Expanding diagnostic capabilities of SuperDARN CANADA radars with Borealis USRP system

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Outline

- SuperDARN operations: pros, cons and way forward
- Borealis USRP system design
- Extended capabilities provided by Borealis
- Summary

SuperDARN: pros and cons

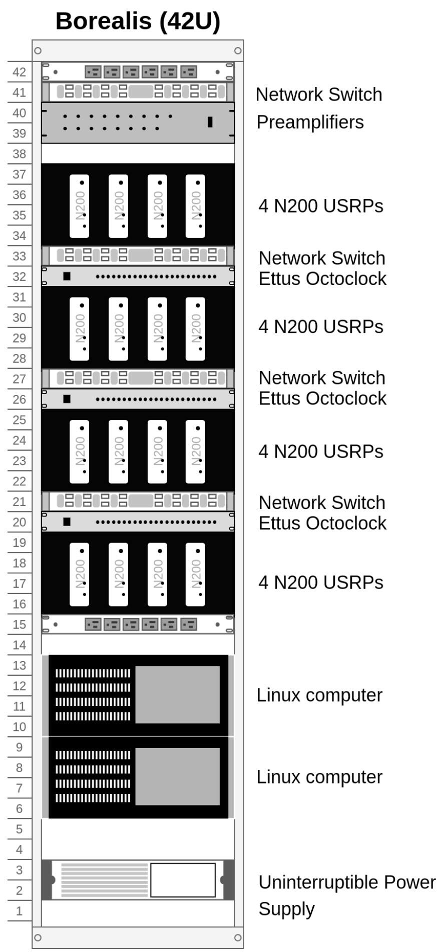
- Advantages of SuperDARN as compared to other instruments:
    - ground-based magnetometers and ionosondes
        - direct measurements of the ionospheric electric field
        - superior spatial resolution
        - large field-of-view
        - covering otherwise inaccessible areas
    - space-born instruments
        - continuous coverage of the same regions
        - 24/7 operation

SuperDARN: pros and cons

- Shortcomings of conventional SuperDARN operations
  - Consecutive beam scanning:
    - non-simultaneous measurements at different beams
    - sampling rate is much larger than the integration time
  - Single sounding frequency –
    - restricted range coverage
    - rare overlapping of scatter regions from two radars (merged V)
    - gaps in data from fixed ranges
  - Etc, etc, etc...
- Way forward – expand operational capabilities with Universal Software Radio Peripheral (USRP) systems:
  - UoA Fairbanks – developed (X300)
  - ISEE – currently developing own system for HOK (N210)
  - University of Saskatchewan – developed Borealis (N200)

Borealis system: hardware

McWilliams, K. A., Detwiller, M., Kotyk, K., Krieger, K., Rohel, R., Billett, D. D., et al. (2023). Borealis: An advanced digital hardware and software design for SuperDARN radar systems. *Radio Science*, *58*, e2022RS007591. https://doi.org/10.1029/2022RS007591



- N200 USRP:
  - 17 per radar site (1 spare)
    - two daughterboards
      - transmit (single channel)
      - receive (two channels)
  - Used channels:
    - 16 transmit channels (main array)
    - 20 receive channels (main + interferometer arrays)
      - 12 unused receive channels
- Network switches
- Preamplifiers
- Ettus Octoclocks
- Two Linux computers (one NVidia GPU)
- UPS

