Utilisation of Aircraft for Calibration of the ICEBEAR Radar

University of Saskatchewan

B. Pitzel[1], G. C. Hussey[1], D. R. Huyghebaert[2, 1], M. F. Ivarsen[1], R. Rohel[1], D. Galeschuk[1], S. Marei[1]

[1]ISAS, Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK, Canada

[2]Leibniz Institute of Atmospheric Physics, Radar Remote Sensing, Kühlungsborn, Germany

CEDAR Workshop 2025

22–27 June, 2025 Des Moines, Iowa

IRRI Date: 25 June Email: **brian.pitzel@usask.ca**

The ICEBEAR Radar

I C E B E A R

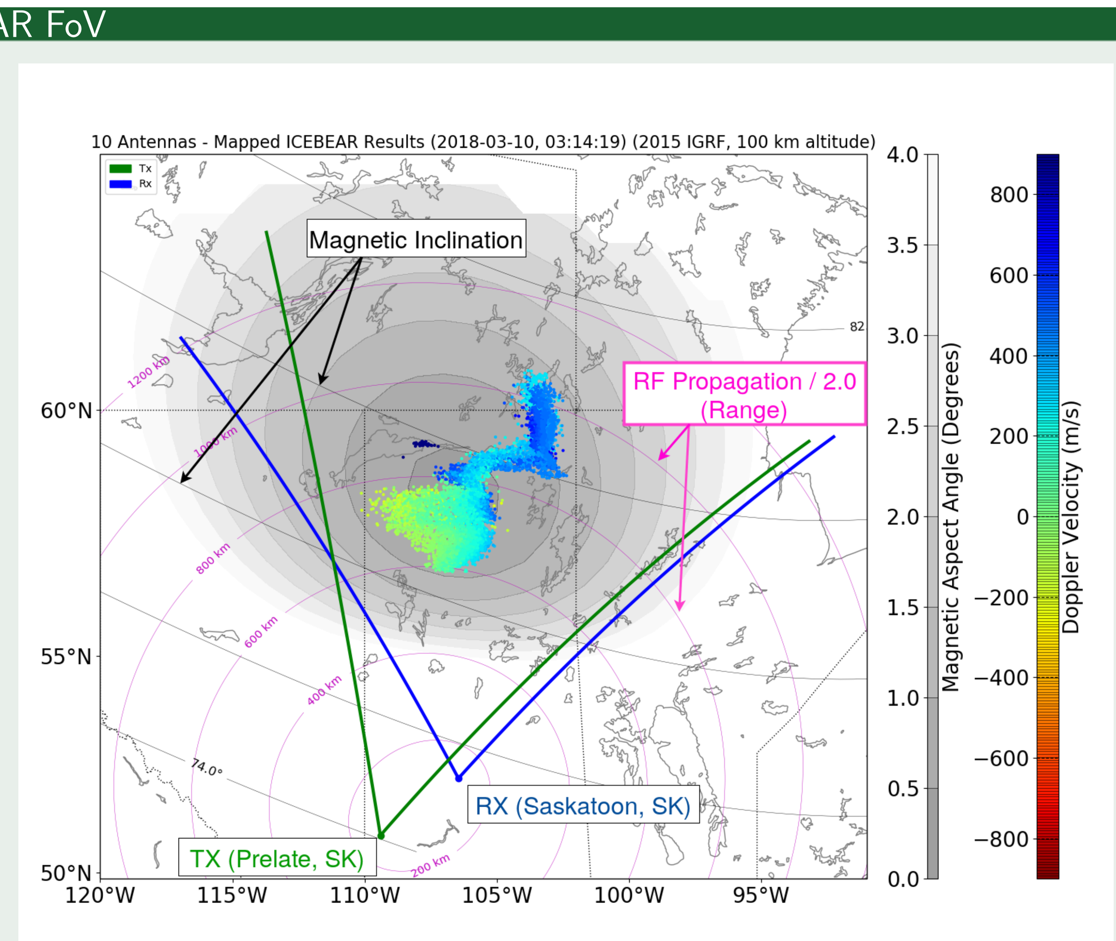
ICEBEAR ⇒ Ionospheric Continuous wave E-region Bistatic Experimental Auroral Radar

