Radars: Powerful tools to study the Upper Atmosphere

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Outline

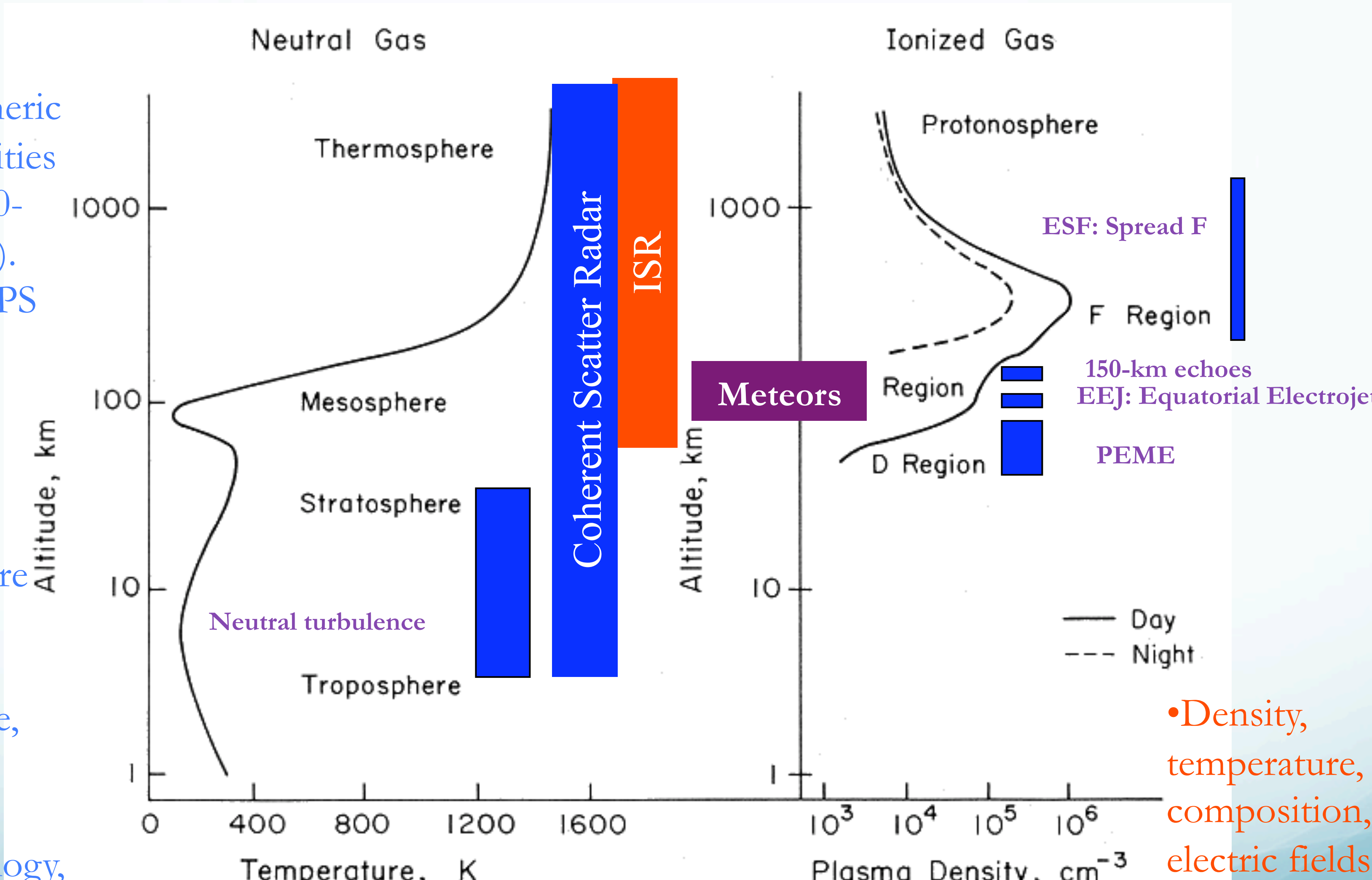
- How the instrument works?
- Some radar considerations
- Incoherent vs. Coherent Scattering
- What physical parameters can be measured/inferred?
  - Examples from Incoherent and Coherent scatter radars
  - Imaging (resolving space and time ambiguities)
- Data processing and analysis for Underspread targets (by Roger Varney)

Basic Assumptions

- were awake during Prof. Kelley's talk (e.g., no need to introduce the Ionosphere)
- every instrument works under some assumptions. As long as those assumptions are valid, the measurement is representative
- knowledge of basic linear systems (ACF is the Fourier Transform of the Spectrum and vice versa)
- want to explore continuing/becoming a radar student

¿What do we study with Radars?

- Ionospheric Irregularities (EEJ, 150-km, ESF).
- SAR, GPS



- Neutral atmosphere dynamics (winds, turbulence, vertical velocities)
- Meteorology, aviation.

- Density, temperature, composition, electric fields
- Modeling, space weather

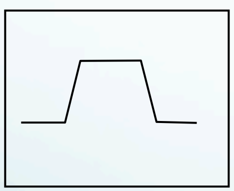
Radar Equation: Hard target

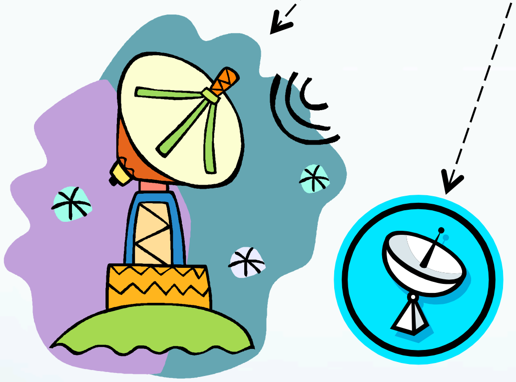
Hard target with radar cross section (RCS) σ

$$P_i \approx \frac{P_t G_t}{4\pi R_t^2}$$

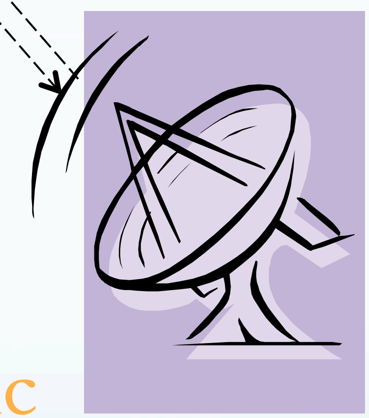
$$\vec{r}_{r1} = \vec{r}_d - \vec{r}_{Rx1}$$

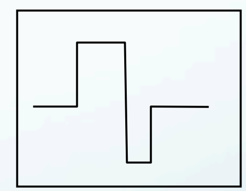
$$\vec{r}_i = \vec{r}_d - \vec{r}_{Tx}$$





$$G \approx \frac{4\pi A}{\lambda^2}$$





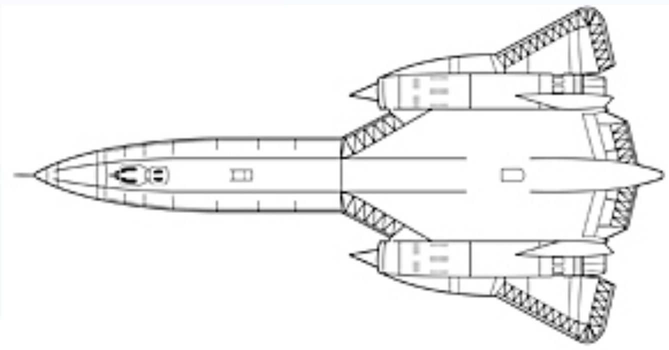
Monostatic

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 R_t^2 R_r^2 L}\sigma$$

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4 L}\sigma$$

Radar cross section examples

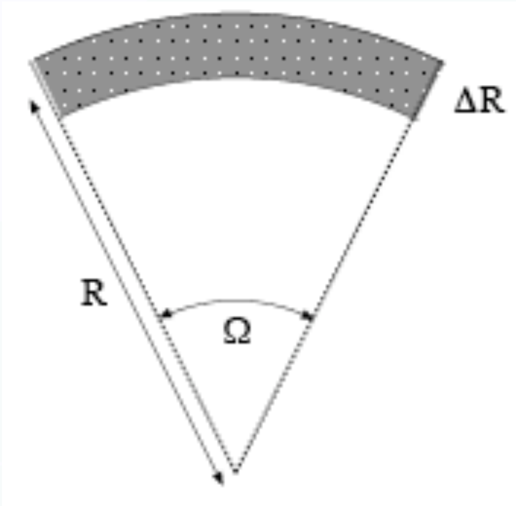
- Ordinary ship or airplane: tens to hundreds of $(\text{meters})^2$
- Stealth bomber (U.S.): < or ~ a few $(\text{mm})^2$!! (for backscatter)



- A single electron: 10^{-28} m^2
- All the electrons in a column 1 x1 x 10 km^3 in the ionosphere at h~300 km, where the electron density is ~ 10^{12} electrons/m^3: $(10)(10^9)(10^{12})(10^{-28})$ m^2 = 10^{-6} m^2 = 1mm^2 !!! But this can be observed (easily) with Incoherent scatter radars!

Radar Equation: Soft target

- Received power dependence
  - Antenna beam shape (antennas, beam forming)
  - Range resolution (rx/tx bandwidth)
  - Volume scattering cross section [area/volume] (medium)



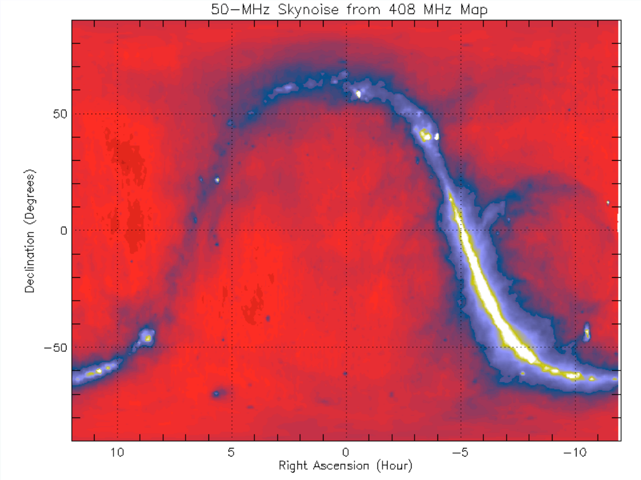
$$V = \Omega R^2 \Delta R$$

$$G = \frac{4\pi A}{\lambda^2} = \frac{4\pi}{\Omega}$$

$$P_r = P_t A \frac{\Delta R}{4\pi R^2 L} \sigma_v$$

Signal/Noise Ratio

$$SNR \approx \frac{P_r}{k_B T_{sys} B + k_B T_{sky} B}$$



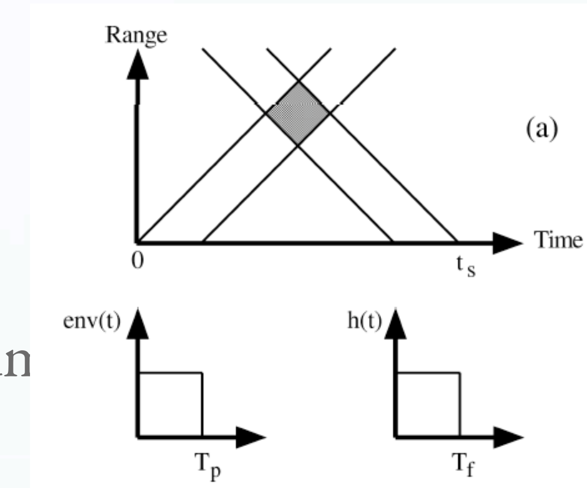
Radar	~PA MW Hectares	T noise (K)
Arecibo	14	100
Jicamarca	16	20,000
Sondrestrom	0.1	100
EISCAT Svalbard	0.2	100
JULIA	0.16	20,000

Most sensitive

Most powerful

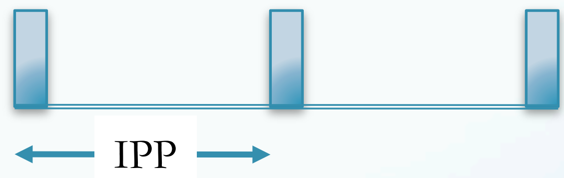
Average Power

- In most radars, finite pulses (τ) are sent at regular intervals (Inter pulse period or IPP).



