Incoherent and coherent scatter radars

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The World of ISRs

- 1962: Jicamarca (Peru)
- 1963: Arecibo (Puerto Rico)
- 1974: Millstone Hill (USA)
- 1981: Tromsø (Norway)
- 1983: Sondrestromfjord (Greenland)
- 1995: Longyearbyen (Norway)
- 2006: Poker Flat (Alaska)
- 2008: Resolute Bay (Canada)
- 2011: PANSY Syowa (Antarctica)
The EISCAT Incoherent Scatter Radars
The ionosphere results when rays of light from the sun knock electrons out of atoms of the neutral air.

It varies on time scales of seconds, minutes, hours, days, years, …..
Other effects

- Aurorae
- Communications
- Power systems
- Space craft
Incoherent Scatter

High power pulse

Very sensitive receiver

Only \(~0.0000000000000000001\)% of the transmitted power is returned!

Complex signal processing extracts the frequency spectrum

Iterative fitting reproduces the shape of the ionosphere

Electrons reflect the pulse....
Incoherent Scatter

Thomson scatter is re-radiation by free electrons of incident electro-magnetic wave energy.

Radar cross-section per electron:

$$\sigma_R = 4\pi \left(\frac{q^2}{4\pi \varepsilon_0 m_e c^2}\right)^2 = 10^{-28} \text{ m}^2$$ is extremely small.

Equivalent to 1 cm$^2$ (small coin) at 400 km range.

The scattering electrons are electrostatically bound to the heavy ions, within the Debye length, giving a typical spectrum of ion motion.

(Doppler shift: $V_{\text{los}}/c = \Delta \lambda/\lambda_0$)

$$f(\nu) = \sqrt{\frac{m}{2\pi kT}} ^3 (4\pi)^2 \nu^2 \exp\left(\frac{-m\nu^2}{2kT}\right)$$

$$\nu_p = \sqrt{\frac{2kT}{m}}$$

[Graph showing Maxwell-Boltzmann molecular speed distribution for Noble Gases]
Summary Data

Four basic parameters:
Electron density
Electron Temperature
Ion temperature
Ion velocity

Raw data available for further analysis:
shorter integrations
different gating
different weightings
other parameters
etc.

‘IS radar is the most powerful ground-based tool’
Data examples

- **Dusty plasma**

- **Time vs. Altitude**

- **Cosmos**

- **Iridium**

- **Monthly median ESR $N_O$**
  - $Kp=2$, Alt. $= 350\text{km}$, $00 < UT < 18$
18 Days of high latitude data...

5-23 February 2001
Ionospheric modification

HF heater
4-8 MHz 1.2 MW
Plasma laboratory
Effects on
Density
Temperature
Luminosity
Some caution...

Having a data plot is not the same as knowing what is going on:

1. What you see depends on where and how you look
2. Variations in ISR data can be ambiguous
3. Knowing some physics helps you make sense of the data
4. Combining with data from other instruments gives better context

Always remember:

- The data can depend strongly on the design of the experiment
- The ISR technique can be prone to both systematic and random errors
- If the data look unusual - be suspicious!
- Eliminate possible sources of error before you publish your new discovery!
A simple EISCAT data set

What can we see in this plot?

- The height structure of the E and F regions
- The diurnal variation of the ionosphere
- Aurora
- Electron and (maybe) ion heating
- The trough region
- Atmospheric tides
- Plasma blobs/irregularities
Altitude and Latitude...

Elevation, $\xi = 21^\circ$

Trough in $N_e$ with enhanced $T_e$

Altitude $h$

Range, $r$

Elevation, $\xi$

$\Delta \lambda$

Poleward moving event
- Incoherent Scatter Radars see weak ion-acoustic structures in **any direction**.
- Coherent Scatter Radars only see large amplitude structures aligned with the magnetic field. HF radars use refraction to bend the rays so as to hit **perpendicularity to B** in the F region.
- F region magnetic field-aligned echoes should drift at ExB since ions and electrons both ExB drift.
Echoes for both radars come from collective scattering, or plasma irregularities.

<table>
<thead>
<tr>
<th>Radar</th>
<th>Incoherent</th>
<th>Coherent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>~1MW</td>
<td>~10s kW</td>
</tr>
<tr>
<td>Frequency</td>
<td>Fixed (UHF/VHF)</td>
<td>Variable (HF)</td>
</tr>
<tr>
<td>Range resolution</td>
<td>100’s m – 10s kms</td>
<td>15 – 45km</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>ms</td>
<td>mins</td>
</tr>
<tr>
<td>Field of View</td>
<td>Narrow</td>
<td>Wide</td>
</tr>
<tr>
<td>Parameters</td>
<td>Ne, Te, Ti, Vi</td>
<td>Vlos, power, spectral width</td>
</tr>
<tr>
<td>Radar operations</td>
<td>Coded pulses</td>
<td>Multi-pulse</td>
</tr>
</tbody>
</table>
HF frequencies

- HF signals are refracted in the ionosphere as they traverse electron density gradients.
- Backscatter:
  - from field aligned irregularities where Bragg condition is satisfied:
    - \( k_i = \pm 2k_r \)
  - from the ground
- Radar wave vector, \( k_r \) must be orthogonal to the magnetic field line.

Advantages of using HF frequencies:
1) Refraction of signals provides access to targets in the F-region where \( \mathbf{E} = -\mathbf{V} \times \mathbf{B} \)
2) Refraction of signals extends the radar field-of-view to >3500 km
3) Low power requirements allow for continuous operation
Multi-beam Doppler Velocity Map
SuperDARN Radars

- Global network of ionospheric radars
- Work at HF frequencies (8 – 20MHz)
- Parameters:
  - Line of sight velocity (ExB drift in F-region)
  - Spectral Width
  - Backscatter Power
- Braggscatter:
  - Only receive data when beam is perpendicular to B-field (scatters off density structures along the B-field)
- Large field of view
- Global convection maps – Also interhemispheric
Locations

Northern Hemisphere
21 radars

Southern Hemisphere
9 radars
Some Northern Hemisphere Radars (ca 2012)

- Antenna design has evolved over the years
Ionospheric Convection Maps

- Data taken from all radars
- Fitted to a model (with various input parameters, eg. solar wind data)
- Produce full hemispheric convection map: ExB ionospheric velocity
Ionospheric Convection Maps

Northern hemisphere

Southern hemisphere
SuperDARN / EISCAT
SuperDARN / EISCAT

High ion temperatures (EISCAT) caused by fast plasma flow (SuperDARN)