- 50 MHz VHF E-region bistatic radar experiment
  - 49.5 MHz centre freq. with 100 kHz bandwidth
- Fully digital
  - digital waveform generation
  - digital reception
  - GNURadio/UHD for hardware interface and control
  - DigitalRF for data storage
- Independent signal/RF paths for all antennas
  - allows for *processing* and/or *re-processing* of data to enhance different characteristics
- Horizon viewing (typically up to 45° elevation, can go higher)

Technical Details

- Tx: 10 channels (antennas) / linear array (only 2–4 needed)
  - ↪ ~800 W (max.) continuous wave (CW) each with self- and remote-monitoring
- Rx: 10 channels (antennas) / T-configuration (July 2019)
- Core: Ettus Research X300 digital transceivers (Tx/Rx)
- Signal: pseudo-random phase modulation on CW carrier
- Timing: phase coherence between Tx and Rx (from accurate GPS timing)
- **Simultaneous** high temporal and spatial resolutions
  - ↪ easily changed/configured
- FoV: 'imaging' or 'mapping' field-of-view (FoV)
  - ↪ Nominal FoV down boresight (north)
  - ↪ Capable of imaging behind Rx
- Resolution nominal/typical:
  - temporal: 1.0 s
  - range/azimuth/elevation: 1.5 km
  - Doppler: 10 Hz (~30 m/s)

ICEBEAR FoV



Baseline Visibility

- Main interferometric ICEBEAR data product
- Cross-correlation of signals on antenna pair
- Normalised visibility between antennas 1 and 2 from Farley et al. (1981):

$$V_{12}(r,\omega) = \frac{\left\langle V_1(r,\omega)V_2^*(r,\omega)\right\rangle}{\left\langle |V_1(r,\omega)|^2\right\rangle^{1/2}\left\langle |V_2(r,\omega)|^2\right\rangle^{1/2}}$$

$\arg(V_{12}(r,\omega))$: phase difference between antenna pair
$|V_{12}(r,\omega)|$: coherence of visibility
$V_{1,2}(r,\omega)$: complex voltage sample from antenna 1, 2
r: range gate
ω: Doppler frequency
$\langle\cdot\rangle$: ensemble (temporal) average

Spherical Wave Harmonic Transform

- Performed for each range-Doppler bin
- Synthesis: 45 unique baseline visibilities $V_{ij}(k_0)$ ⇒ 1 sky brightness map $B(\Omega_k)$

$$B(\Omega_k) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} Y_{lm}(\Omega_k)\frac{k_0^2}{2\pi^2(-j)^l}\sum_{ij=1}^{Q} V_{ij}(k_0)J_l(k_0 r_i)Y_{lm}^*(\Omega_i)$$

l and m : spherical harmonic degree and order
$Y_{lm}(\Omega_k)$ and $Y_{lm}^*(\Omega_i)$: spherical harmonic functions
k_0 : wave number
$B(\Omega_k)$: brightness distribution in the sky
Q : number of baselines

$V_i(k_0)$: measured visibilities
r_i : distance between antennas for a given baseline
Ω_k : angular components of k (pointing direction)
Ω_i : angular components of baselines
$J_l(k_0 r_i)$: spherical Bessel function of the first kind