- The pulse length determines the range resolution ($\Delta R = c\tau/2$), the IPP, the maximum unambiguous range ($R_{max} = c\ \mathrm{IPP}/2$)

- Transmitters are peak-power limited and not always uses the available average power



$$\text{duty cycle} = \frac{\overline{P}_t}{P_t} = \frac{\tau}{\mathrm{IPP}}$$

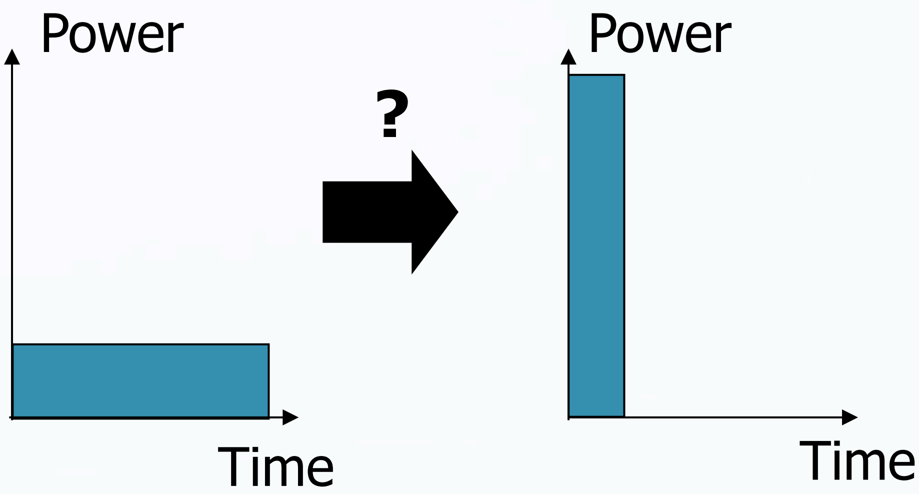
$$\therefore \overline{P} = \frac{\tau P_t}{\mathrm{IPP}}$$

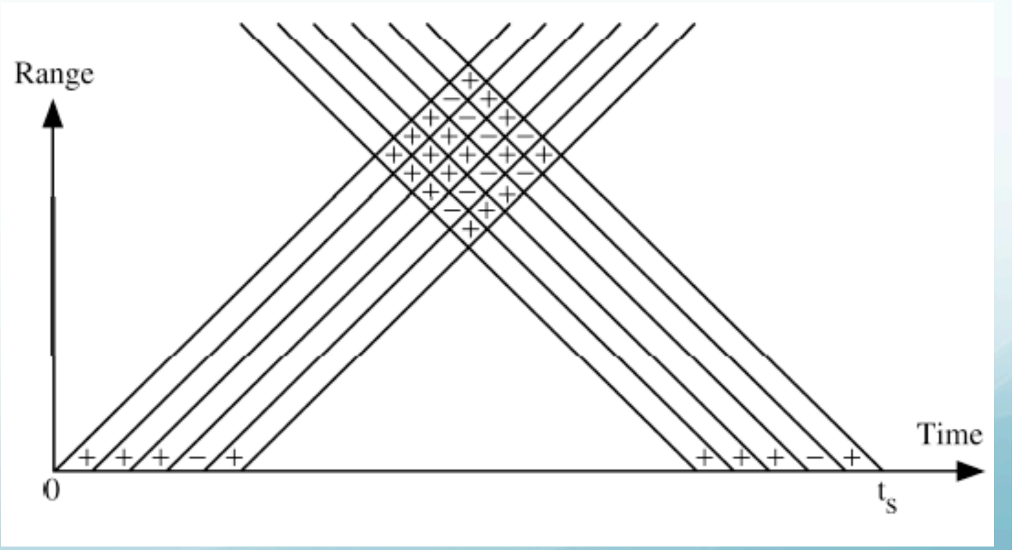
- How can we make use of the available duty cycle?

Pulse Compression!

The basic idea of pulse compression

- Can we transform a long, low power, pulse into a short, high power pulse with the same total energy (same number of joules)?
- And if so, how do we do it?
  - Frequency modulation (chirping)
  - Phase modulation (e.g., Barker, complementary code, alternating codes, ...

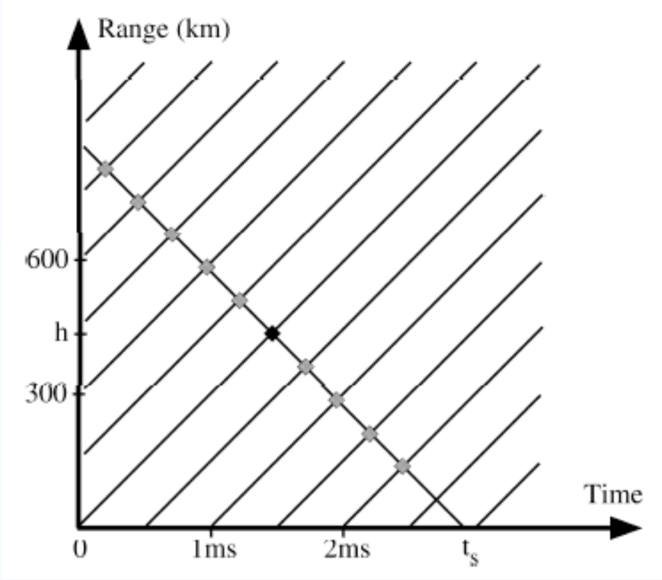


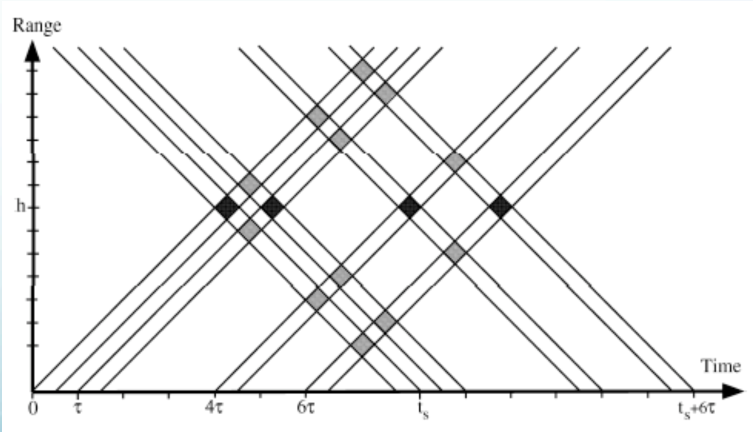


[see details later]

Range and Frequency Aliasing

- The usual radar practice of transmitting a series of pulses at regular intervals and sampling the return at regular intervals can lead to "aliasing" in range and/or Doppler shift
- To avoid range aliasing we want to use a large IPP. But to avoid frequency aliasing we need a short IPP
- With some targets, we can find an IPP that satisfies both requirements (Underspread)
- But for other targets, no such IPP exists. Such targets are called "overspread"





[adapted from *Farley and Hagfors* ISR book]

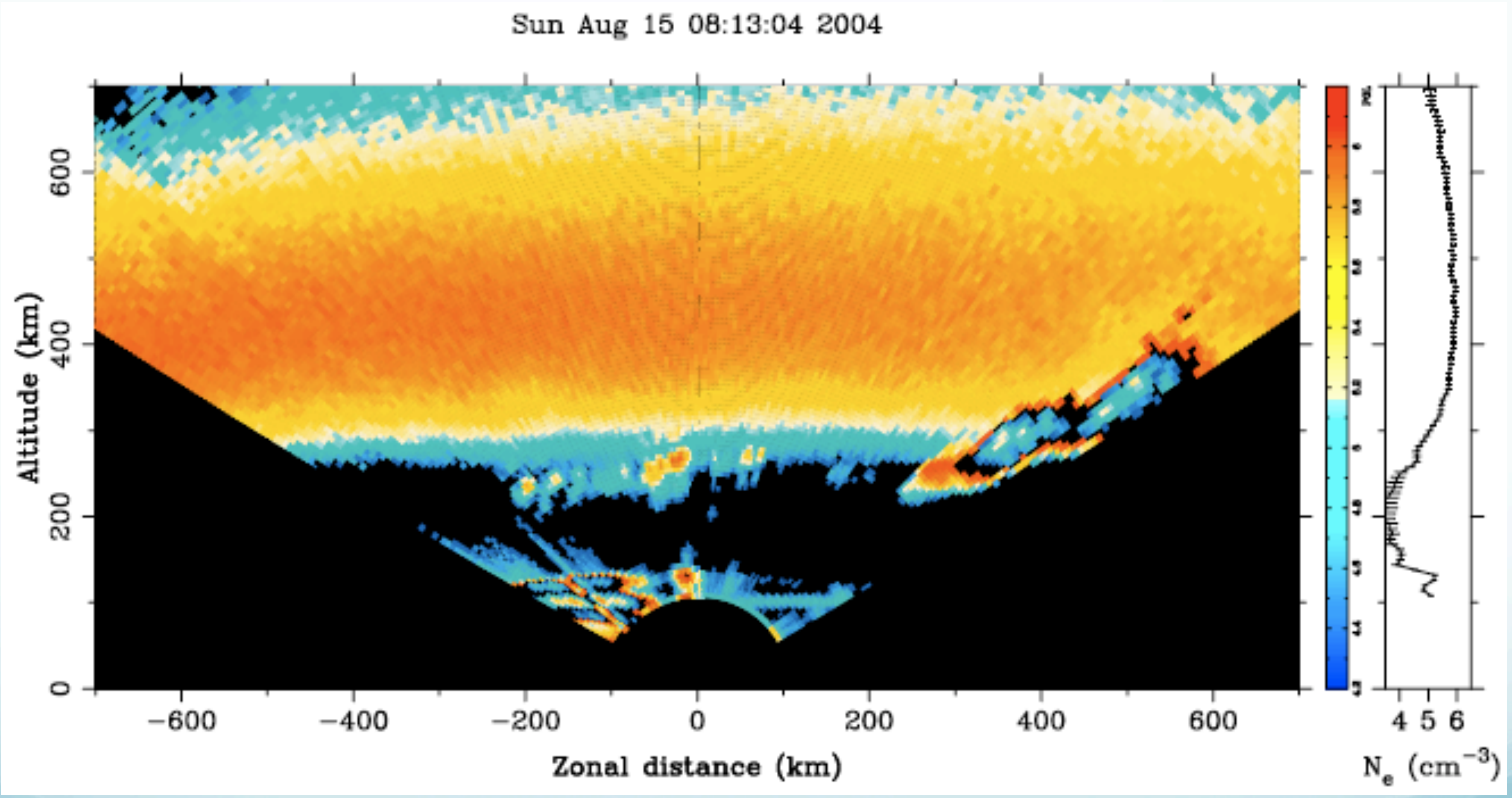
Upper Atmosphere Radar Applications

Type	Region	Measurements/ Techniques	Examples
Incoherent Scatter Radars	Ionosphere/ Protonosphere	Electron density, ion composition, temperatures and drifts	UAF ISR chain, EISCAT
Coherent Scatter Radars	Lower and Upper atmosphere	Plasma physics, convection tracer, neutral dynamics, interferometry/ imaging	JULIA, SuperDarn, MST, Specular meteor radars, Radar Imagers
Ionosondes	Ionosphere Bottomside	Plasma concentrations, "drifts"	Digisondes, CADI, VIPIR, ...

Incoherent vs. Coherent Scattering Radars

Description	Incoherent	Coherent
Power-Aperture	Large	Varies
Target	Volume-filling	Varies (volume filling, field-aligned, point-like, …)
Cross-section dependence	N, Te, Ti, Vz, Vx, Vy, %	Varies
Cross-section "strength"	Equivalent to a dime in the F region	Varies (e.g., EEJ is 40-60 dB stronger than IS)
Upper atmospheric parameters	Most of them measured	Most of them inferred
Overspread/ Underspread	Mostly overspread	Both
Operations	Few days a year	Long term

