# HiCal3: Calibration of PUEO

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# Payload for Ultrahigh Energy Observations (PUEO)

- PUEO flew for 23 days from Dec 20, 2025 to Jan 12, 2026
  - 96 horn antennas (main instrument)
  - 8 low freq antennas deployed during ascent
- Calibration by HiCal3 and GroundCal
- Groundcal: 3 locations pulsing at 1 Hz
  - Long Duration Balloon Facility (LDB)
  - Taylor Dome
  - S+200
- HiCal3: 2 payloads that followed PUEO in flight

Figure: PUEO carried out to launch pad.

# Why HiCal3?

- Companion payloads follow PUEO throughout flight
- Direct signals and reflections off the ice
  - surface roughness
  - index of refraction
- Polarity measurement of direct and reflected signals
- Follow up to HiCal1 (ANITA 3) and HiCal2 (ANITA 4)
  - Higher fidelity pulsers
  - Controlled Hpol and Vpol tied to GPS second
  - larger range to PUEO

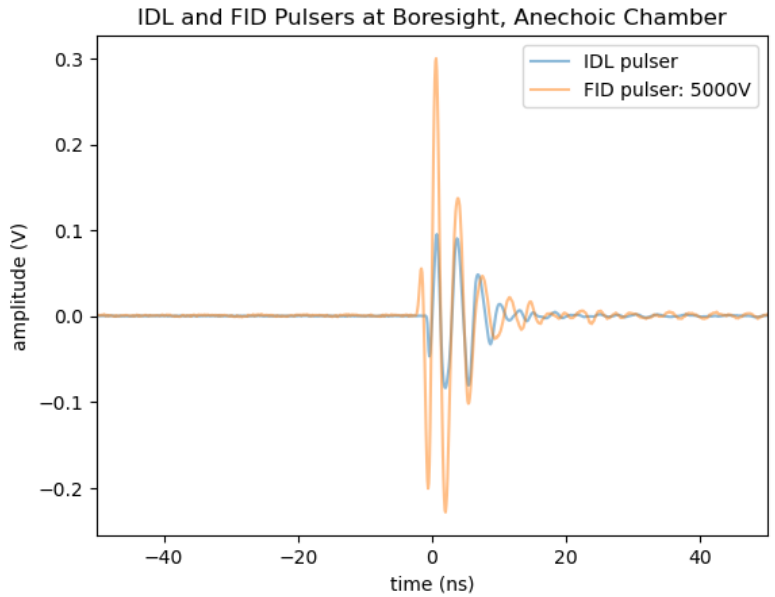
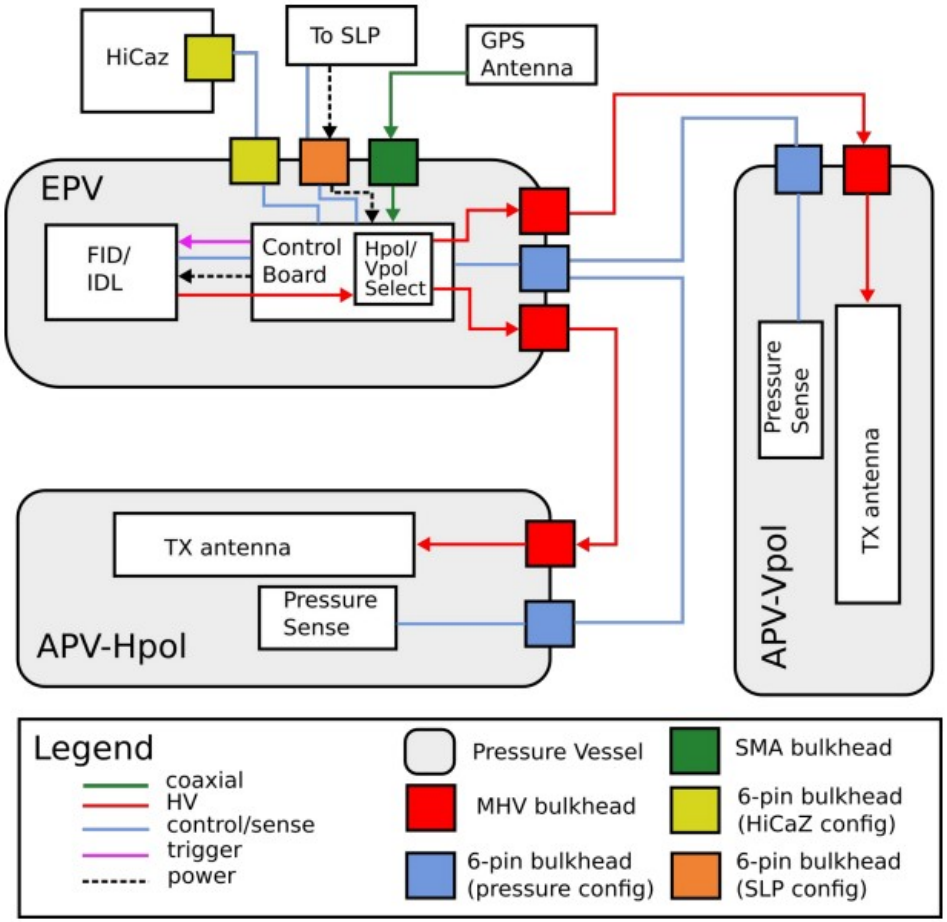