Borealis operations: transmit

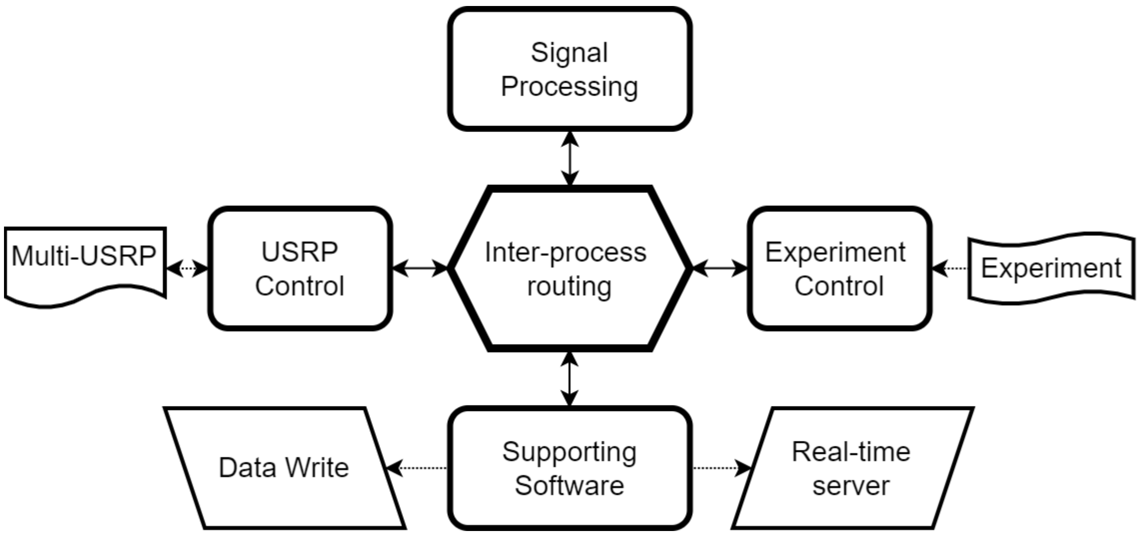
- Fully digital signal generation for each transmit antenna using N200:

  "For every pulse sequence, the transmit thread obtains the sequence parameters and metadata from the experiment control, such as the center frequency, the pulse samples for each antenna, and the relative timing of when to send each pulse in the sequence. The parameter details are used to output the correct pulse waveforms with the correct timing."

Borealis operations: receive

- Receive signal processing:
  - USRP
    - Input sampling
      - 100-MHz rate in 8-20 MHz band (ring buffer)
    - Output sampling (to GPU)
      - 5-MHz band centred at a given central frequency between 8 and 20 MHz
  - GPU
    - multi-stage filtering/downsampling using modified Frerking method
    - beamforming
    - I&Q output sampled at 3.33 KHz (300 μs) passed to CPU
  - CPU
    - generating conventional data products (RAWACF, FITACF) in both DMAP and HDF5 formats

Borealis system: software



- Python modules
- C++ (GPU)
  - CUDA
- Bash scripts

Borealis deployment to date

- Operating at all Canadian radars since Sep 2021
  - SAS
  - PGR
  - INV
  - CLY
  - RKN
- Being deployed at
  - HAN
  - WAL

