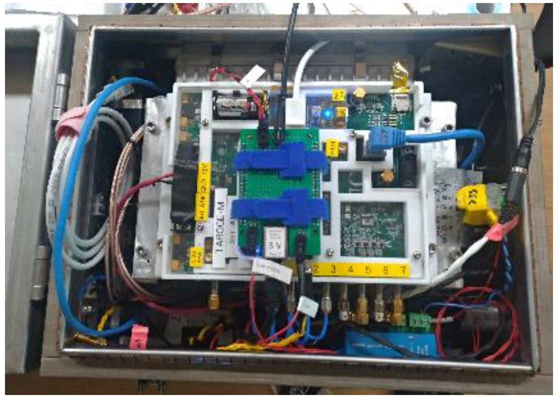
- 8-channel SST board:
  - proven performance in ARIANNA experiment
    at Ross Ice Shelf & South Pole
  - triggering
    - channel lvl: dual-sided threshold in 5 ns
    - station lvl: 3 out of 4 H pol coincidence in 32 ns
    - CW rejection: real-time FFT by Mbed
  - sampling
    - 1Gsample/s, 12-bit ADC, 256 samples



bandwidth based on RF background (2019)



- single-board computer (BeagleBone Black)
  - system monitoring
  - online event filtering for transfer
  - → **prioritizing Hpol pulse events**
- Inmarsat modem
  - remote control & data transfer



[4] J. Nam et al., PoS(ICRC2019)967. [9] A. Anker et al., Advances in Space Research 64 (2019) 2595.
[8] S. Kleinfelder, E. Chiem, and T. Prakash, Proc. of 2014 IEEE NSS/MIC (2014) 1.