Figure: HiCal3 dipole Tx to Toyon Rx recorded in anechoic chamber, overlayed for HiCal3 FID and IDL pulsers.

# HiCal3 Design

- Electronics Pressure Vessel (EPV)
  - pulser
  - control board
  - HiCaz: records azimuth based on solar position
  - GPS
- RF chain splits to Hpol and Vpol
- Antenna pressure vessel (APV)
  - HiCal3 Dipole Antenna
  - Physically oriented to Hpol, Vpol



# HiCal3 Payloads, A and B

- EPV pulser
  - HiCal3A: FID pulser - commercial
  - HiCal3B: IDL pulser - custom made at KU
- High Voltage RF chain pressurized during flight
- Larger EPV top
  - pulser
  - control board
- APV (middle, bottom)
  - HiCal dipole antenna
  - Hpol and Vpol orientation

Figure: HiCal3 A payload staging shortly before launch.

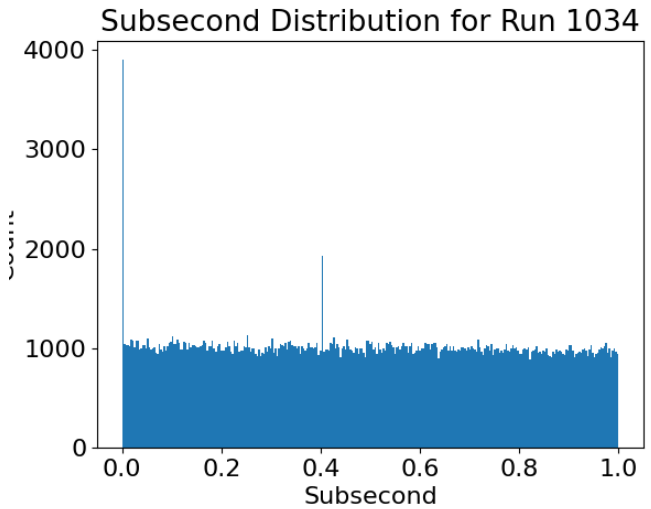
# HiCal3 payload flights

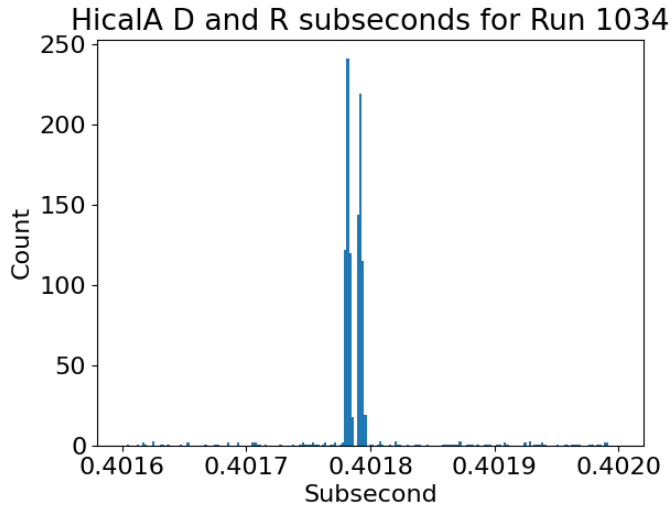
- HiCal 3B: launch Dec 21, 6:31 am (NZDT), flight time 5 days 2 hours
  - Initial trajectory away from PUEO due to winds, eventually corrected
  - $\approx$ 650 km to PUEO by run 892
  - Balloon leak led to early termination
- HiCal 3A: launch Dec 21, 8:11am (NZDT), flight time 12 days 0 hours
  - Within 250 - 600 km of PUEO for entire flight
  - Solar power issue limited uptime and pulse telemetry.
- Both pulsers seen by PUEO during flight