Coherent and Incoherent Echoes



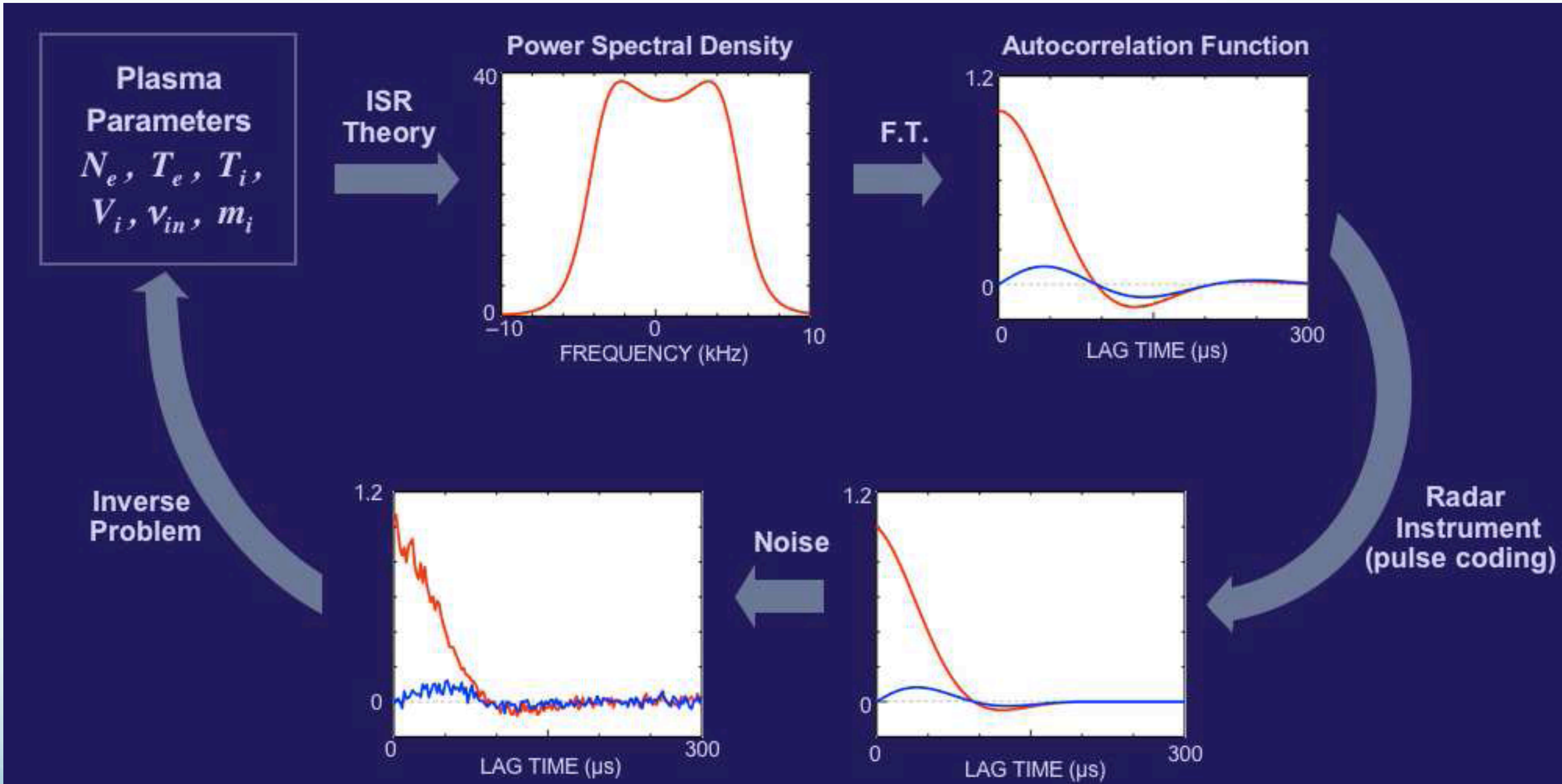
[from *Hysell et al.*, 2006]

What physical parameters can be measured/ inferred?

- From "conventional" measurements
  - Power – Relative Plasma density
  - Spectrum/ACF shape – Ionospheric parameters
  - Spectrum/ACF "moments" – ??
  - Multiple beams – Vector velocities/Electric fields
- From "unconventional" measurements
  - Polarization – Faraday rotation – Absolute Plasma density
  - High bandwidth – Plasma line – Absolute Plasma density, Temperature
  - Multiple antennas - Interferometry/Imaging – Spatial/ Temporal discrimination

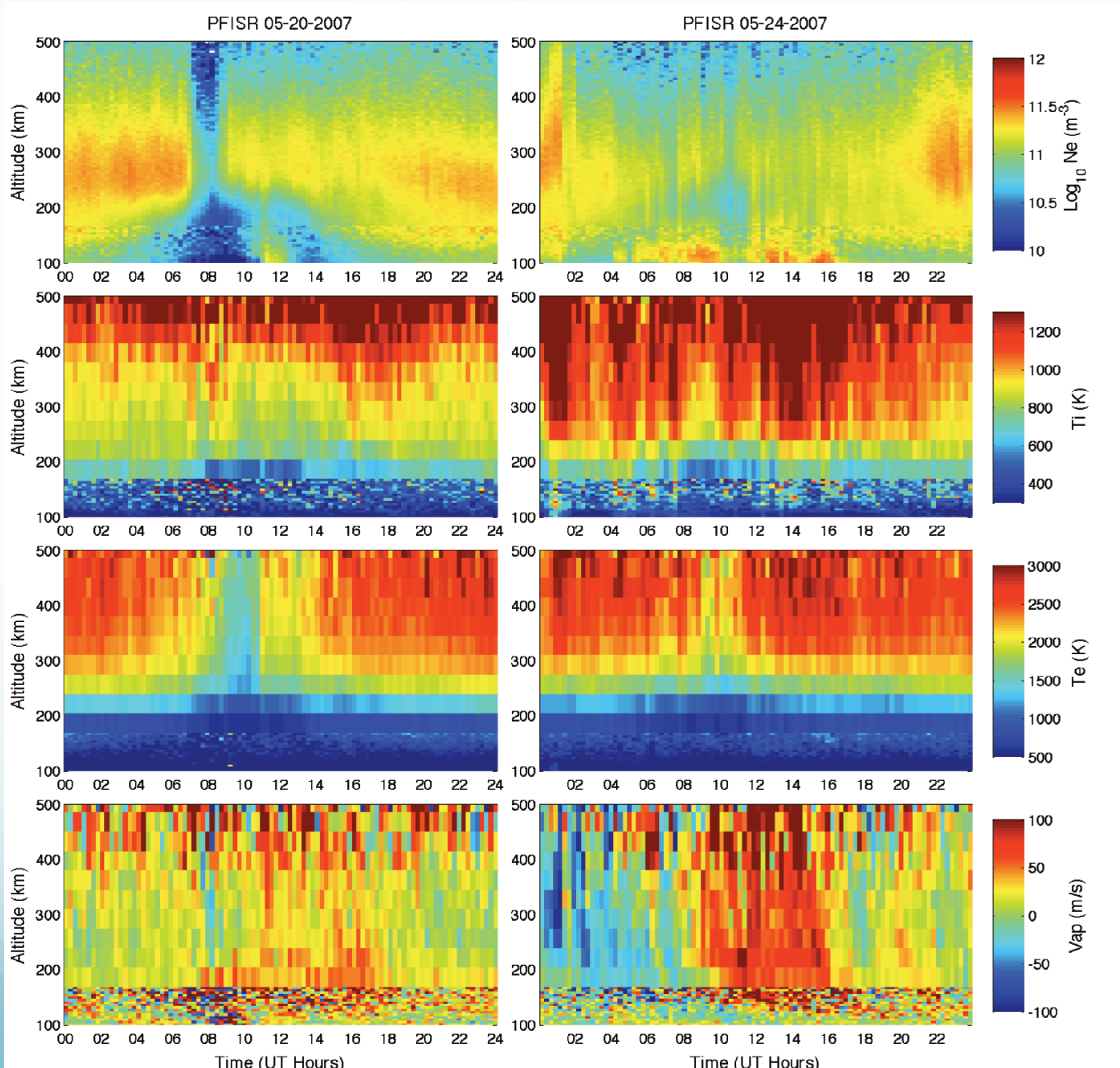
Only ISRs

Spectra/ACF Fitting



[from *Nicolls et al.*, 2008]

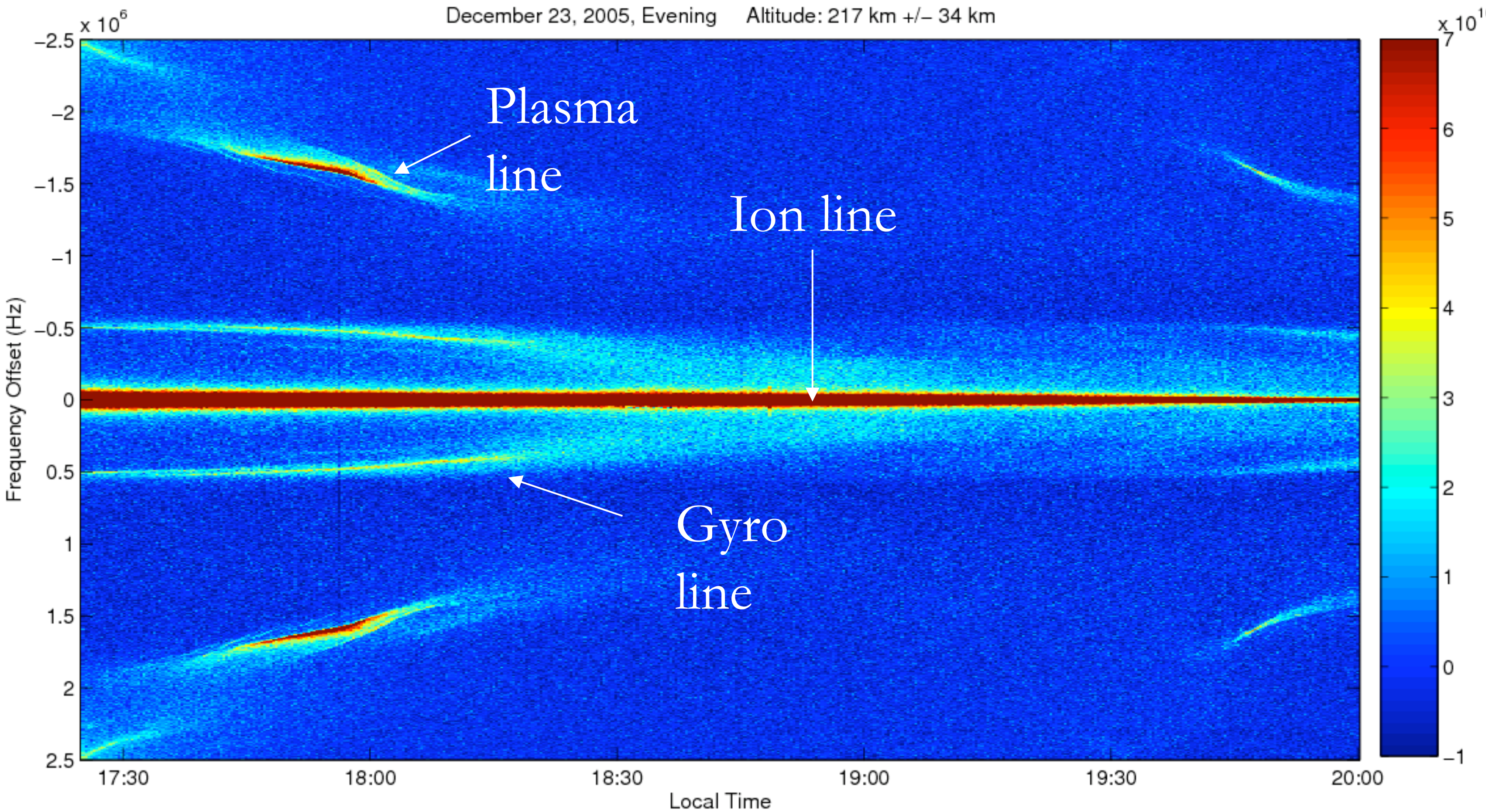
Measured ISR Parameters from Ion line



- Altitude-time plots of
  - Electron density
  - Ion temperature
  - Electron temperature
  - Ion velocity

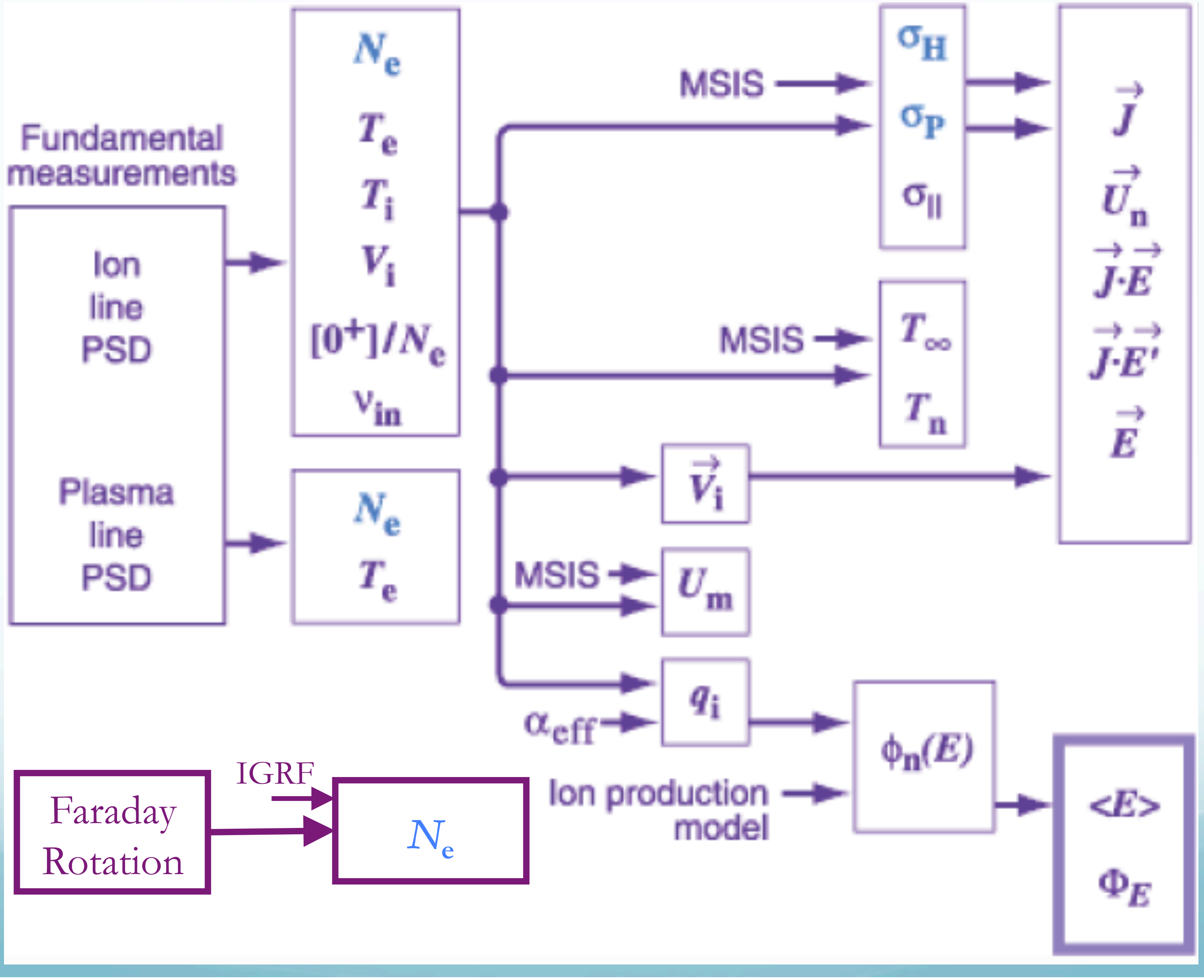
[from *Nicolls et al.*, 2008]