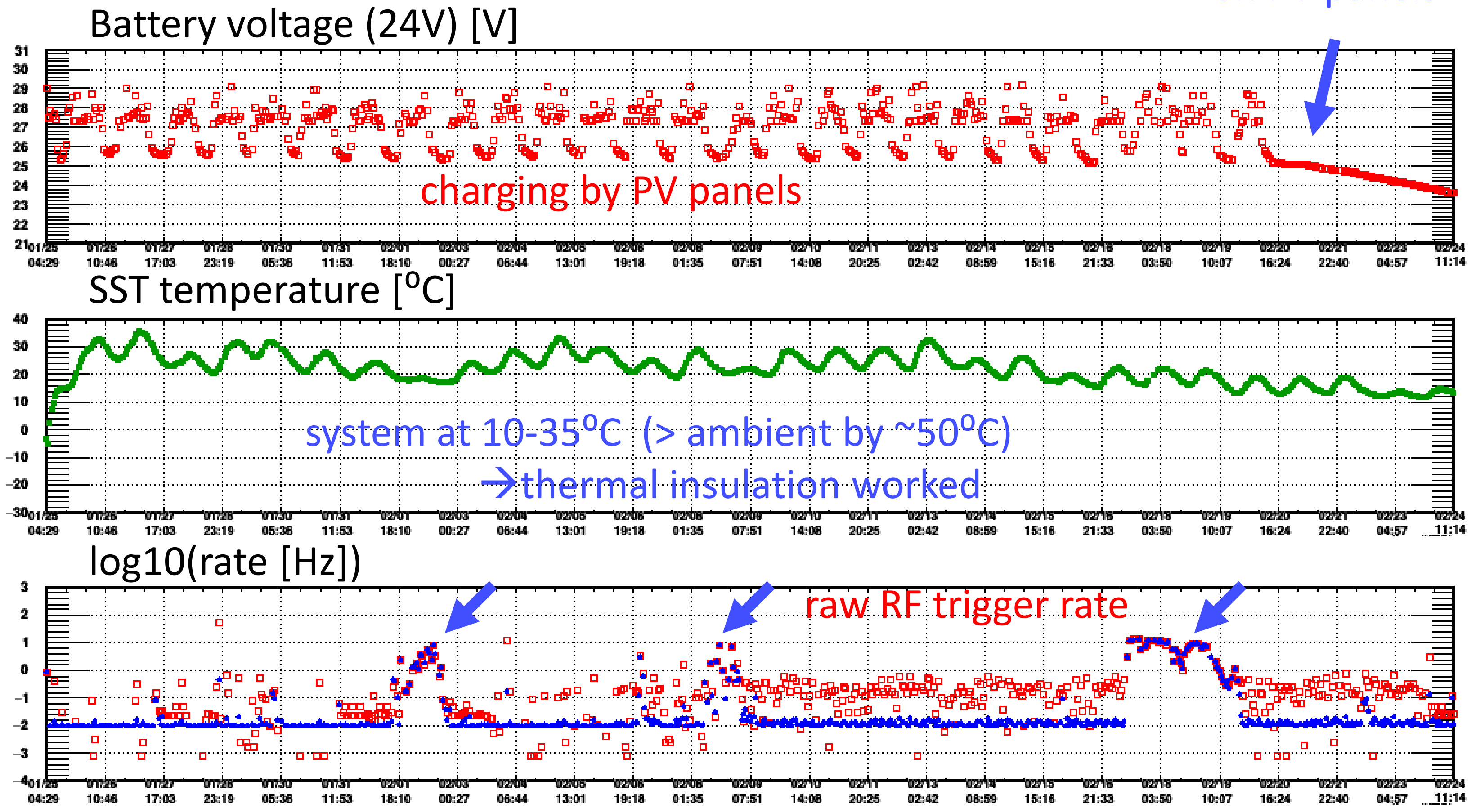
TAROGE-M operation in 2020

- continuous operation during 01/25 and 02/24
- failed at cold start after 02/24

  → DC/DC converter malfunctioning at low temperature
- typical event rate 1-10 mHz
- periods with high event rate 1-10 Hz
  - few hours to days
  - correlated with bad weather
  - similar to “high-wind” events of HCR station

  → high-wind events account for majority of recorded events

02/20 charging stopped, icing on PV panels



time (UTC)

event rate (RF + 10 mHz forced – CW)

Ref: [7] S. Wang et al., PoS(ICRC2019)462; also PoS(ICRC2017)358.

2020-2021 season

- no activity due to COVID-19 pandemic
- inspection in Nov 2020
  - most of hardware are fine over the winter

→ the installation worked in windy & low-temperature environment

- DAQ system sent back to lab for maintenance and full data access

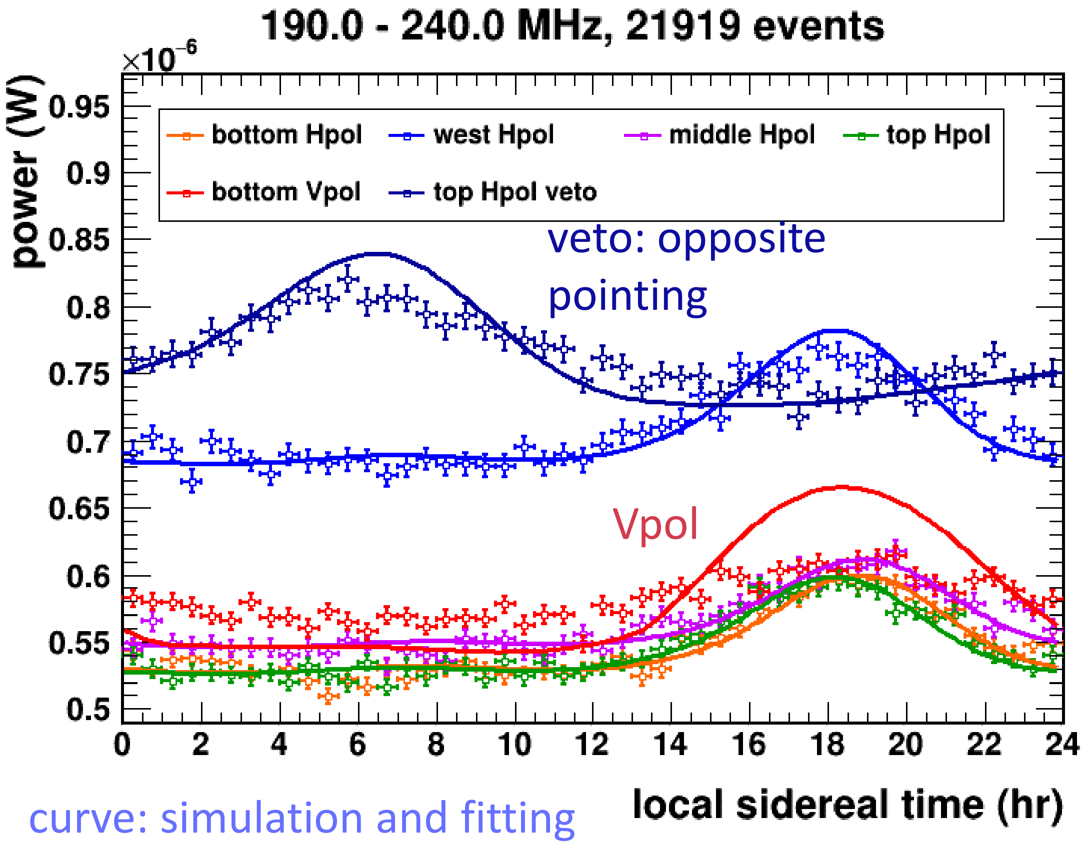
special thanks to on-ice crews of Jang Bogo and Zucchelli stations for help

a few guy wires get loose, a few antenna elements damaged

main system intact

In-situ calibration with Galactic noise variation

Data: 2020/01/25-02/24



curve: simulation and fitting
marker with error bar: observed mean with error of mean