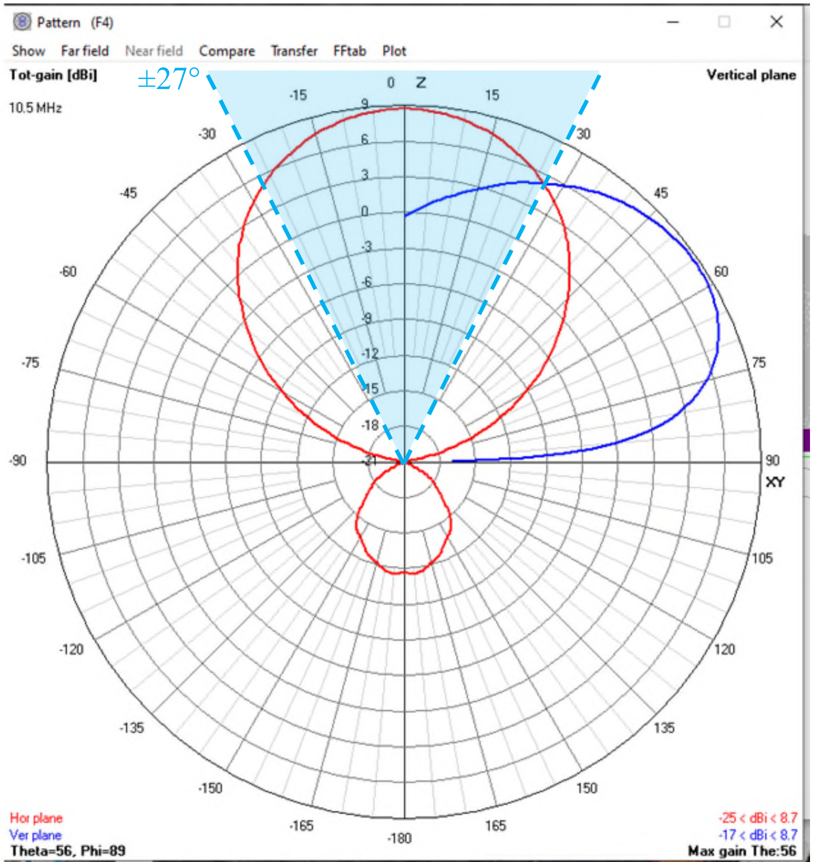
New diagnostic possibilities

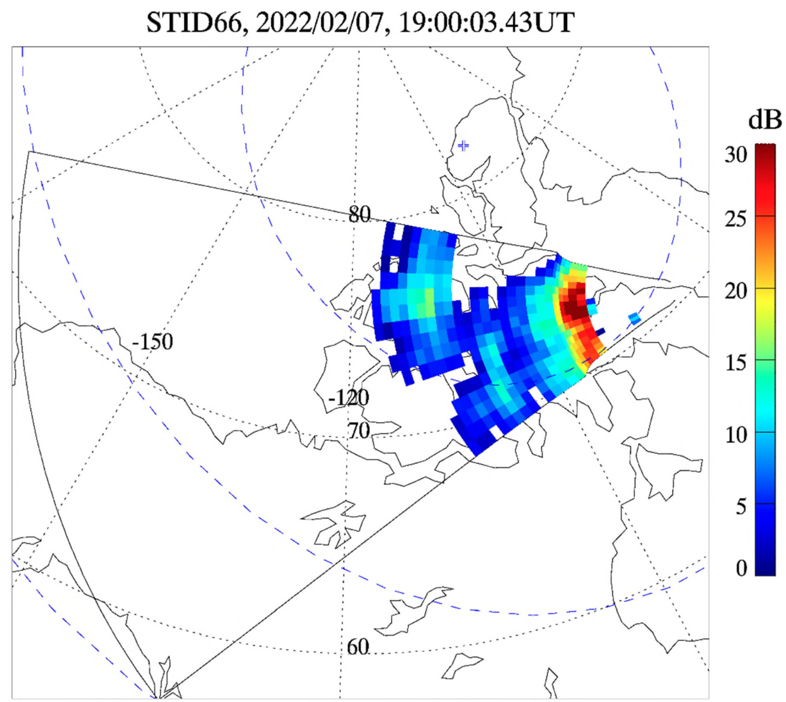
- Wide-beam transmission: true imaging (simultaneous sampling of the whole FoV)
- Multi-static measurements: extended coverage, additional LoS directions
- Multi-frequency measurements: extended group range coverage and additional information on ionospheric density profile
- Phase pulse encoding (e.g., Barker code): improving group range resolution without losing signal power
- Etc, etc, etc...

Example 1: True imaging operations

- True imaging
  - wide-beam emission using two antennas out of 16
  - narrow-beam reception from the multiple directions using I&Q samples from each antenna
- Advantages
  - simultaneous sampling of all beam directions
    - allows to improve the full field-of-view sampling rate and/or the integration time (anything between 3.5 and 60 s)
- Side effects
  - SNR decrease ~18 dB
  - 16-fold increase in data volume if using the same integration time