Ion, Plasma, Gyro lines



[Courtesy A. Bhatt]

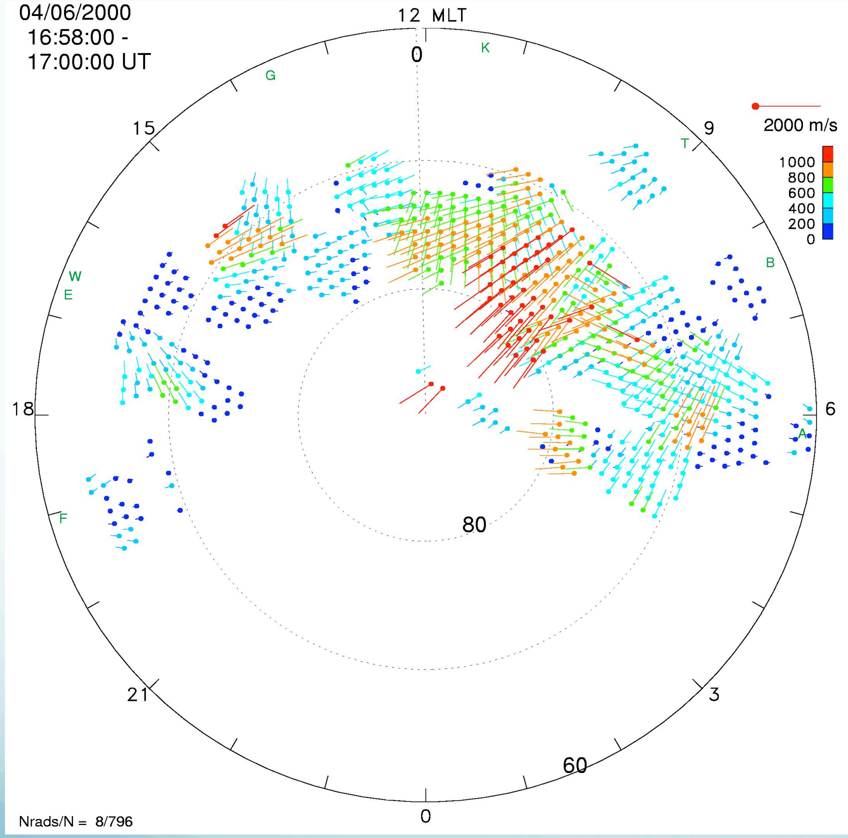
Measurable Parameters Flow Diagram

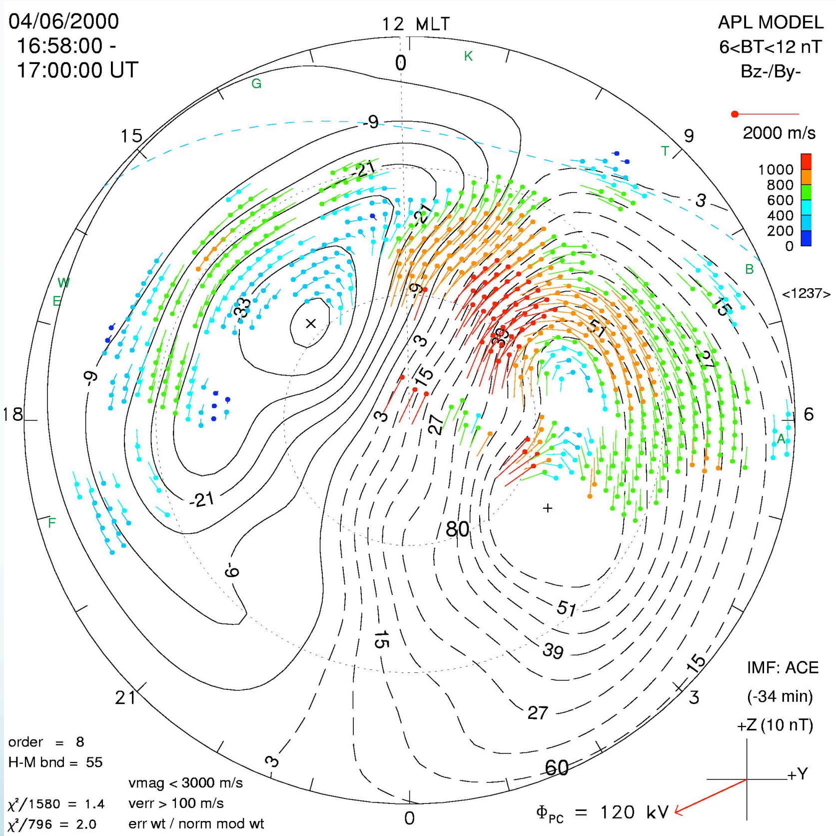


Mapping the global convection pattern

Line-of-sight velocities from first moment

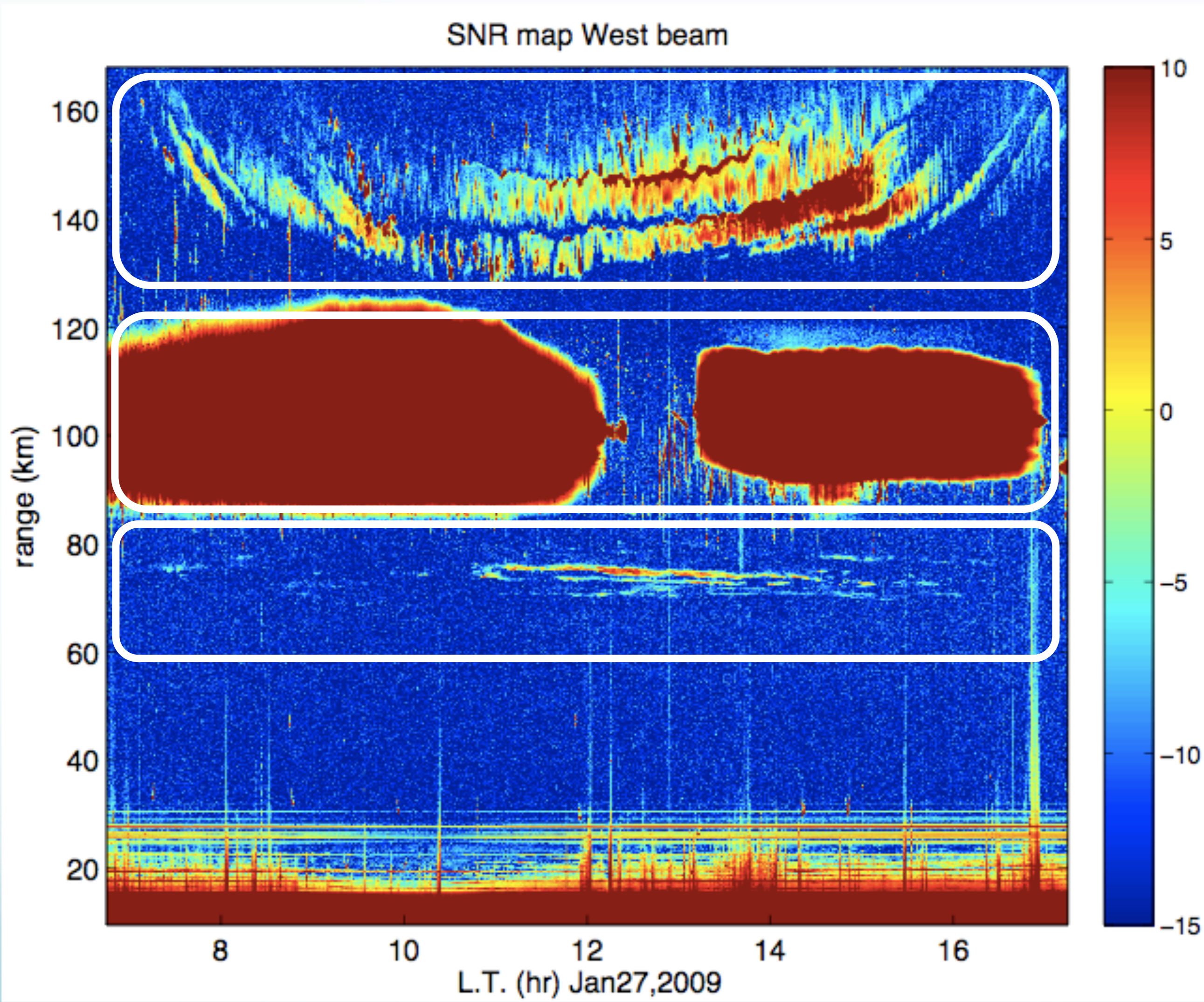
Fitted potential pattern





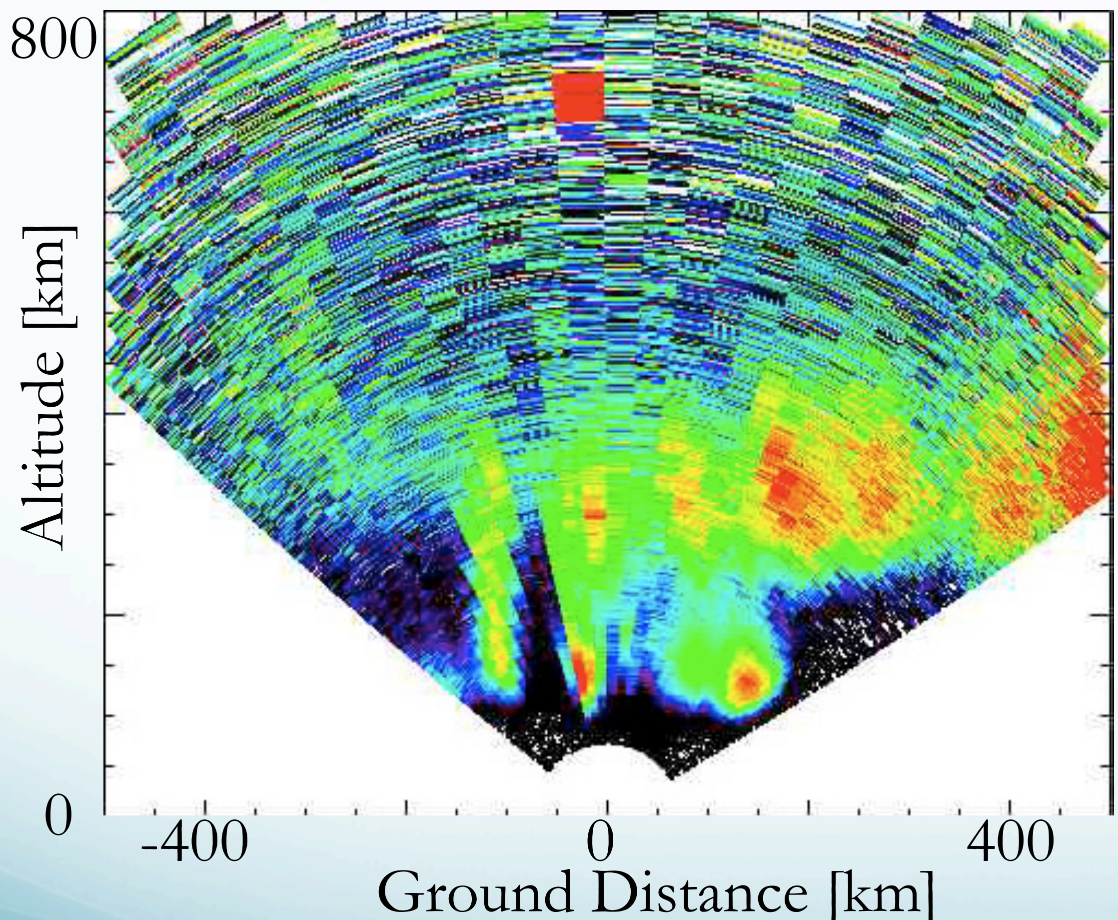
[*Ruohoniemi and Baker*, 1998]

Coherent echoes below 200 km



- ExB drifts from 150-km first moment.
- Plasma physics from EEJ spectra
- Plasma physics and lower thermosphere winds from non-specular meteor trails (see highlight talk by M. Oppenheim)
- Mesospheric winds from mesospheric echoes