Figure: HiCal A launch

# HiCal3 events seen by PUEO

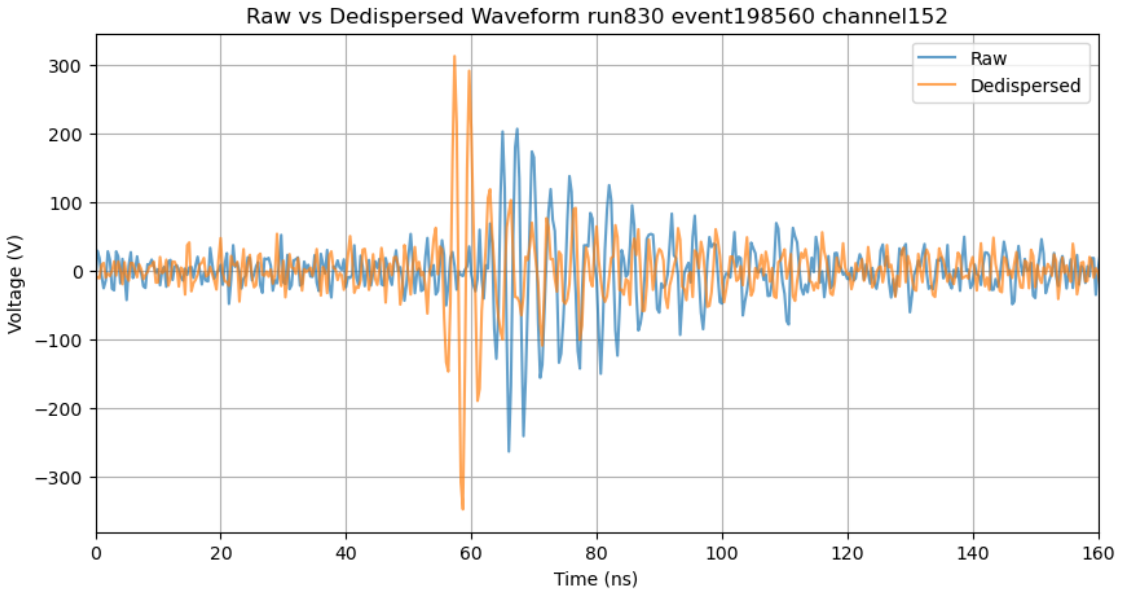
- HiCal3 events determined by timing
- HiCal pulse time controlled by GPS timestamp
  - 3A: 0.4s
  - 3B: 0.6s
- GPS coordinates and pulse time matched to PUEO triggered events
- later confirmed by reconstruction to HiCal GPS location
- Example PUEO subsecond trigger times shown for run during HiCal3 A pulsing
- Run 1034: $\approx 22\mu$s between direct, reflected