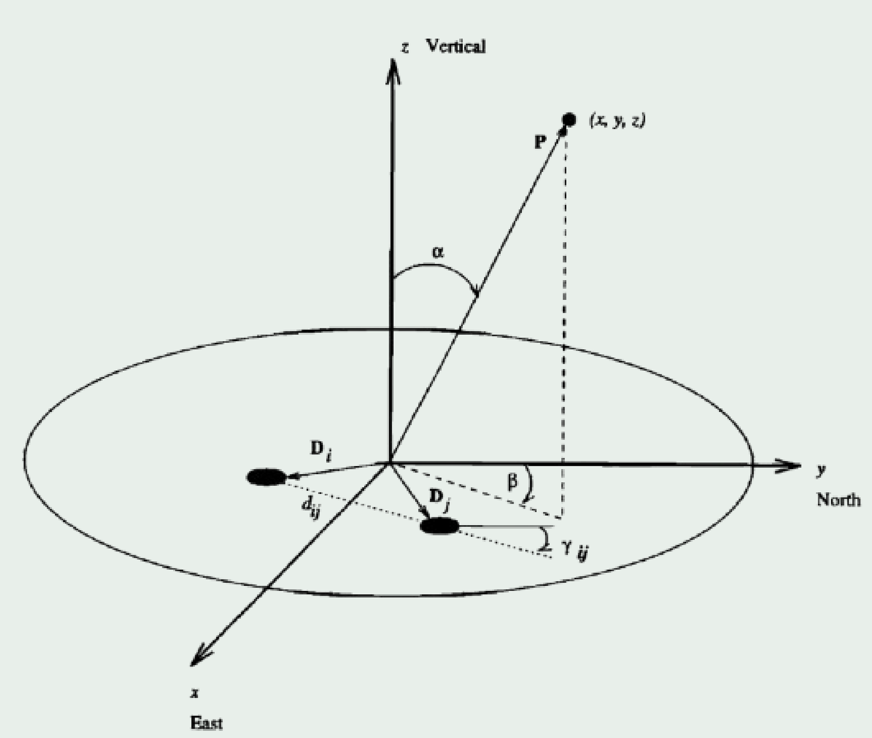
- Interferometric process: **Visibility phase is crucial!**

Measured Visibility Phase

- Phase of point source contains expected phase and error

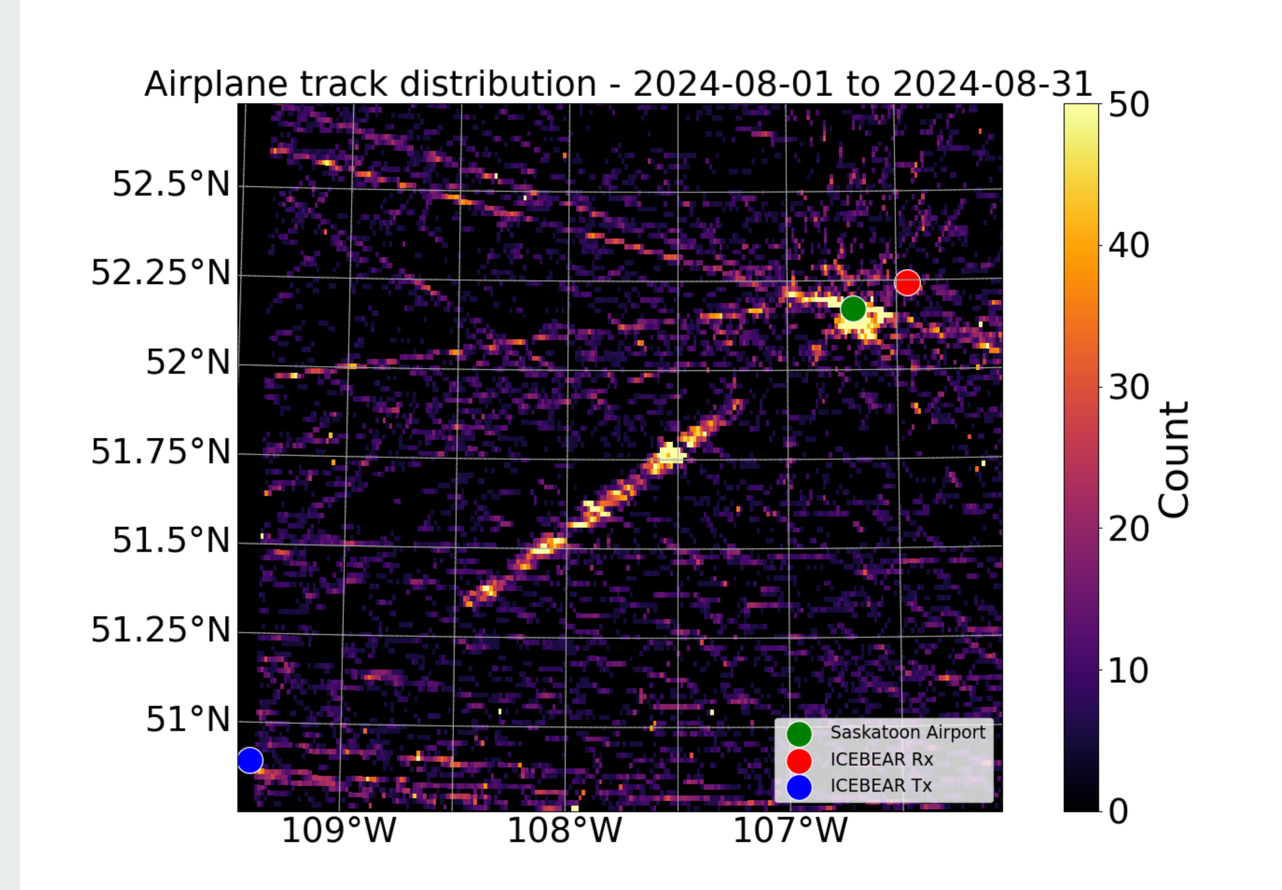
$$\arg(V_{ij}) = \phi_{ij} = k(\mathbf{D_i} - \mathbf{D_j})\cdot\mathbf{n} + \Delta\phi_{ij}$$