Imaging with ISR dishes

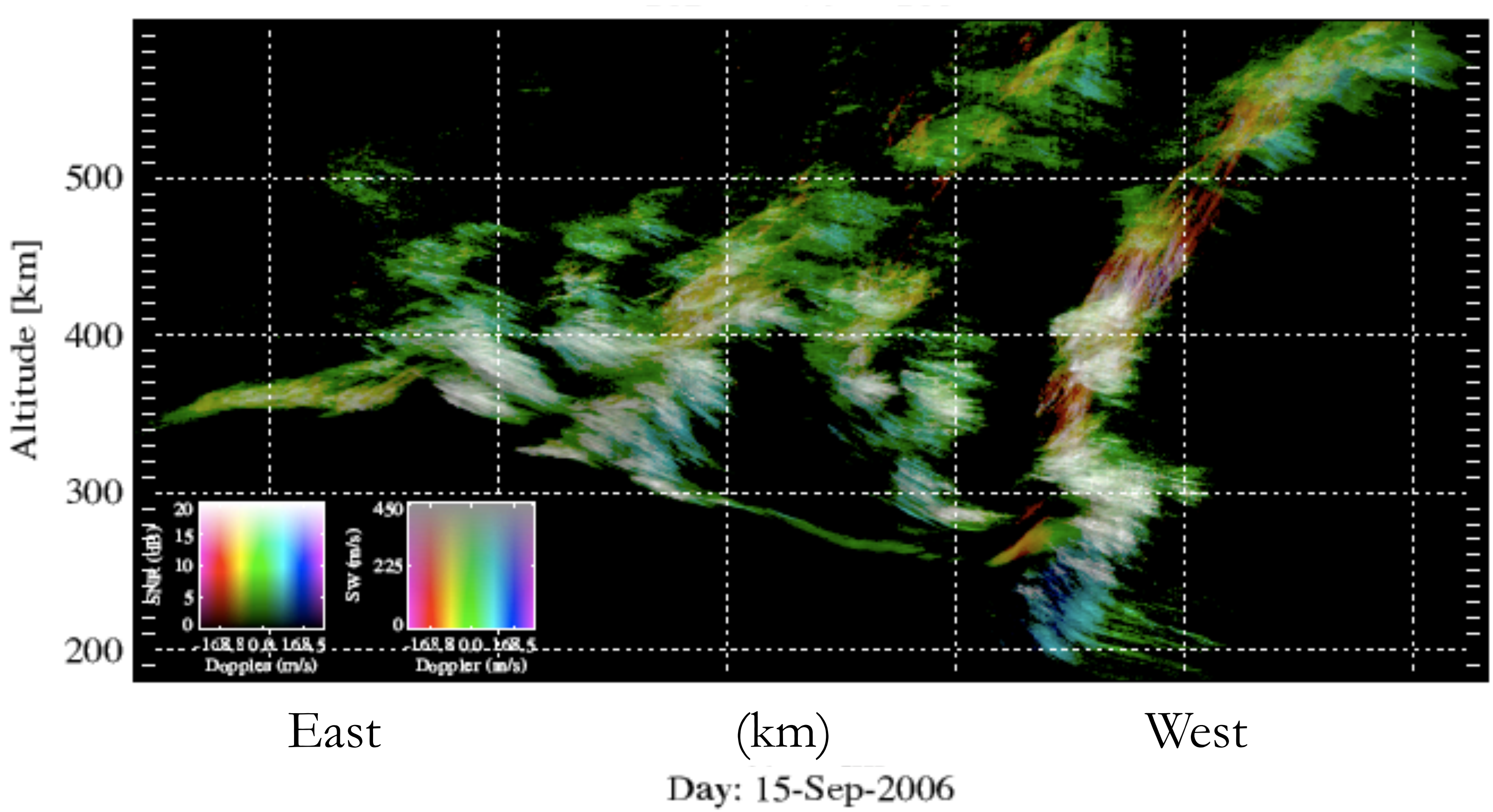


- Each positions is observed with 1,500 consecutive pulses, i.e., every few seconds
- Main assumption: spatial changes are "slow"
- When assumption is not good, fast beam-steering, multi-volume observations are needed:
  - AMISRs
  - EISCAT 3D

(see talk by J. Foster)

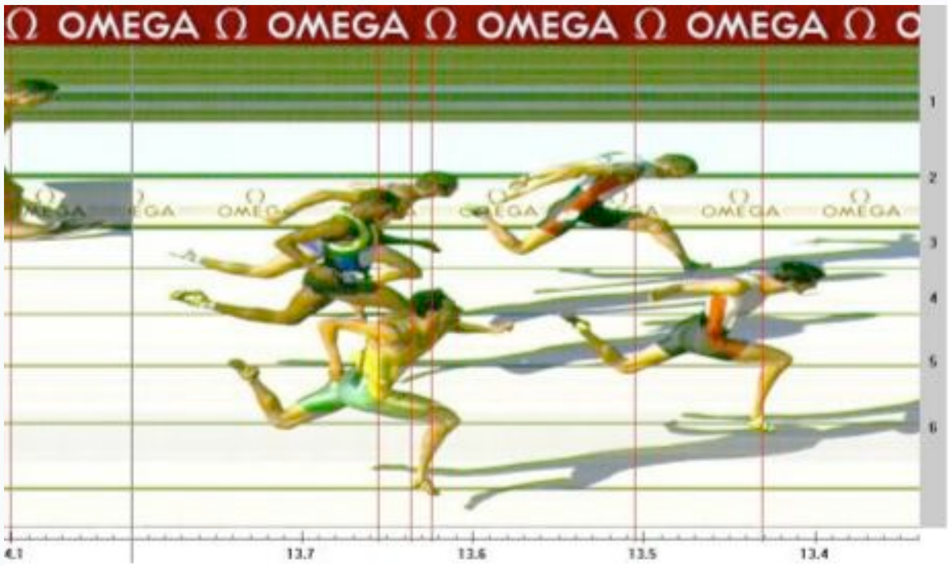
[Courtesy of A. Stromme]

ESF RTDI: Slit camera interpretation



Assuming spatial structures are frozen, drifting across the radar at a constant velocity, the RTI maps could represent “Images” (altitude vs. zonal) of such structures.

Slit-camera Analogy and Problems



- In some applications like races it is useful
- In many other applications it provides misleading results:
  - Slow structures are stretch out
  - Fast-moving structures are compressed.
  - In general, it is difficult to discriminate space-time features.