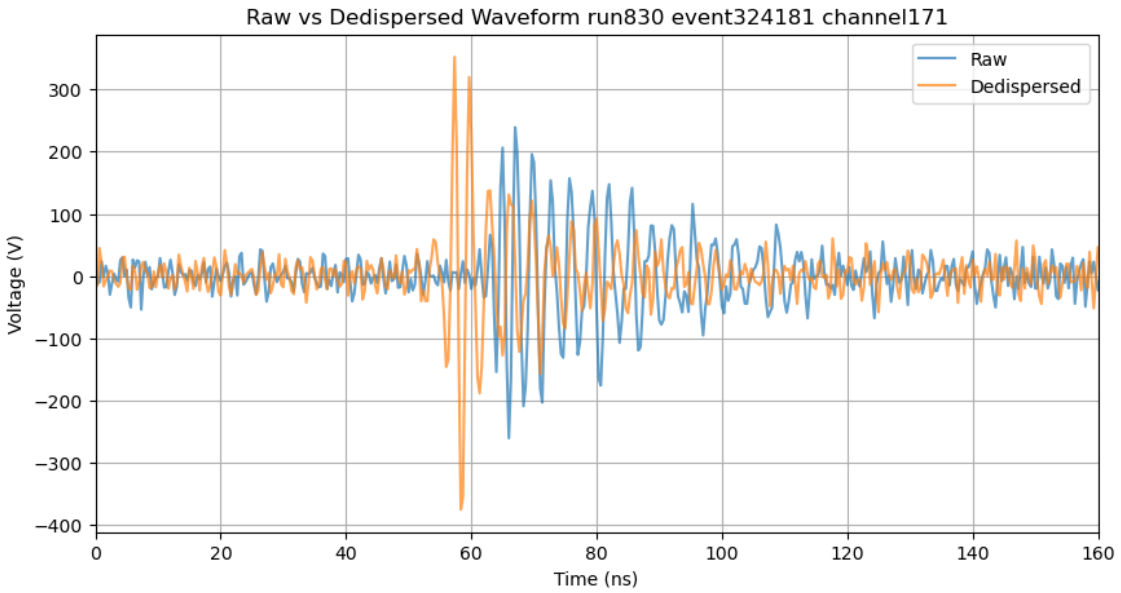


# Dedispersion of HiCal event waveforms

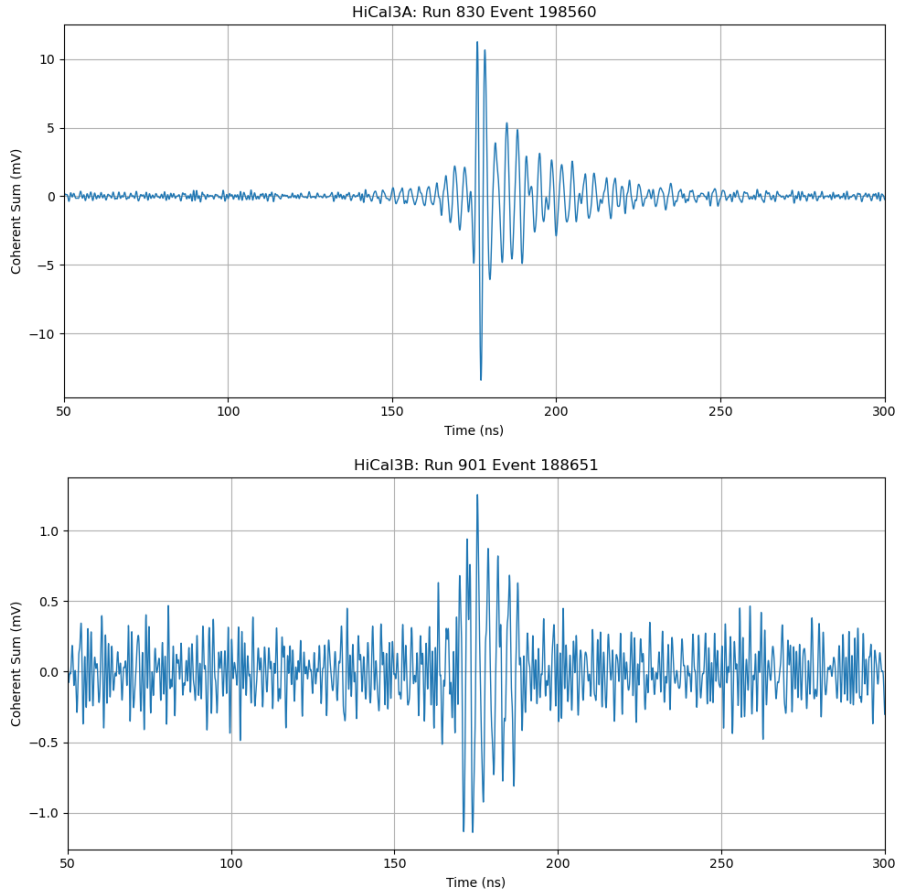
- FFT of PUEO impulse response used
- Adjust phasors of signal in frequency domain to sharpen signal
- no adjustment in gain/amplitude
- Single channel raw waveforms overlayed with dedispersed (right)