ϕ_{ij} : phase difference between antenna pair
$k(\mathbf{D_i} - \mathbf{D_j})\cdot\mathbf{n}$: expected visibility phase
k : radar wave number
$\mathbf{D}$: vector from origin to antenna
$\mathbf{n}$: unit vector from origin to airplane
$\Delta\phi_{ij}$: error in phase measurement
Average over many echoes : $\overline{\Delta\phi_{ij}} = \frac{1}{N}\sum^N \Delta\phi_{ij}$

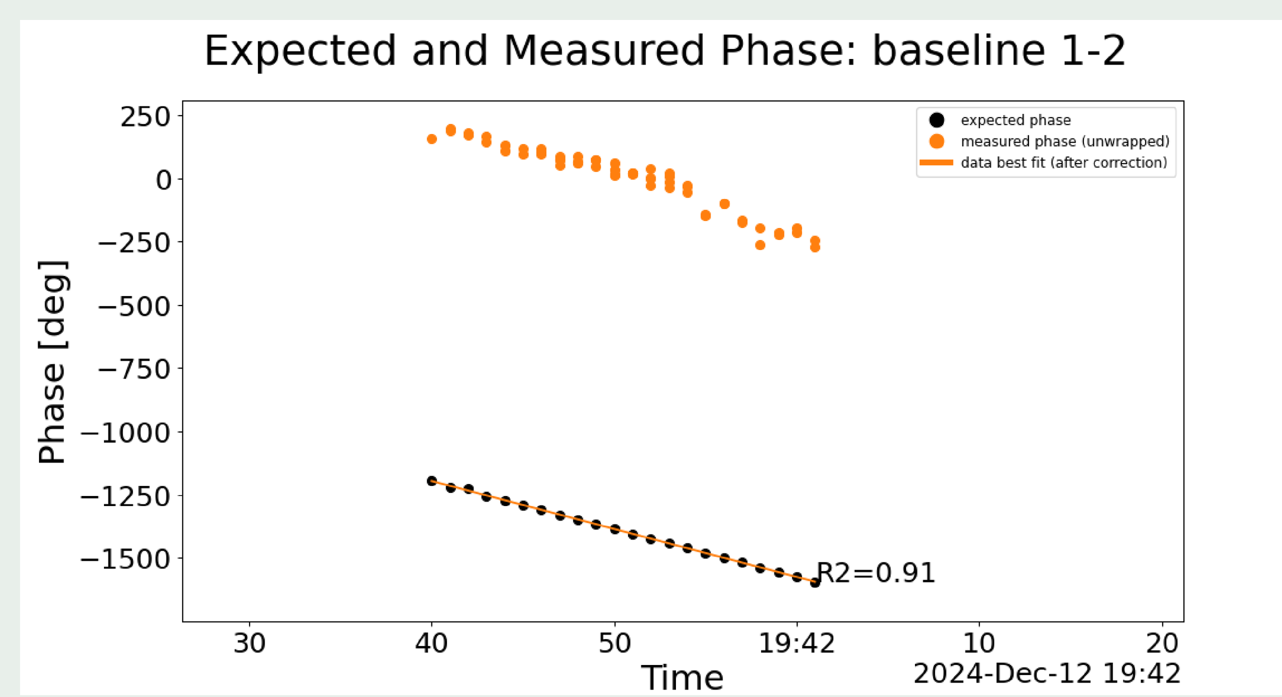


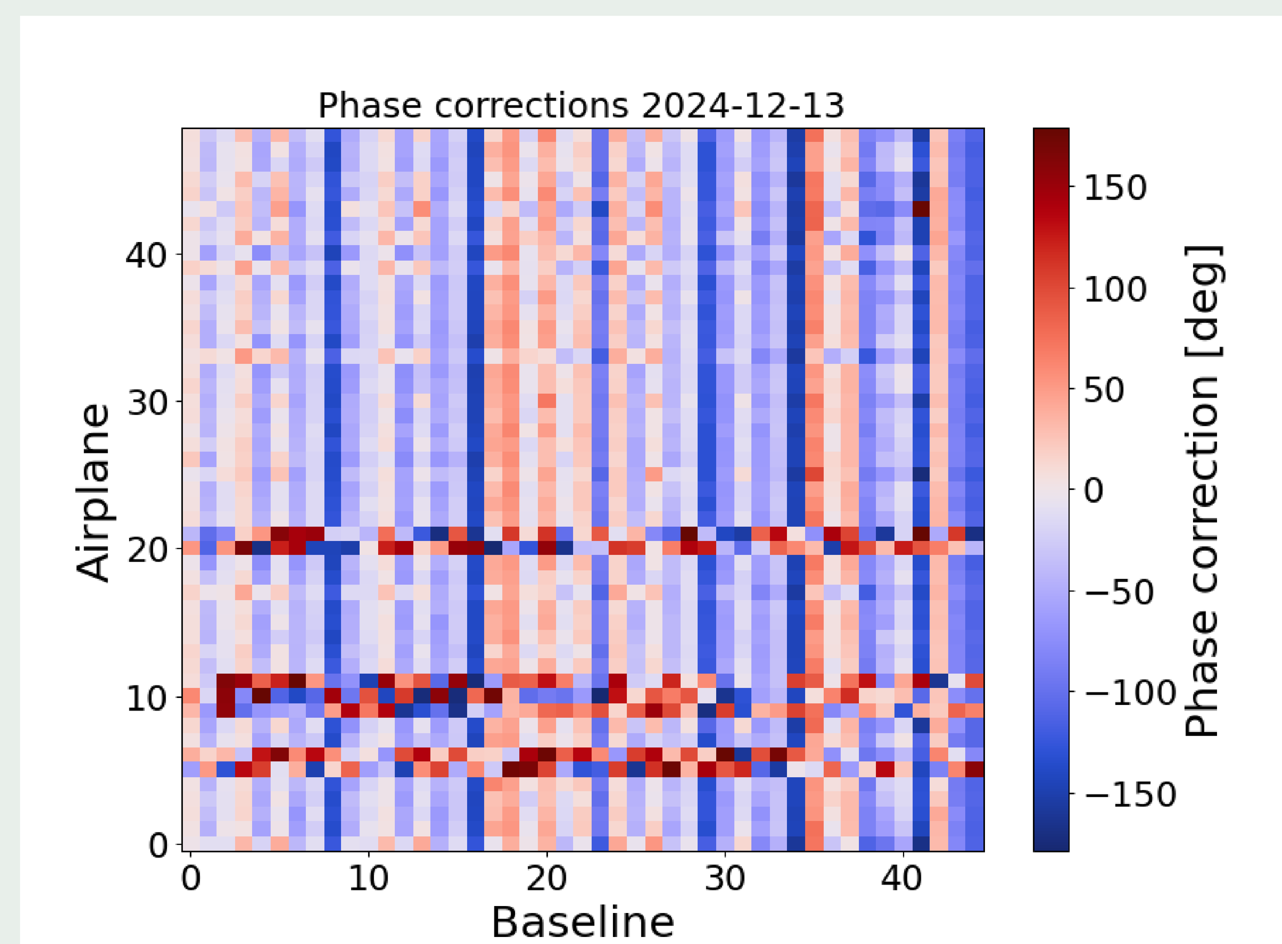
Palmer et al. (1996)