Two-antenna emission: beam pattern

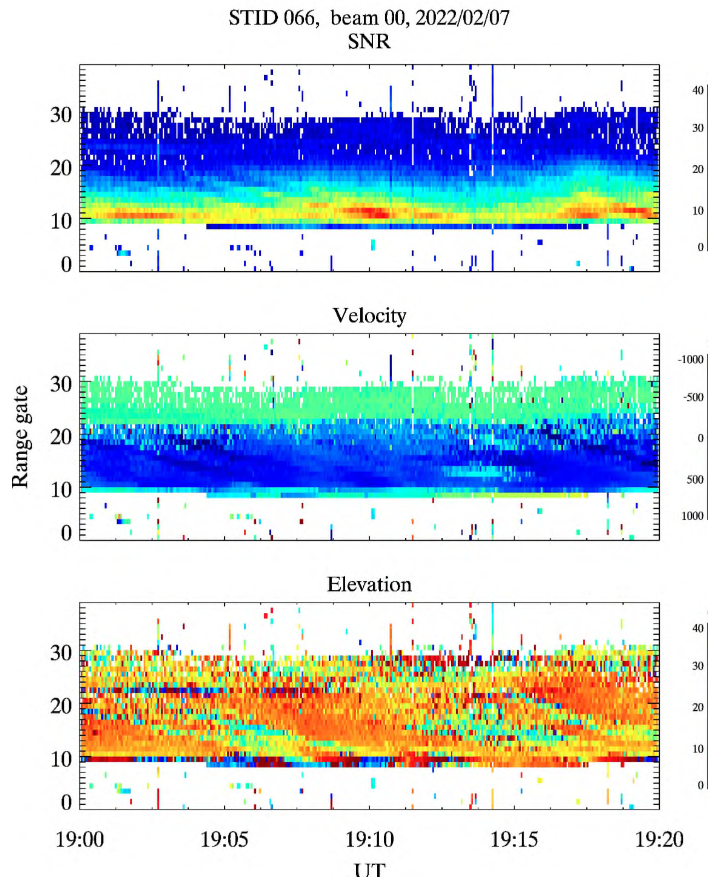




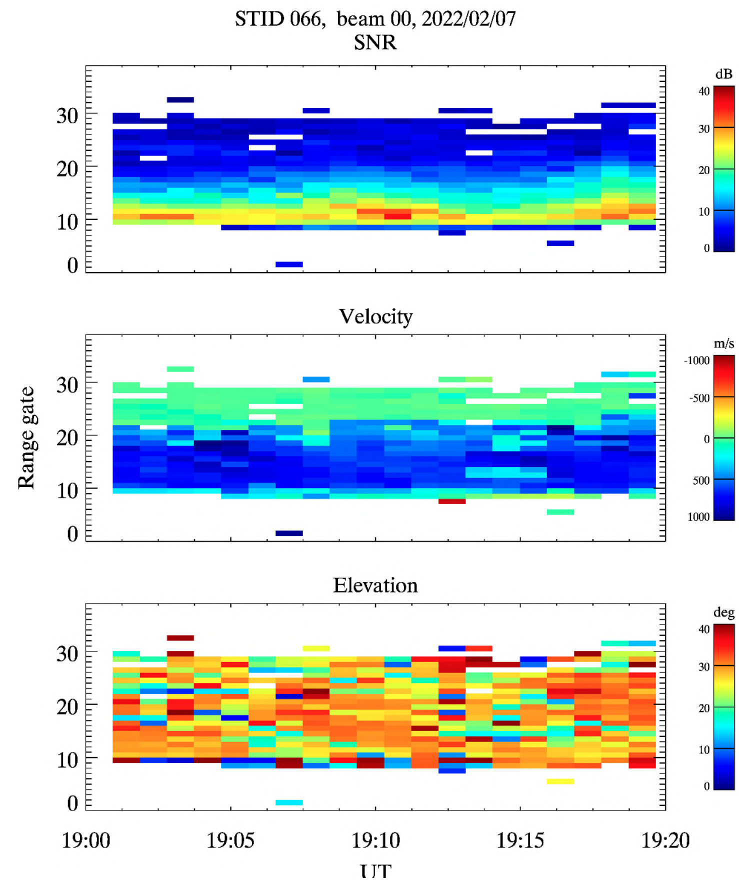
Two antennas (7, 8)
All 16 antennas

Two-antenna emission: sampling

Sampling 3.5 s

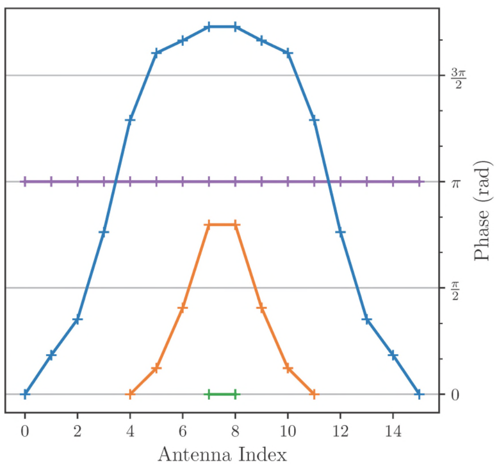


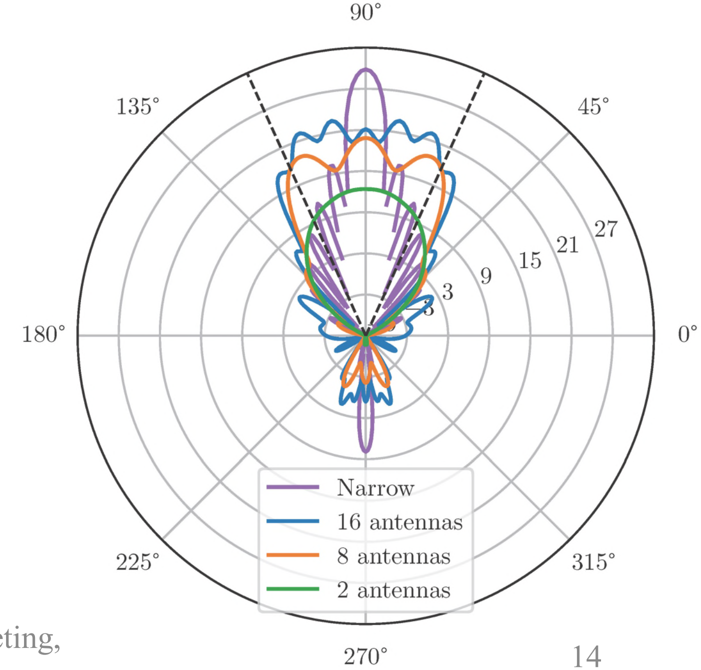
Sampling 60 s



Example 2: Multistatic operations

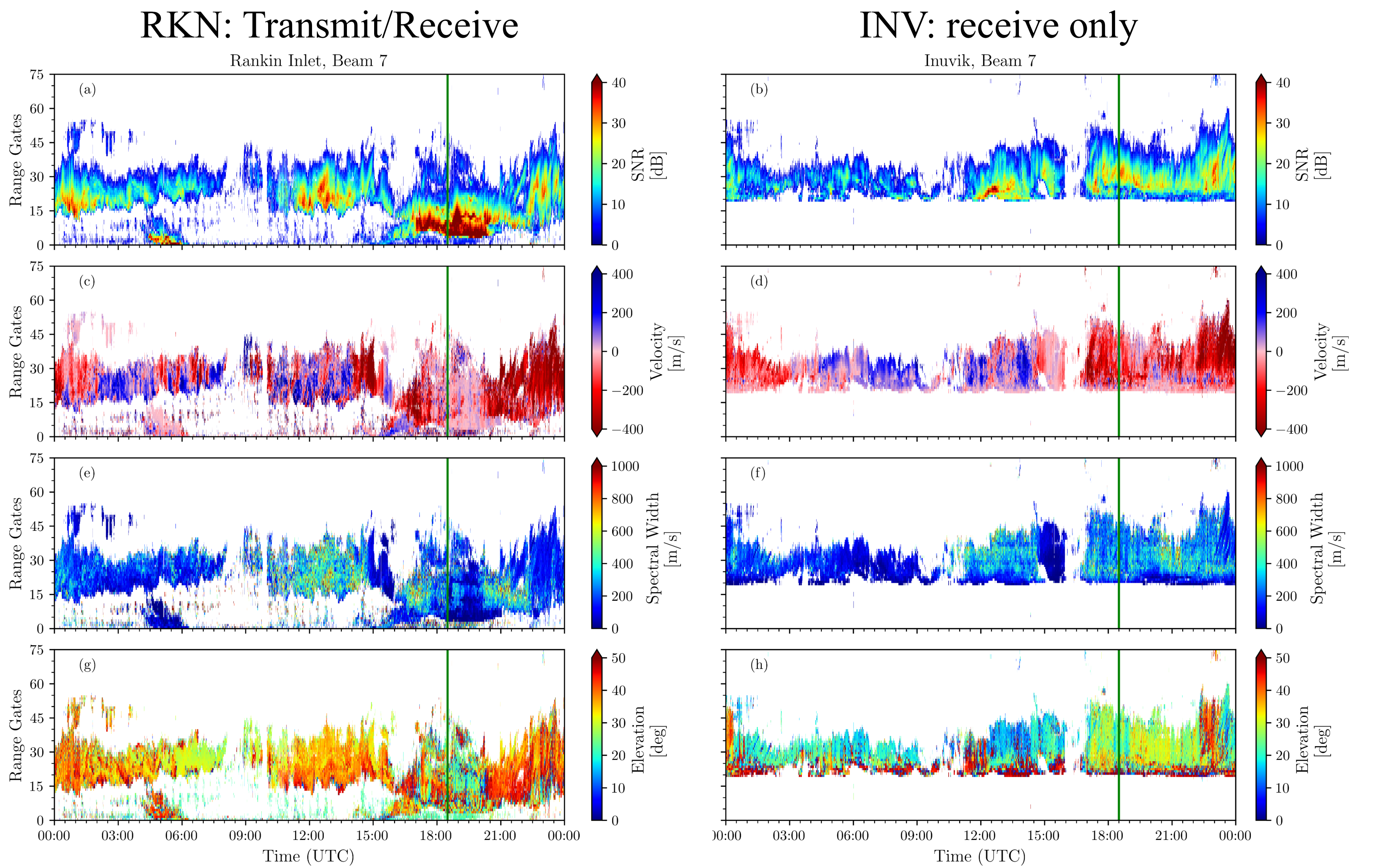
- Previous work:
  - bistatic CVE/CVW – single beam, one effective range gate per integration time (Shepherd et al, 2020)
- Our improvements:
  - <u>wide transmit beam </u>– improved with non-linear phase modulation across all 16 antennas to maximise emitted power (SNR improved by ~9 dB)
  - <u>simultaneous multi-beam reception</u> thorugh post-processing single-antenna I&Q data