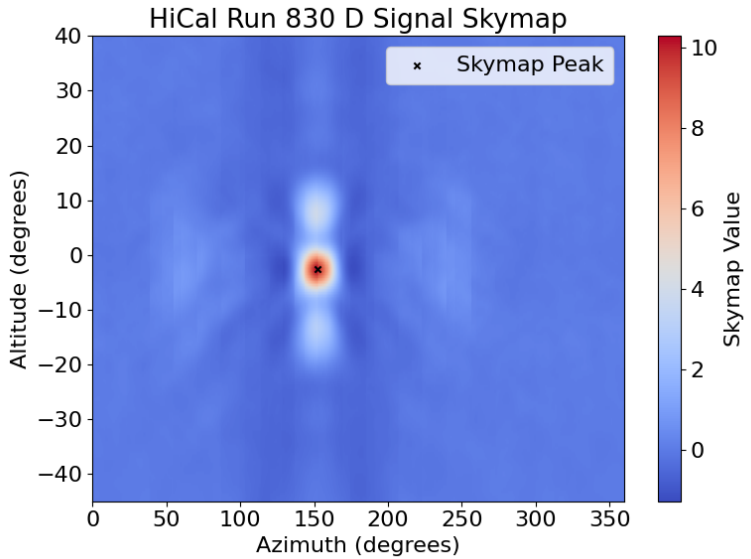
# Reconstruction and coherently summed waveforms

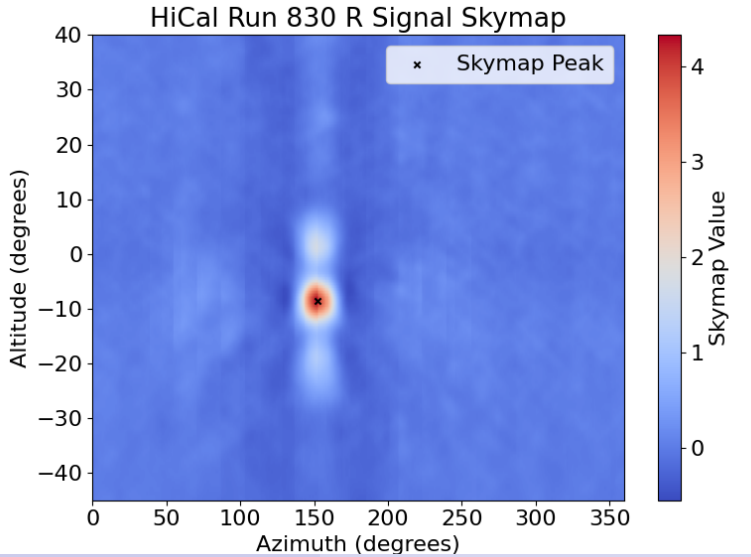
- Signal reconstruction using arrival time on PUEO antennas
  - Cable delays applied
  - Antenna position calibration in progress
- Peak reconstruction location used to produce coherently summed waveform
  - Channels selected around reconstruction location
  - timing overlay determined by reconstructed location
  - dedispersed waveforms summed



# Direct (D) and Reflected (R) event pair reconstruction

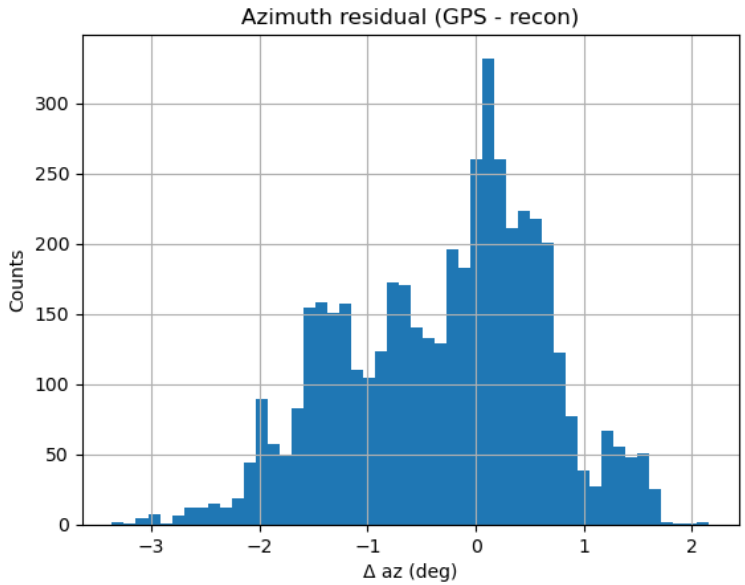
- Direct and Reflected event pairs determined by timing
  - PUEO event matched to expected timing delay between direct and reflected paths
  - often consecutive PUEO events
- D and R pairs confirmed using reconstruction
- Reconstruct to same azimuth, altitude offset by reflection off surface
- Currently D and R event pairs only identified for HiCal3 A