- forced-trigger events every 100 sec to monitor RF background
  - received band power at 190-240 MHz
- Galactic noise modeling following Ref. [12]
  - LFMap: Galactic noise + HFSS: free-space LPDA response + measured RF front-end response
  - fitting receiver noise for constant offset
- overall agreement between observation and simulation
  - Vpol: less variation→ response affected by adjacent Hpol & ground (not modelled)
  - veto: deficient around max → sky partially blocked by hill behind (not simulated)

→ Hpol receiver responses are understood, while Vpol needs improvement

Ref:
[12] S. Barwick et al., Astropar. Phys. 90 (2017) 50.
[13] LFMap, E. Polisensky, Long Wavelength Array (LWA) Memo Series 111.
[14] HFSS 15.0.3 software, Ansoft Corporation.

Drone-borne calibration pulser

- calibrate event reconstruction at near-horizontal directions
  - difficult to access and scan by other means

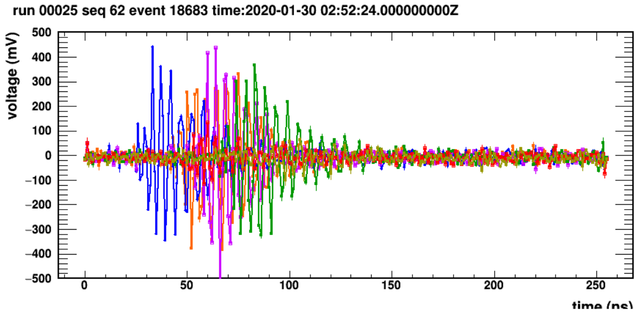
pulser & DGPS module

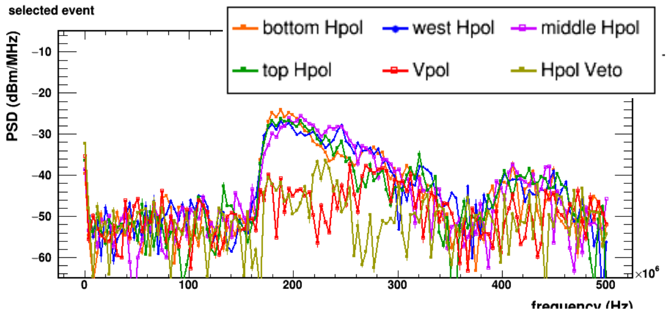
- configurable pulsing strength for stepped power scan
- ~1cm positioning accuracy