Airplane Echoes

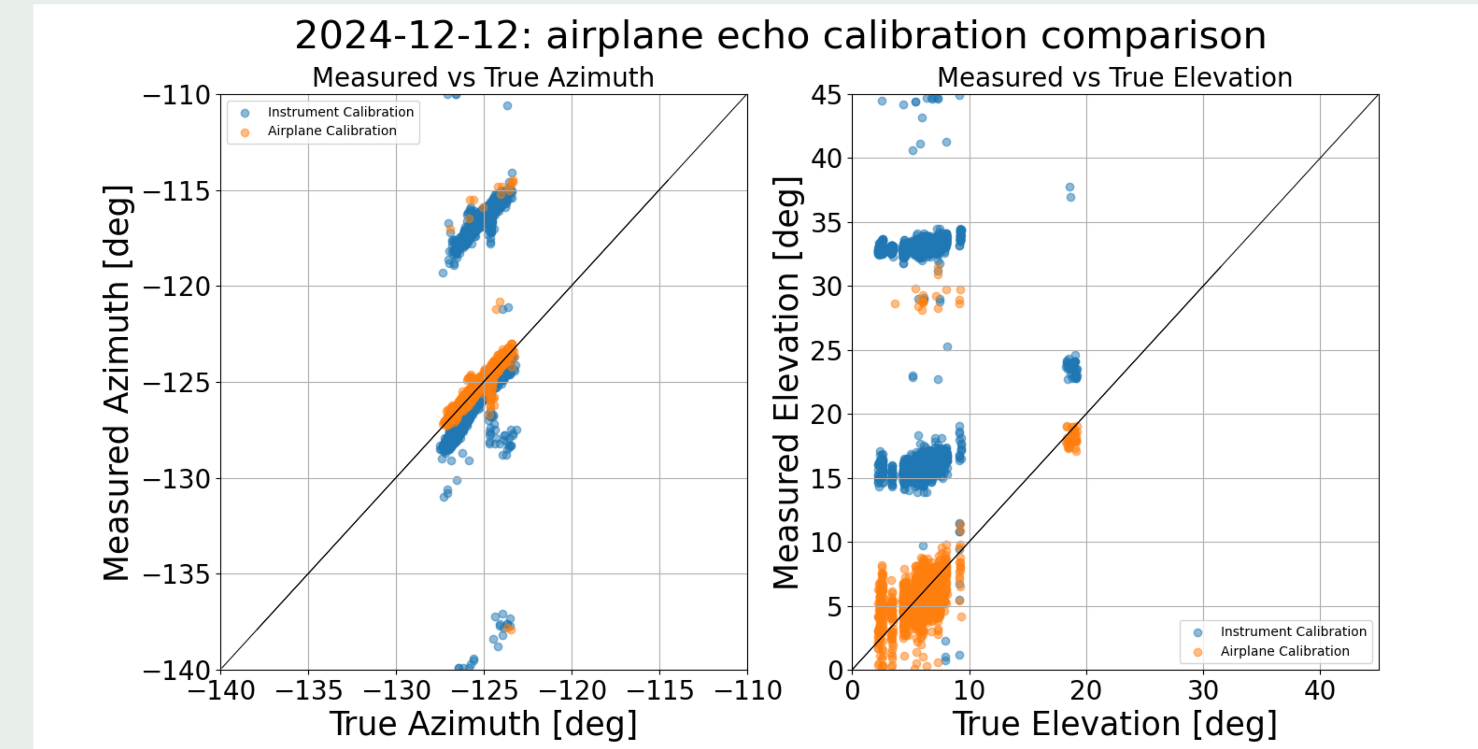


Airplane Phase Calibration

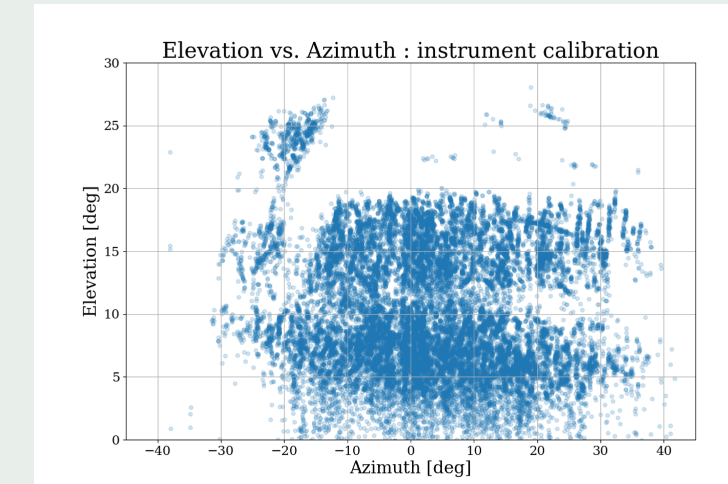


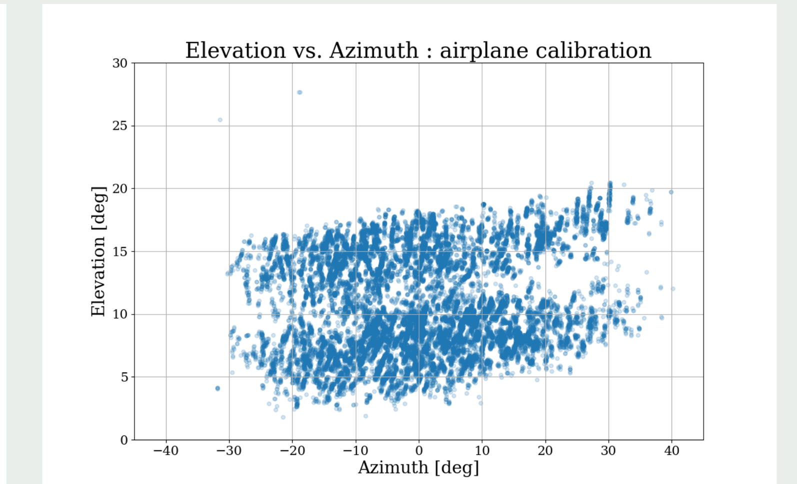


Airplane Calibration Results: Airplane Echoes



Airplane Calibration Results: Meteor Echoes





Summary and Future Work

Summary

- ICEBEAR very reliant on signal phase
  - → phase calibration essential
- Airplanes routinely seen by radar
  - → Point source + high SNR = good calibrator
- Generate baseline calibration based on difference b/w expected and measured phase of airplane echoes
- Excellent results for determining airplane AoA
- Mixed results for scientific targets

Future Work

- Investigate elevation dependence on azimuth in airplane calibrated scientific data
  - → Direction dependent calibration?
  - → Result of multipath effects?
- Use meteor shower radiant as test for calibration on scientific target
- Compare airplane calibration to celestial source calibration

Acknowledgements

References

1. D. Huyghebaert, G. Hussey, J. Vierinen, K. McWilliams, J.P. St.Maurice (2019). ICEBEAR: An all-digital bistatic coded continuous-wave radar for studies of the E region of the ionosphere, *Radio Science*, *54*, 349-364, doi:10.1029/2018RS006747.
2. A. Lozinsky, G. Hussey, K. McWilliams, D. Huyghebaert, D. Galeschuk (2022). ICEBEAR-3D: A low elevation imaging radar using a non-uniform coplanar receiver array for E region observations, *Radio Science*, *57*, doi:10.1029/2021RS007358.
3. D. Farley, H. Ierkic, B. Fejer (1981). The absolute scattering cross section at 50 MHz of equatorial electrojet irregularities, *J. Geophys. Res*, *86(A3)*, 1569–1575, doi:10.1029/JA086iA03p01569.
4. R. Palmer, S. Vangal, M. Larsen, S. Fukao, T. Nakamura, M. Yamamoto (1996). Phase calibration of vhf spatial interferometry radars using stellar sources, *Radio Science*, *31*, 147–156, doi:10.1029/95RS02319.