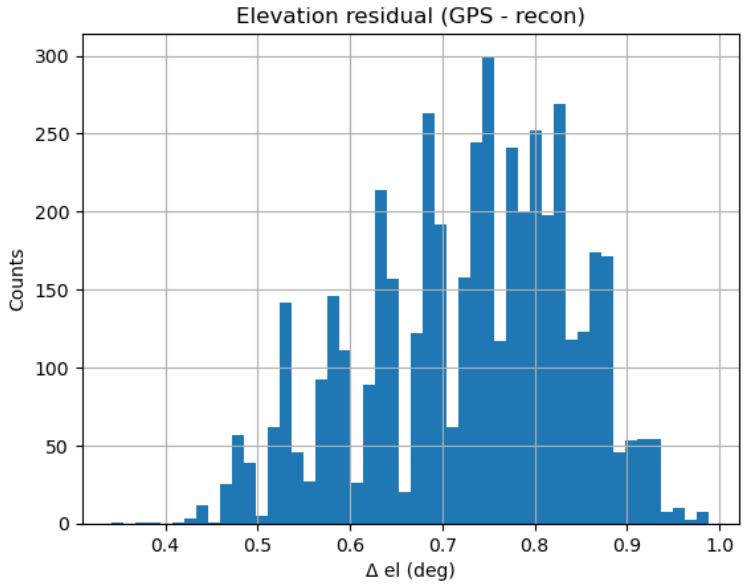


# HiCal3 event reconstruction: pointing resolution

- Early pointing resolution using **uncalibrated** antenna phase centers
- Expected factor 2-4 improvement post calibration
- GPS pointing determined via PUEO navigation
  - heading
  - pitch
  - roll
  - HiCal and PUEO gps coordinates
- Histogram of residuals, gps pointing - event reconstruction



# HiCal polarity analysis

- Compare dedispersed, coherently summed waveforms to HiCal event template
  - Signed cross correlation to template
  - negative correlation indicates polarity flip
- 6073 direct Vpol events analyzed
  - 0/6073 incorrectly reconstructed polarity
- **Further steps:**
- Hpol events incorporating PUEO to HiCal GPS pointing and HiCal's azimuth determined by HiCaz
- Direct and Reflected event pairs
  - signed correlation between D and R event pairs