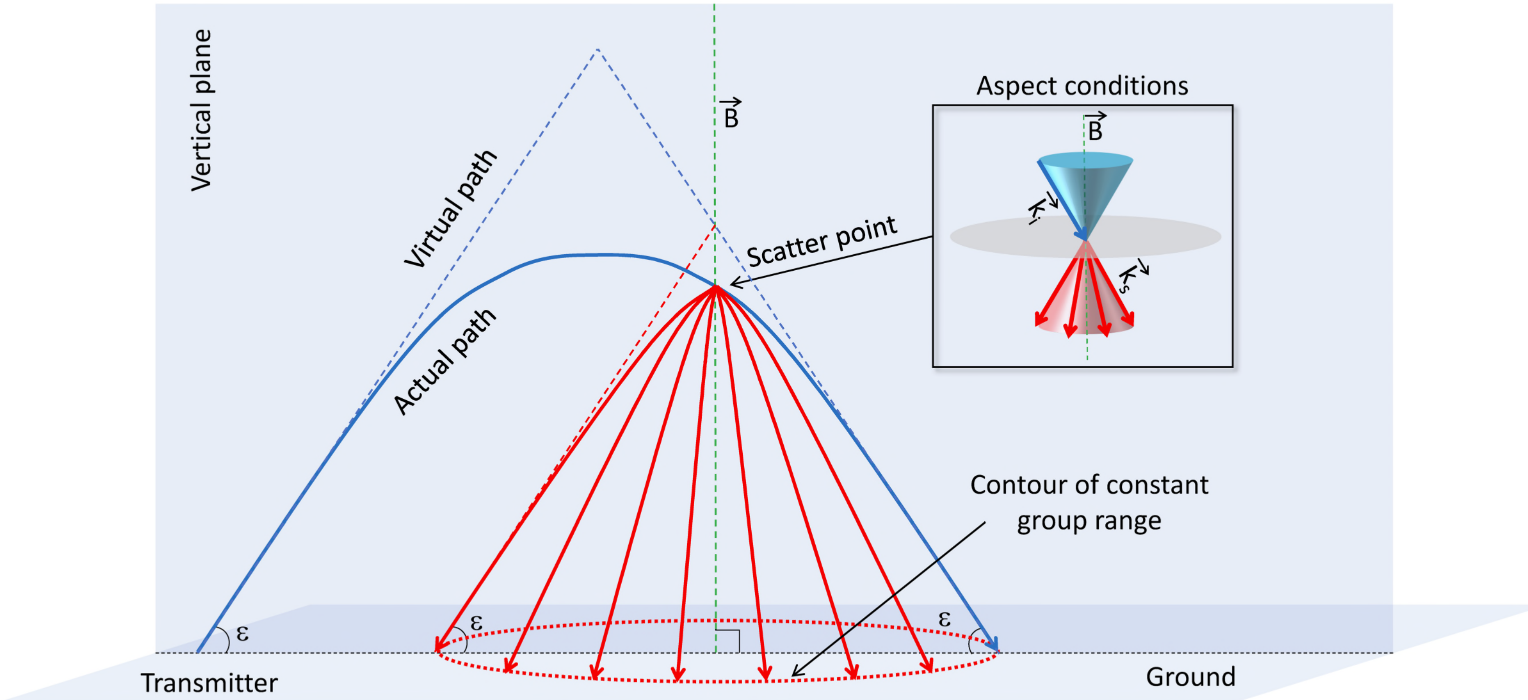


Multistatic test RKN-INV-CLY

10 January 2023

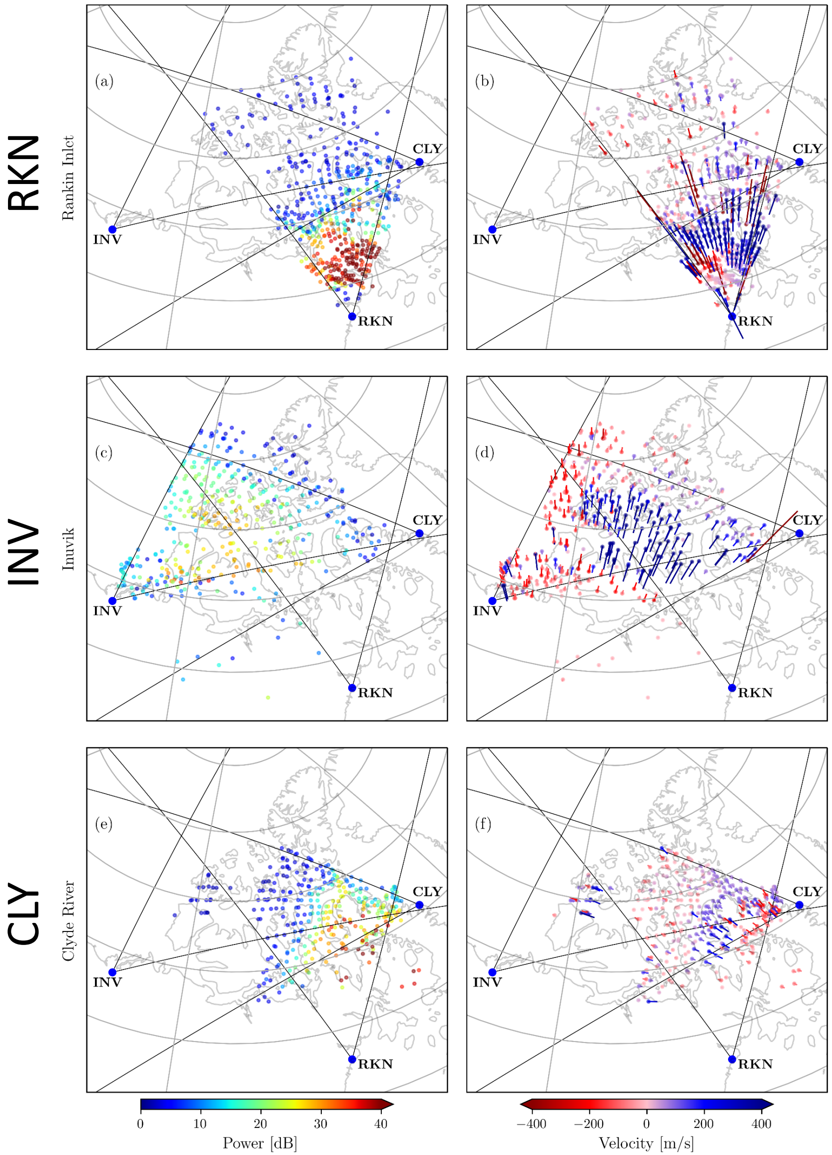


Bistatic geolocation: principles



- Assumptions:
  - Spherically stratified ionosphere
  - Vertical magnetic field
  - Scattering occurs into the cone of equal aspect angle with respect to the magnetic field (aspect conditions)
- Required information at the receive site:
  - <u>Elevation angle</u>
  - Group range
  - Beam direction
  - Great-circle distance and direction to the transmit site

Bistatic geolocation: results



Coverage on an equal-area grid (≈1°x1° LAT):

Site	Total cells	Non-overlapping cells	Overlapping cells
RKN	85	-	-
INV	107	80 (+93%)	27 (31%)
CLY	80	35 (+41%)	45 (53%)
INV & CLY	-	-	21 (25%)

Summary

- Borealis system represents a significant step forward in extending functionality and diagnostic capabilities of SuperDARN radars.
- It is already working at SAS, PGR, INV, CLY, RKN and is being deployed at HAN and WAL
- Among other advantages, Borealis allows for true imaging of the field of view with all beam directions being illuminated and sampled simultaneously. This opens ways for significant improvement in sampling rate and/or statistical reliability of the data.
- The wide-beam emission regime provides an opportunity for multistatic measurements which is shown to provide large increase in both spatial coverage and amount of overlapping data with different line-of-sight directions (true velocity measurements).