DJI M600P drone

biconical Tx antenna

received pulse waveform and power spectrum



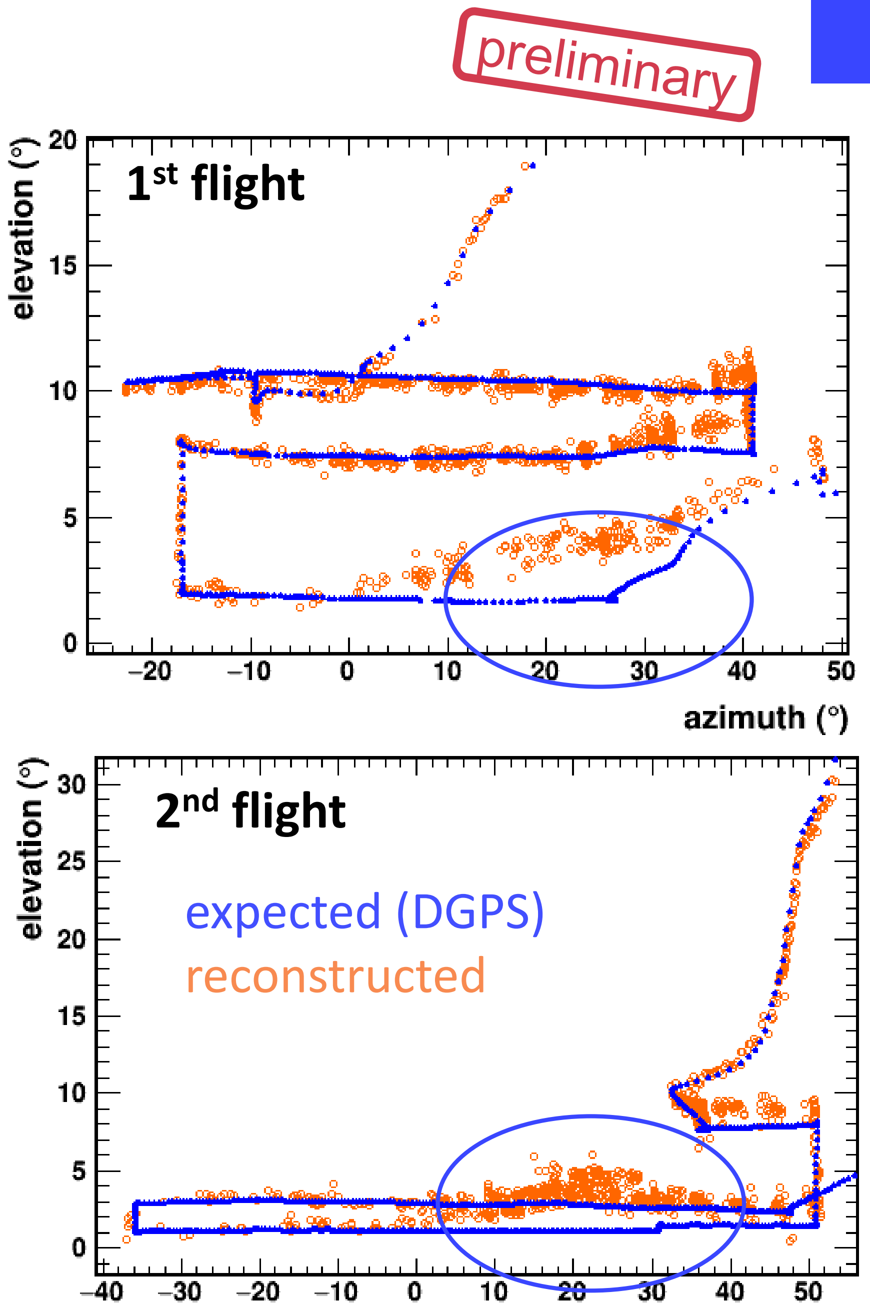


- two flights in 2020/01/30, each ~15 minutes
  - at ~500 m distance, 5 Hz pulsing rate, ~6000 pulses detected
- calibrated the station orientation, phase center of antennas, and internal delay of receiver channels
  - using 10% of events with high SNR inside field of view

the talk about details of drone pulser: C. Kuo et al., PoS(ICRC2021)283.

Reconstruction of drone pulser events

- with interferometric method (similar to Ref. [10])
  - angles → time difference of arrival → waveform cross-correlation
  - Tx & Rx response deconvolved
- mis-reconstructed region with biased elevation (azimuth 10°-35°, elevation < 2°)
  - reflection from the ground and objects nearby
  - → the response can be mapped and subtracted by further drone pulser (Ref [6])
- angular resolution: 0.2° in azimuth, 0.3° in elevation is obtained



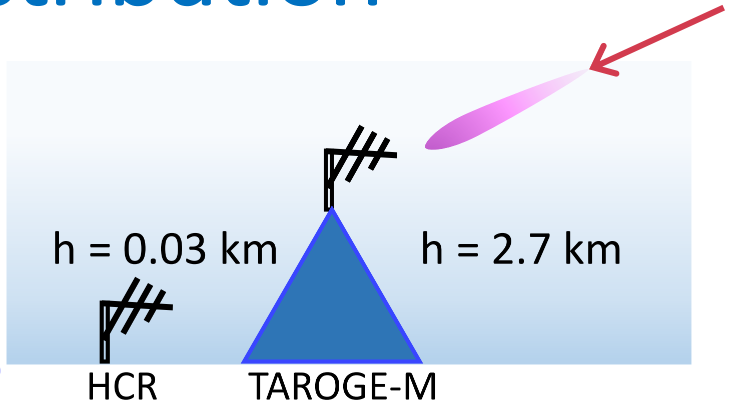
0° elevation: horizontal
0° azimuth: geographic north, + to west