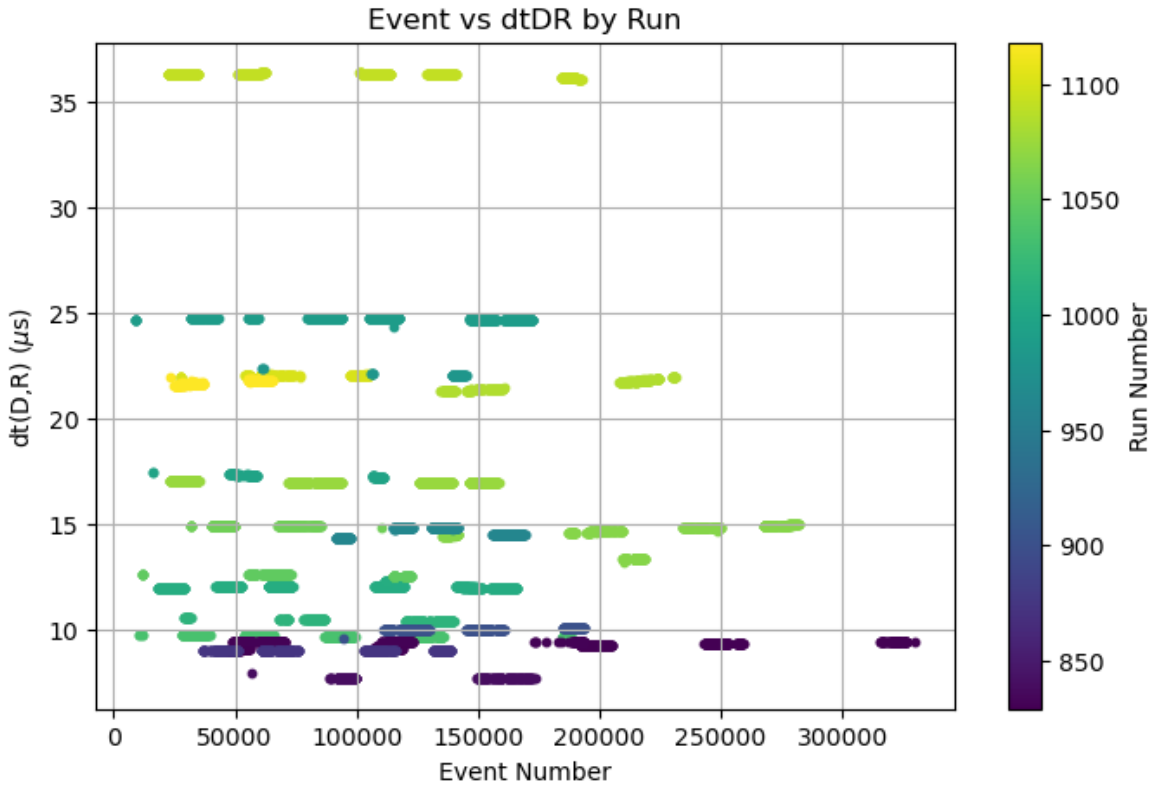
# Summary and future plans

- Signal seen by PUEO from both HiCal3 A and B payloads
- HiCal Events identified using GPS timing and coordinates
  - confirmed via reconstruction
- Antenna calibration
- Ongoing polarity study
- Further HiCal D and R waveform studies planned for study of polar surface ice properties

Backup Slides

# HiCal run subseconds - distinct D/R peaks

- Direct (D) and reflected (R) event pairs taken from subsecond cut
- Only found event pairs for HiCal A



# HiCal3 Instrument Data

- HiCal3 instrument saved information for each pulse during flight
  - GPS timestamp
  - lat, lon, altitude
  - temperature, pressure inside pressure vessels
  - HiCaz values for azimuthal calculation

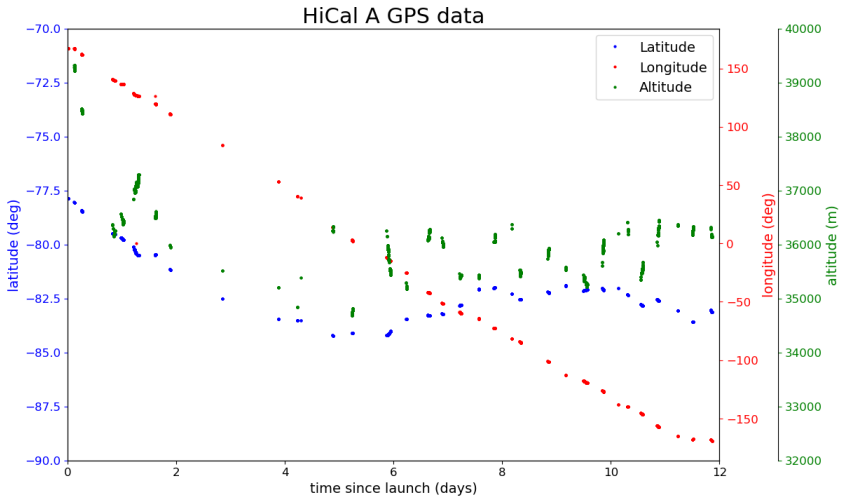



Figure: HiCal A latitude, longitude, and altitude throughout flight

# HiCal Polarity: Signed cross correlation

- Reflected events expected to invert relative to direct event pair, resulting in negative sign correlation
- Same sign correlation would indicate polarity inversion
- Signed correlation of HiCal direct events compared to template
- Noise injected into event waveform to find SNR where correlation falls off
- Reflected events for high SNR HiCal A event pairs have CSW snr up to 20.