Aperture Synthesis Configuration

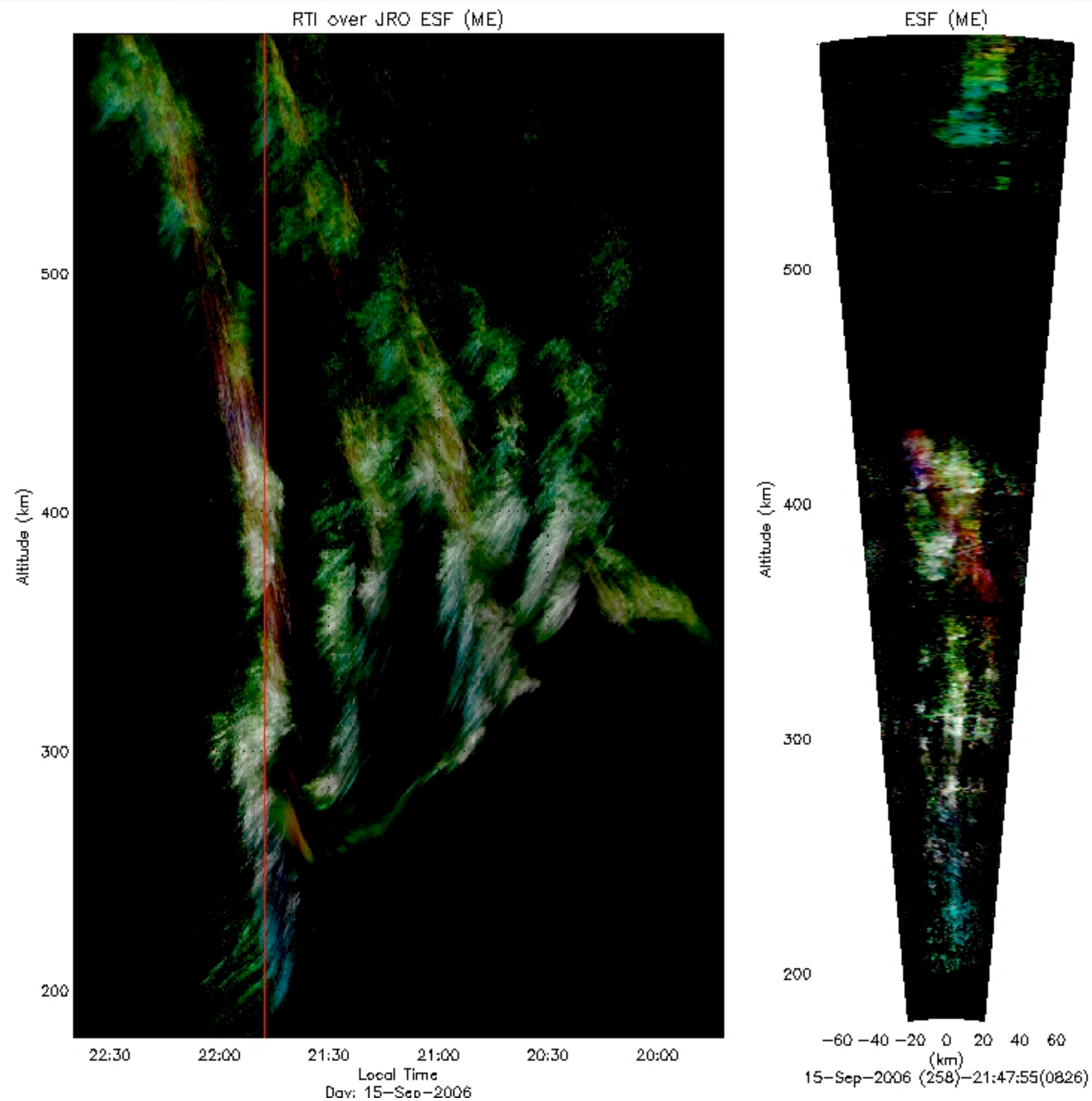
ESF Imaging: Narrow view

500

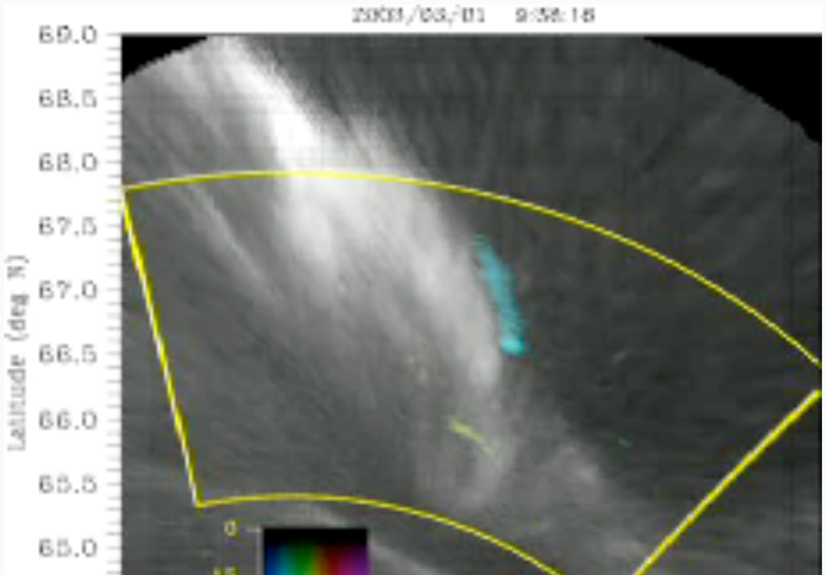
400

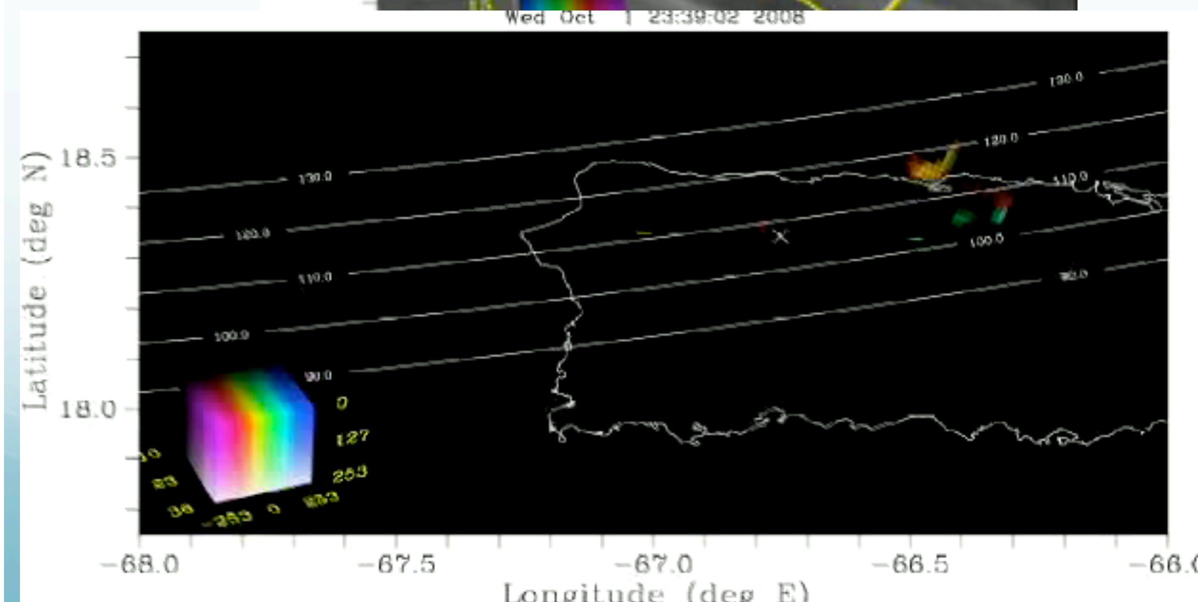
300

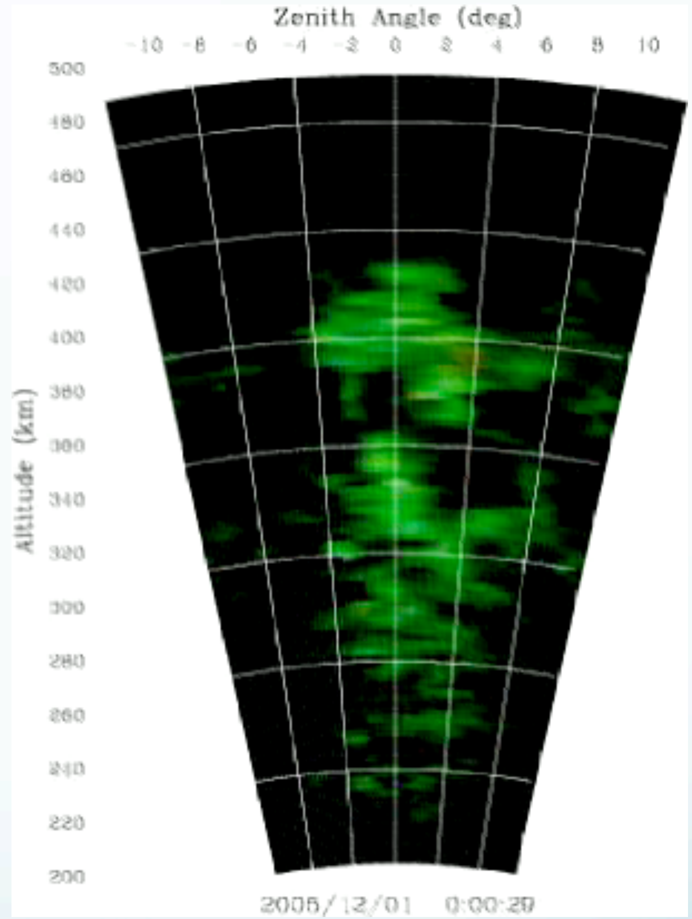
200



Imaging: Wider View





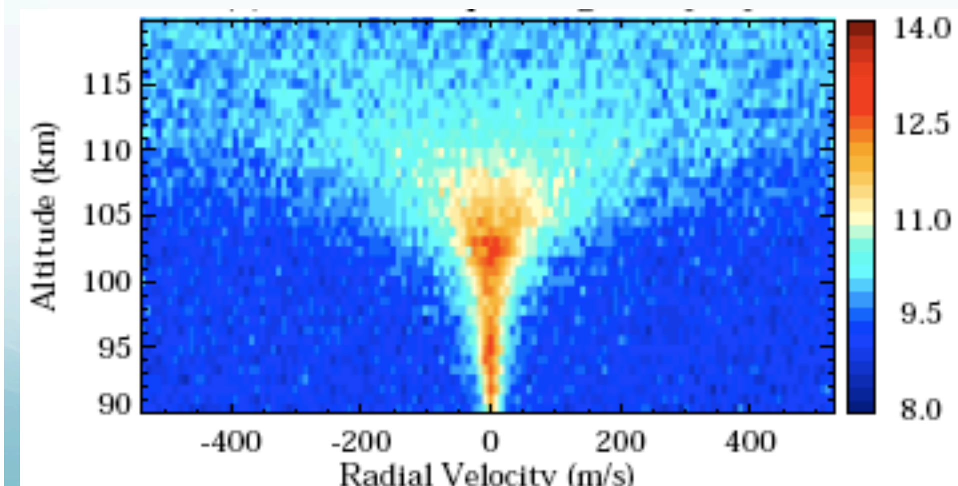


[Courtesy of D. Hysell]

Underspread Targets

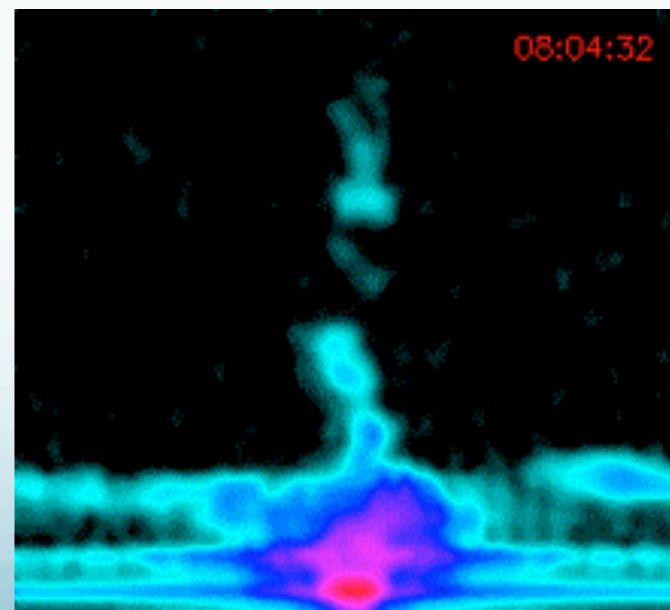
Incoherent

- Perpendicular to B
- Collisionally Dominated (e.g. D-region ionosphere)

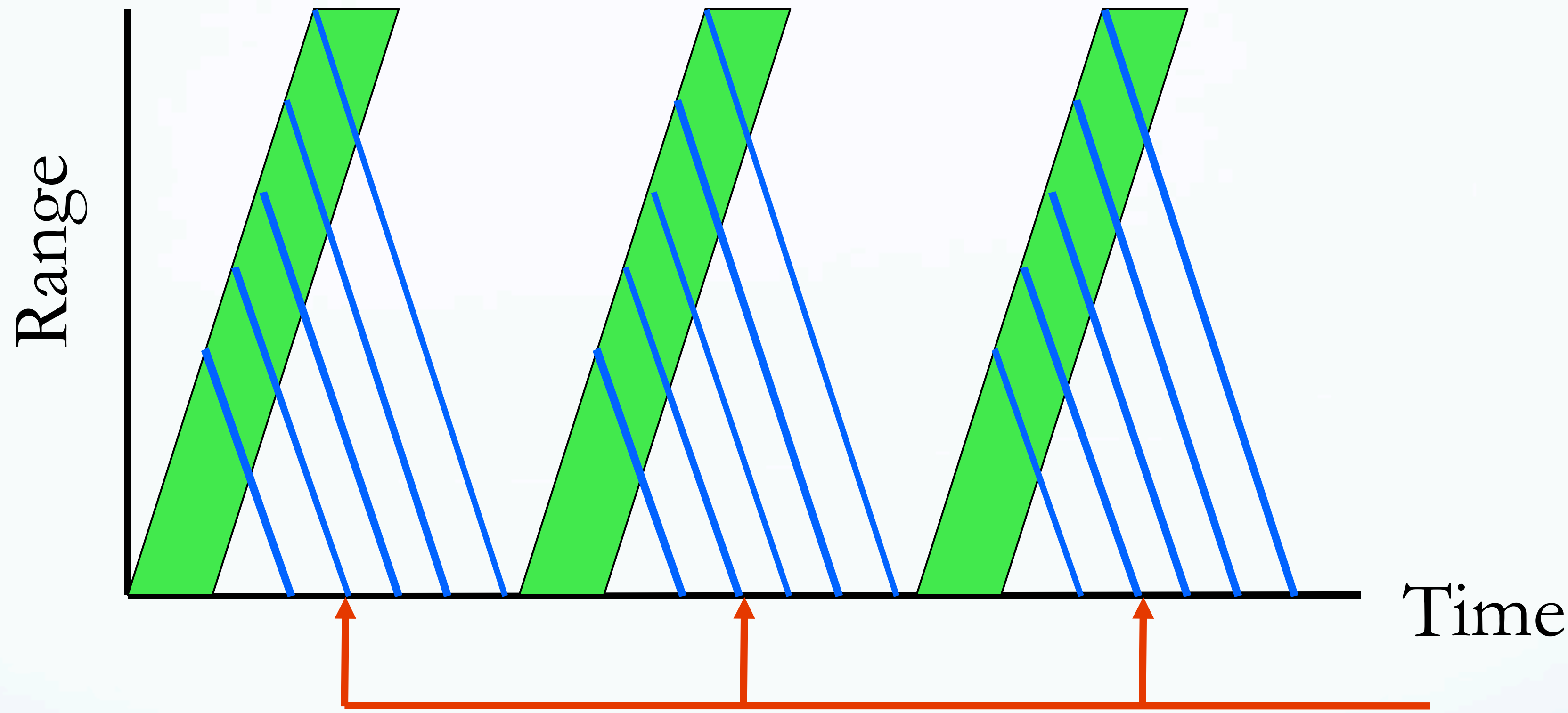


Coherent

- Turbulent Layers (e.g. MST Radars)
- Polar Mesospheric Summer Echoes (PMSE)
- 150-km Echoes

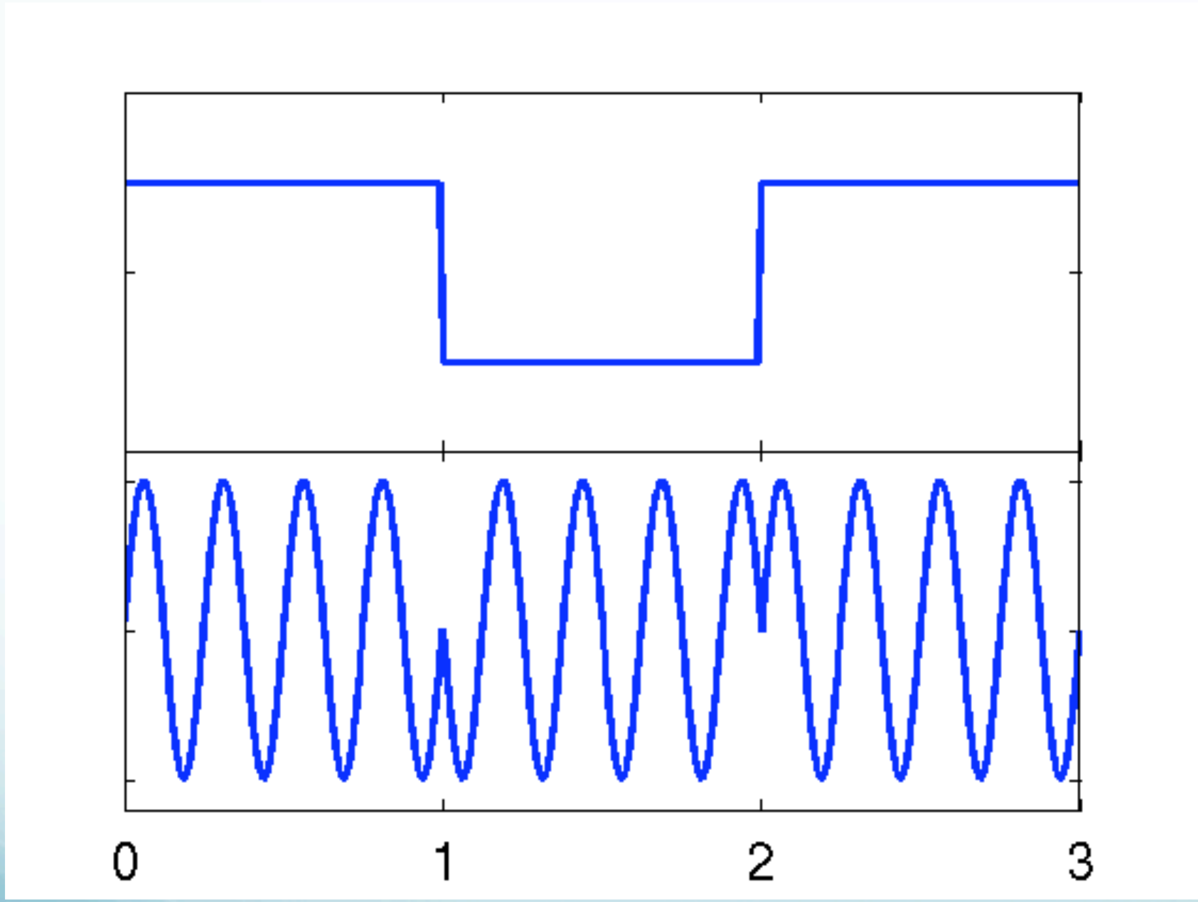


Range-Time Diagram



- Assume each range is independent
- The returns from each range form a time series sampled once per IPP