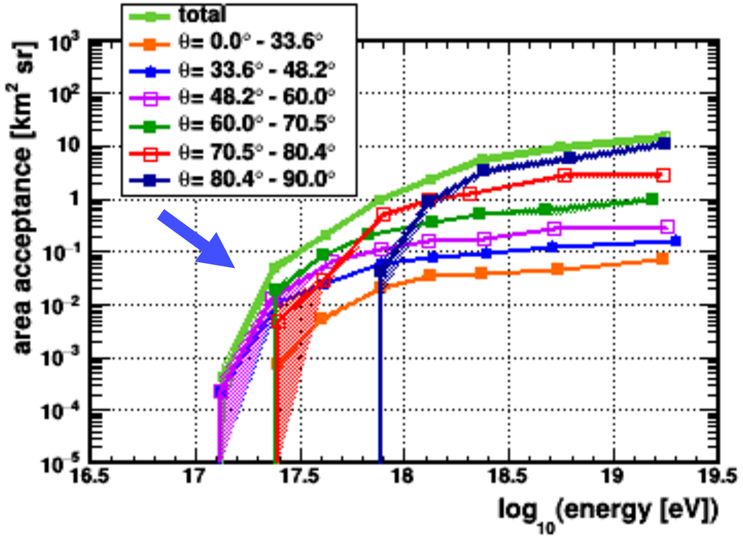
Ref.: [6] Y. Chen et al., PoS(ICRC2021)263. (talk)
[10] A. Romero-Wolf et al., Astropar. Phys. 60 (2015) 72.

preliminary

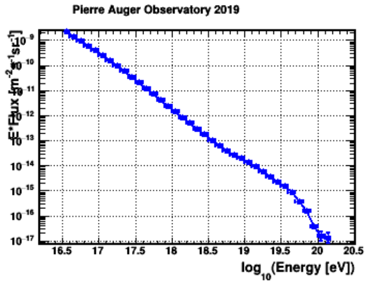
Cosmic-ray acceptance and angular distribution

- detection simulation modified from HCR's [7]
  - use ~2000 CoREAS showers for HCR's as approximation
  - receiver response + SST trigger simulation
- energy threshold at ~300 PeV
- most sensitive to inclined cosmic rays at $\theta = 60^o \sim 85^o$
- event rate: 0.57/day, 17 events in 30 days



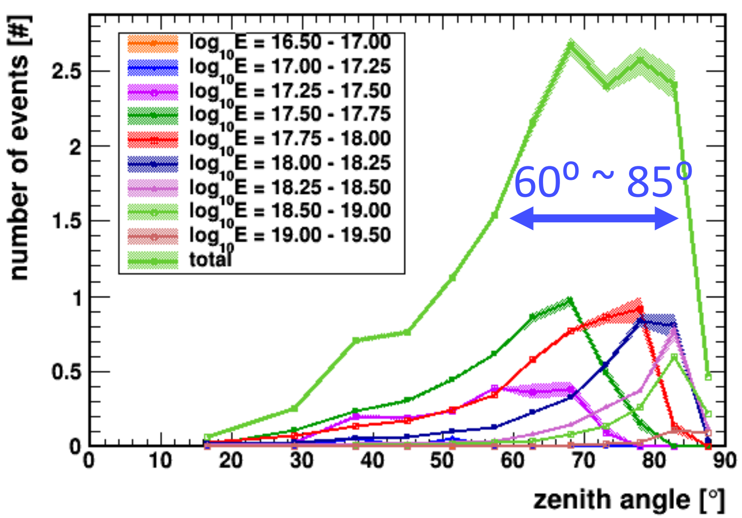


CR flux:
Auger 2019



trigger threshold: 60 mV (~4σ)
3-out-of-4 Hpol coincidence

Auger CR spectrum, live time 30.00 days: 17.1 events



Ref:
[12] S. Barwick et al., Astropar. Phys. 90 (2017) 50.
[7] S. Wang et al., PoS(ICRC2019)462
[17] Auger, PoS(ICRC2019)450
[16] CoREAS, T. Huege, M. Ludwig, and C. James, 2013

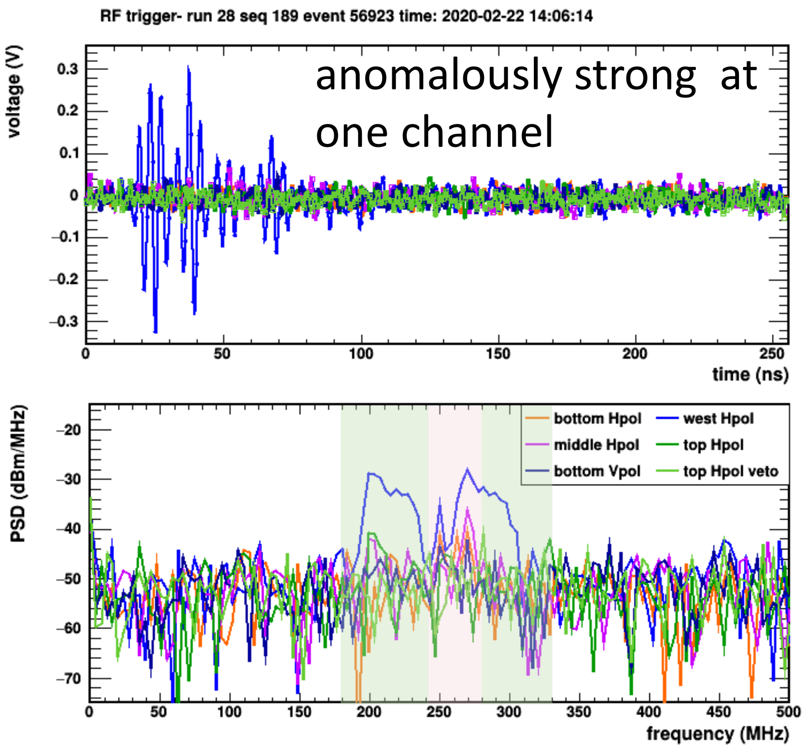
Ultra-high energy cosmic-ray events are expected in TAROGE-M data preliminary

Cosmic-ray event selection criteria

CR is / has
- Hpol dominated
- comparable power &
- similar waveform btw Hpol
- rare

- preliminary CR search in 30-day data
  - 1,257,122 RF-trigger events
  - majority: high-wind events
  - empirically set cut, to be optimized
- online event filtering:
  - define lower passband power (LPB) at [180-240] MHz & [280-330] MHz
  - Hpol to Vpol power ratio > 3.6 dB
  - high-wind rejection
    - channel similarity: max to min Hpol LPB ratio < 7.5 dB
  - Hpol / veto LBP ratio > 1dB
- offline analysis: reconstruction cut
  - avg correlation coefficient > 0.7
  - from front directions
  - temporal clustering cut: no other selected events in $\pm$600 s

high-wind event example



CR candidates

preliminary

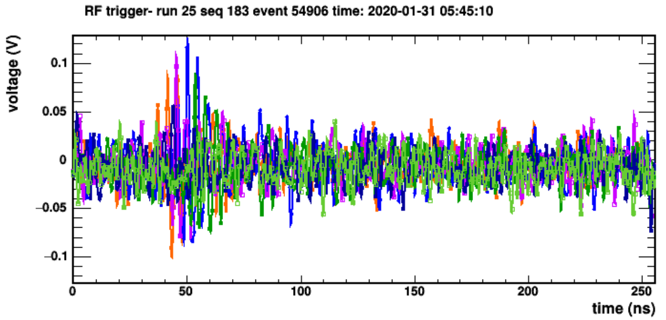
- 5 candidate events were identified
  - more events at inclined angles as expected

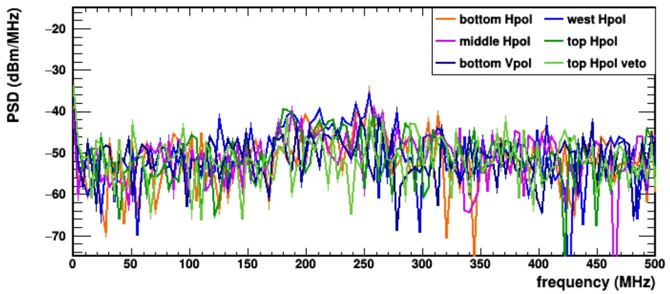
→ TAROGE-M is able to detect UHE air showers

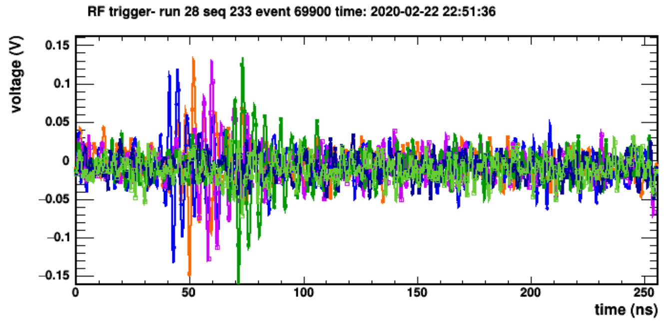
run	event	timestamp (UTC)	avg. x-cor coefficient	azimuth (°)	zenith (°)	H/V power ratio
25	54906	2020/01/31 05:45:10	0.81	−62.2	25.5	2.4
26	50916	2020/02/07 17:11:37	0.88	46.7	66.6	6.4
26	68712	2020/02/08 04:36:31	0.84	−14.8	42.7	4.7
26	244803	2020/02/10 20:33:35	0.80	14.8	78.5	3.3
28	69900	2020/02/22 22:51:36	0.86	6.1	49.7	4.8

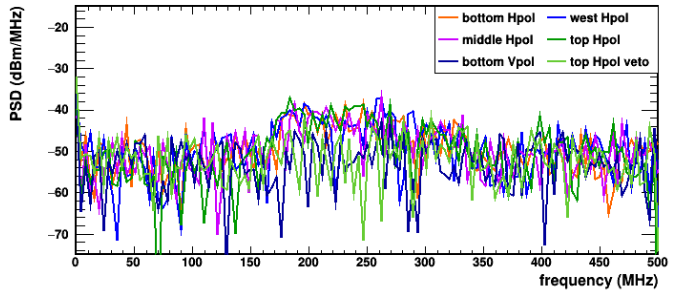
- lower than expected number (5 vs 17)

→ improved analysis cut and simulation in progress

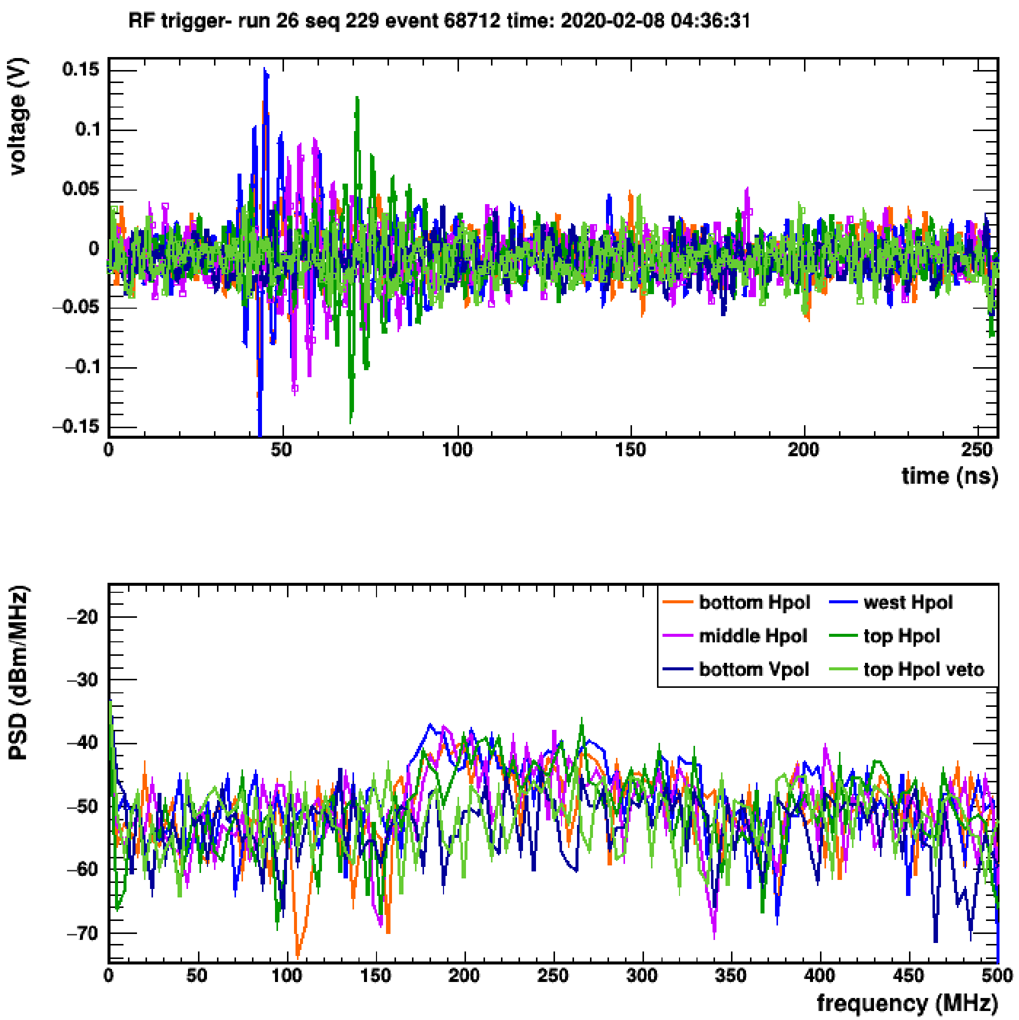


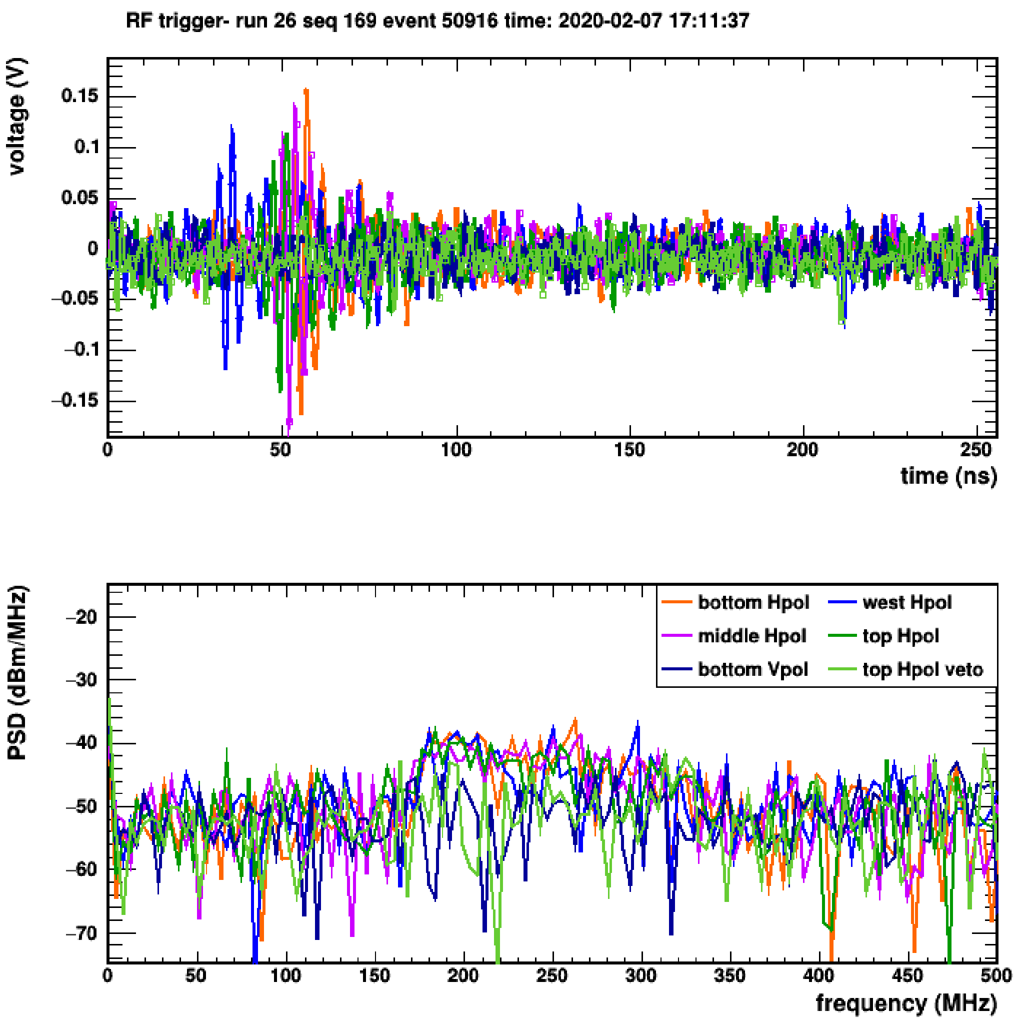






CR candidates





Summary

- high-altitude radio detector for UHE cosmic rays, tau neutrino and ANITA's anomalous events
- TAROGE-M station atop Mt. Melbourne
  - proof of concept in Antarctic mountain environment
  - ~30 day operation before power interruption in 2020
- Galactic noise observed
  - receiver calibrated
- drone cal. pulser at near-horizontal directions
  - 0.3^o angular resolution
- CR candidates found → able to detect EeV air showers

Future works

- fulfil long-term operation in summer
  - replace problematic power parts with military-grade ones
- add two more Hpol for better angular resolution
- calibration below horizon
  - further scan with drone pulser (0^o to -10^o)
  - install ground-based pulser: continuous monitoring
- build more stations
  - other candidate sites at MtM

Thank you !

at the top of Mt. Melbourne
2019/12/24, SH Wang