Binary Phase Codes



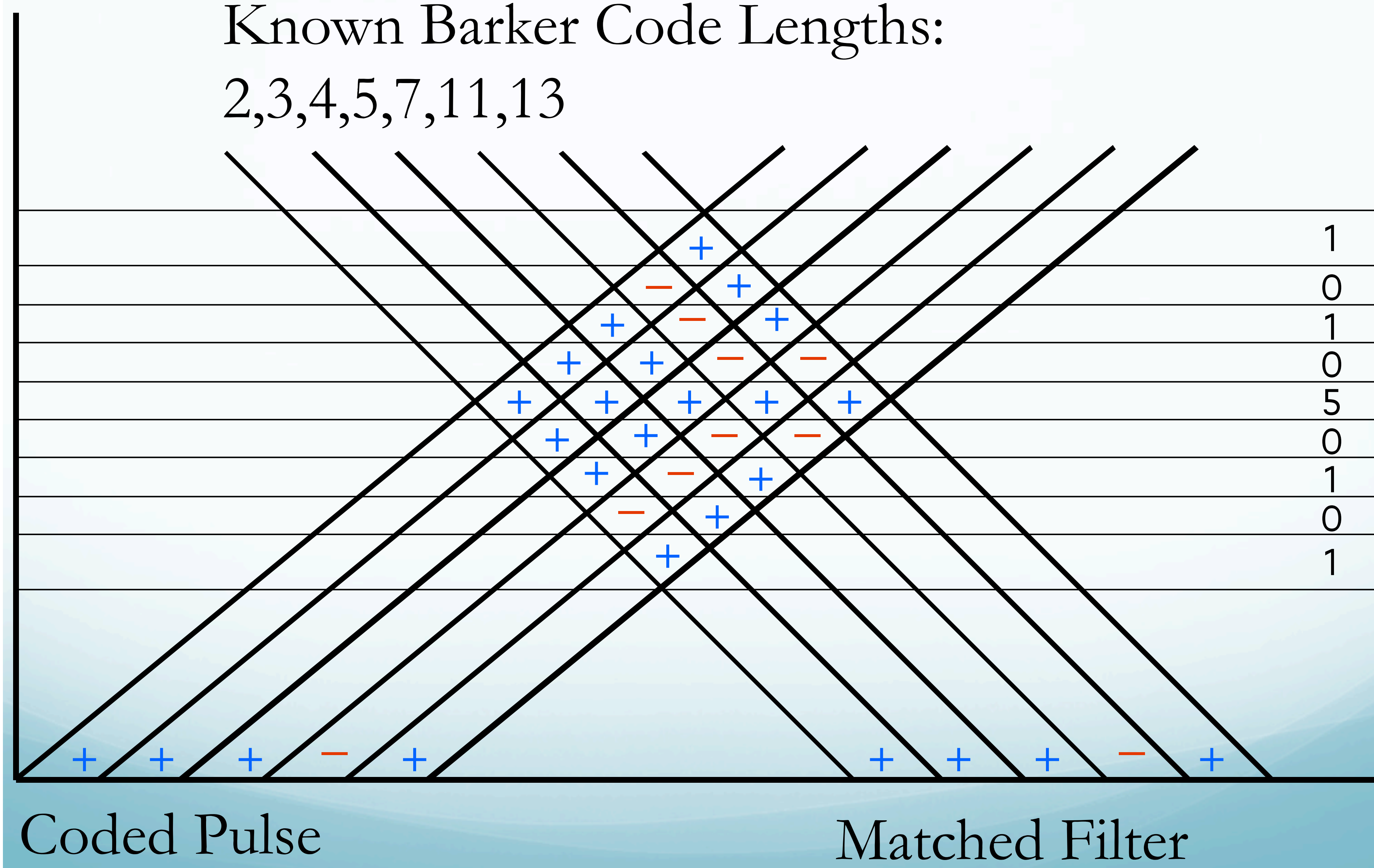
Code

Transmitted Waveform

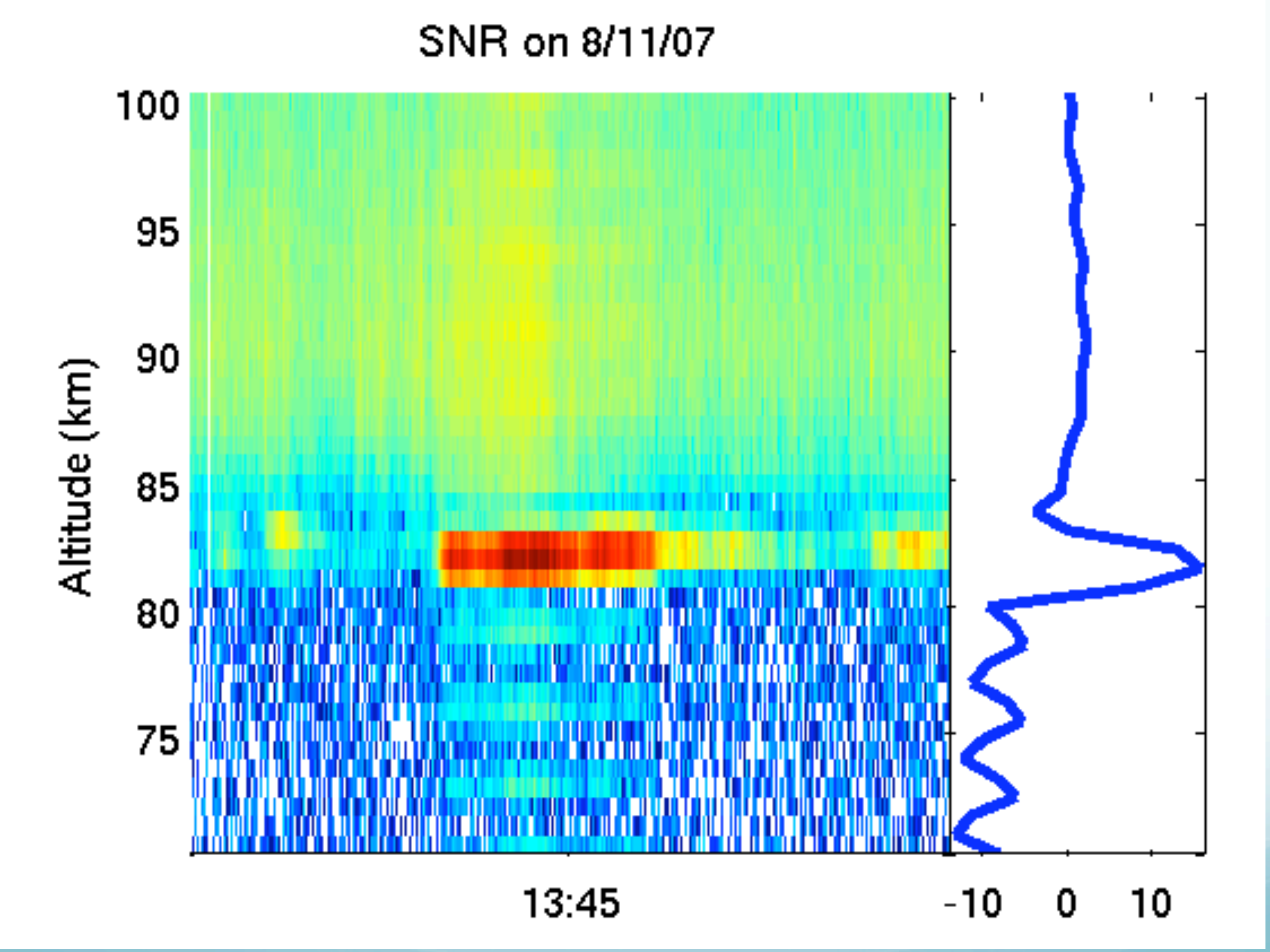
Barker Codes

Known Barker Code Lengths:

2,3,4,5,7,11,13

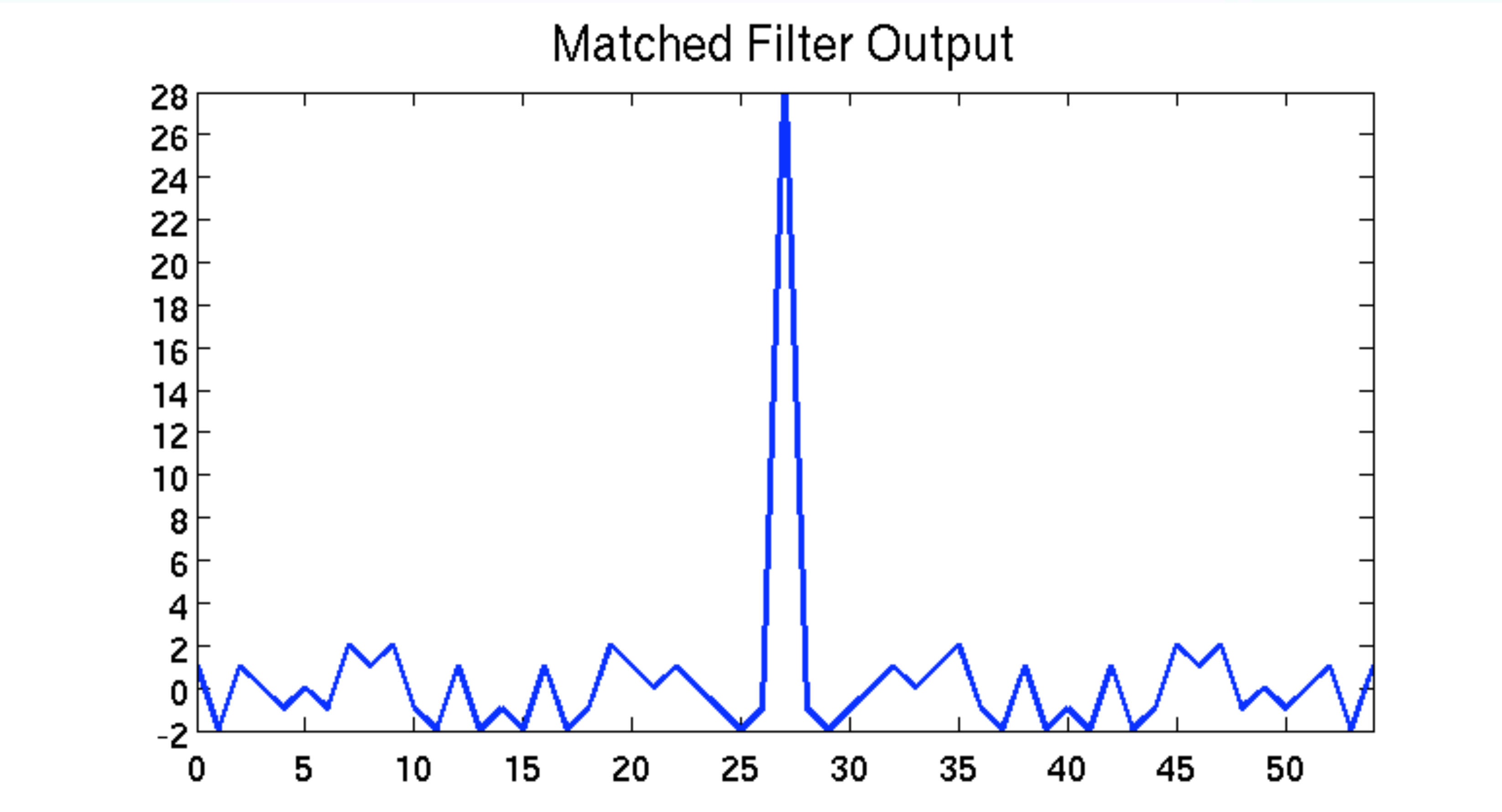


Range Sidelobes



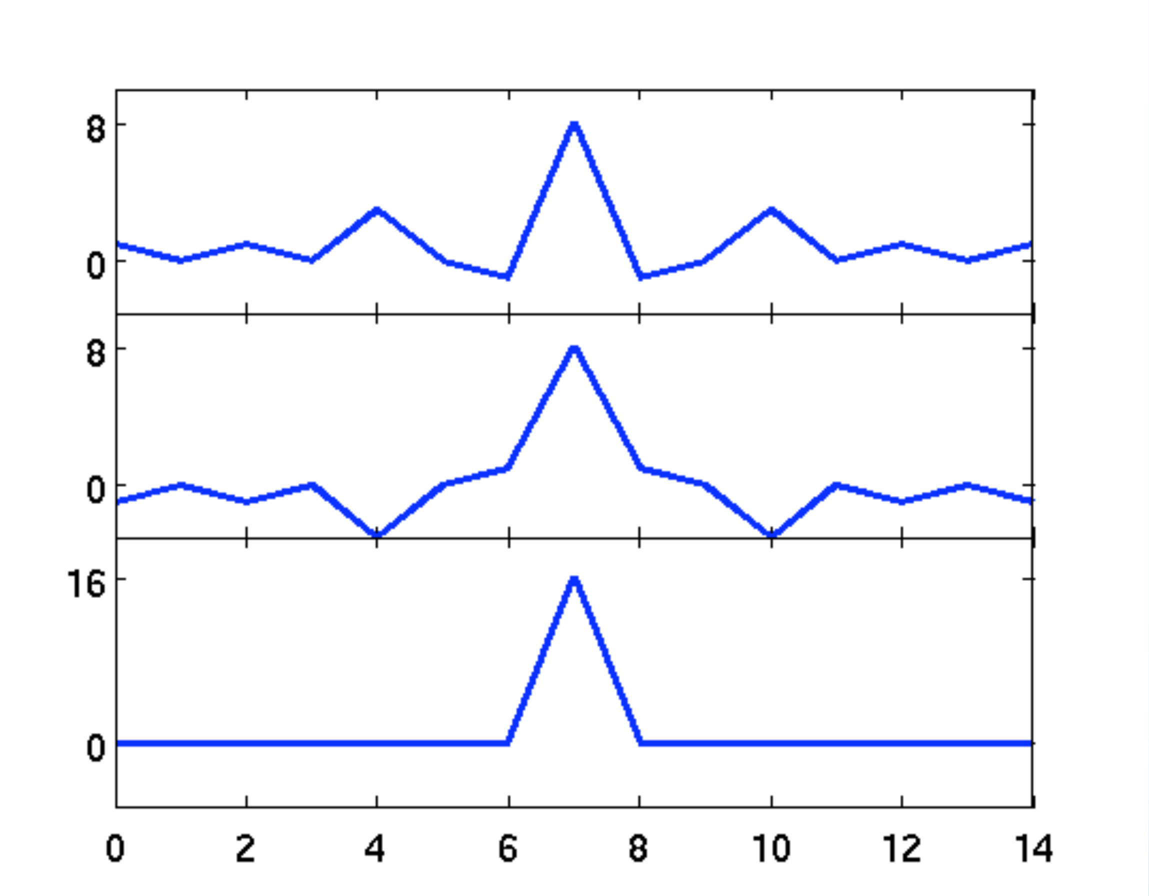
Other Binary Phase Codes

+---++++---+---+---+--+-++-+



Complementary Codes

Autocorrelation Functions



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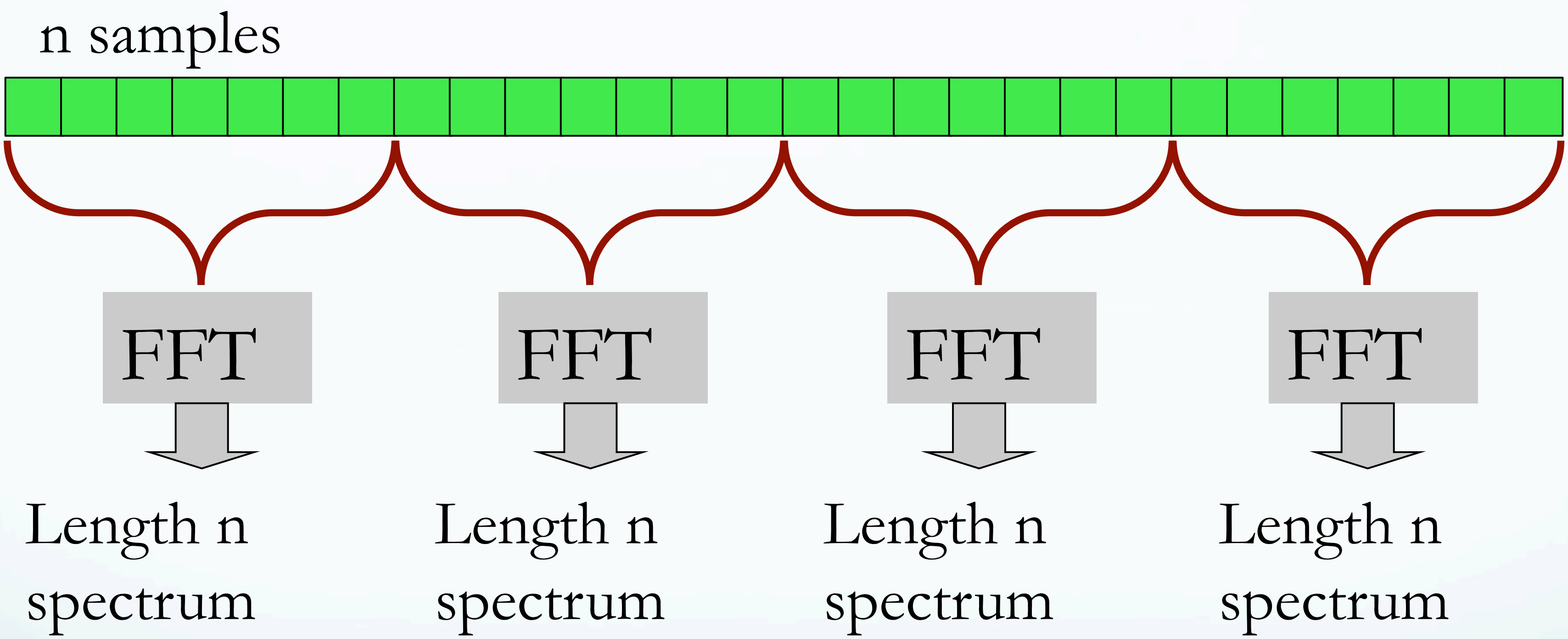
sum

Pulse to Pulse Spectra

Voltage Samples



- Nyquist Frequency: 0.5/IPP
- Spectral Resolution: 1/(n*IPP)

Typical Numbers

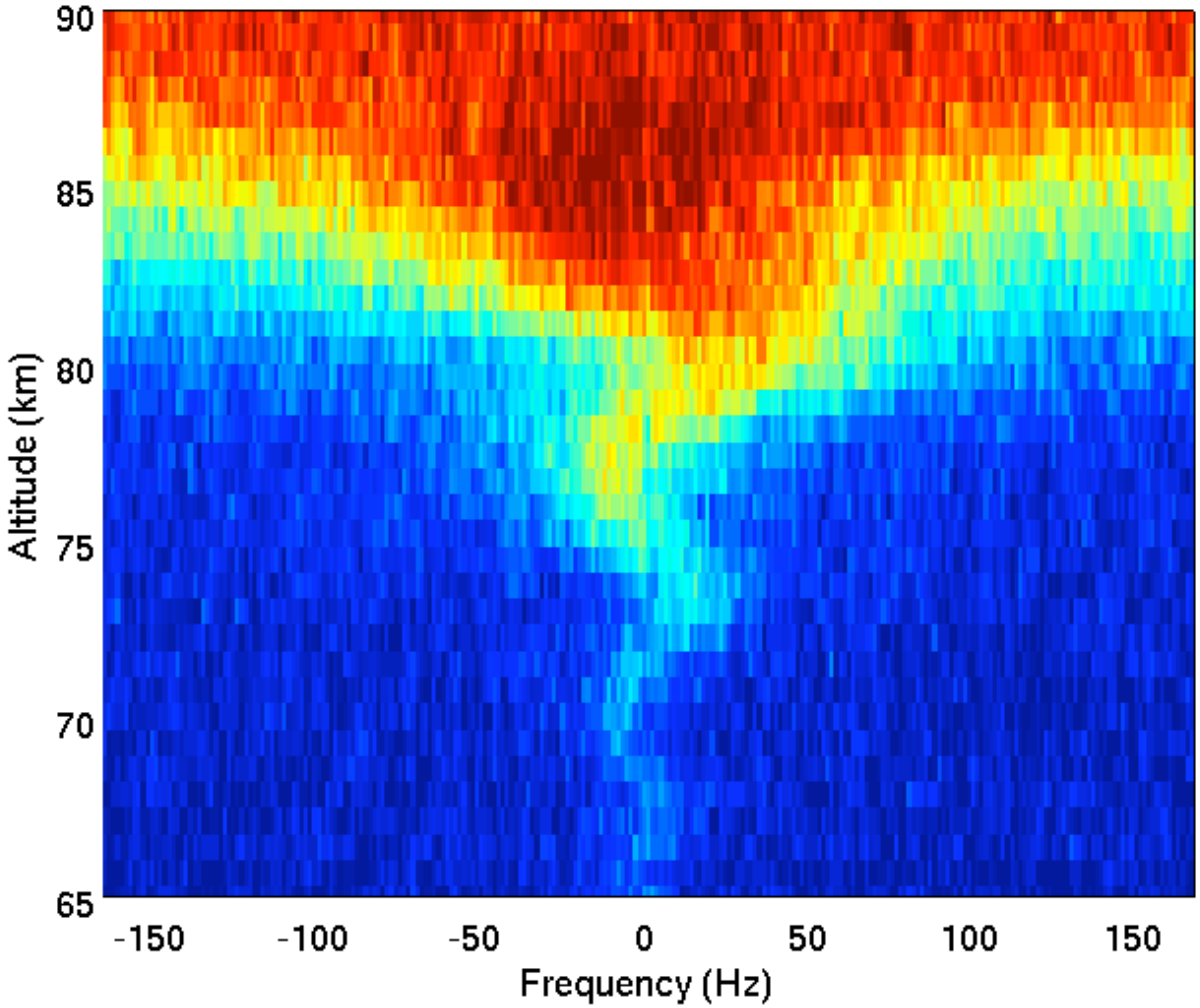
JRO Perp. **B**

- IPP = 6.66 ms
- Nyquist = 75 Hz (225 m/s)
- N = 64 pulses
- Frequency Resolution = 2.35 Hz (7 m/s)

PFISR D-region

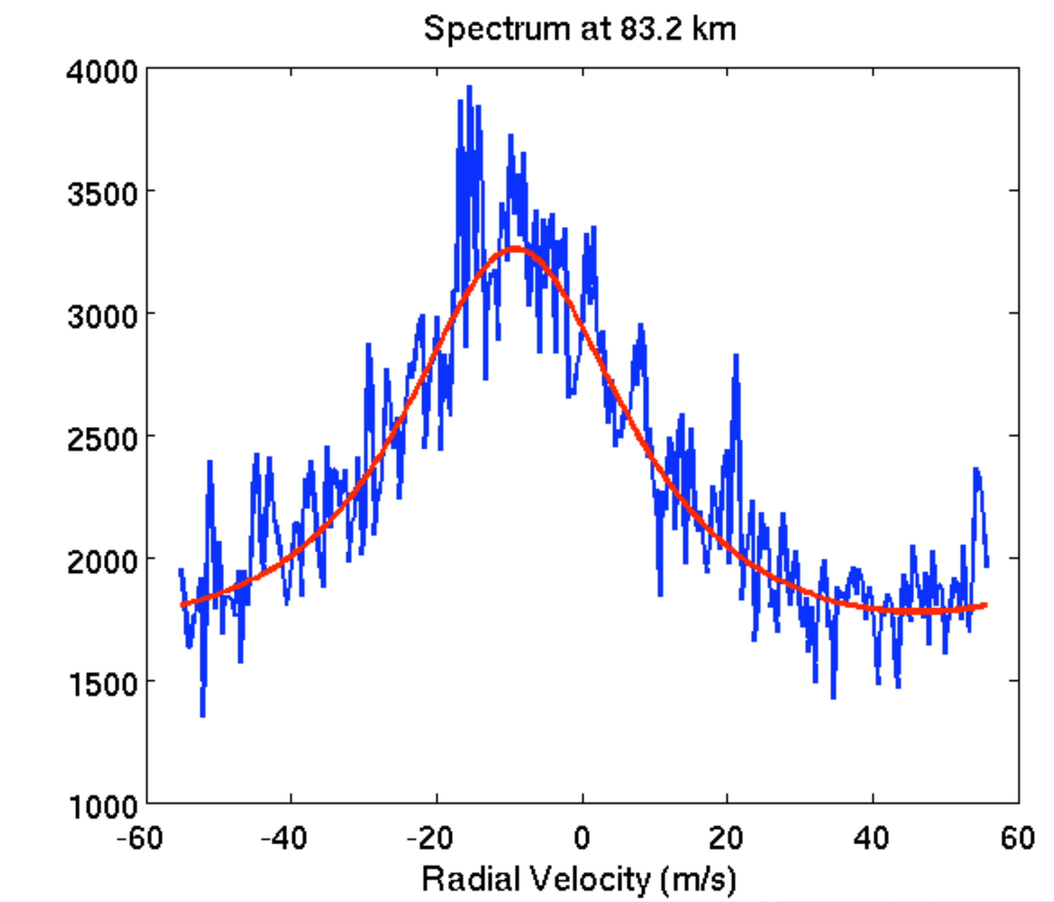
- IPP = 3 ms
- Nyquist = 167 Hz (56 m/s)
- N = 128 pulses
- Frequency Resolution = 2.6 Hz (0.87 m/s)

Example Spectra



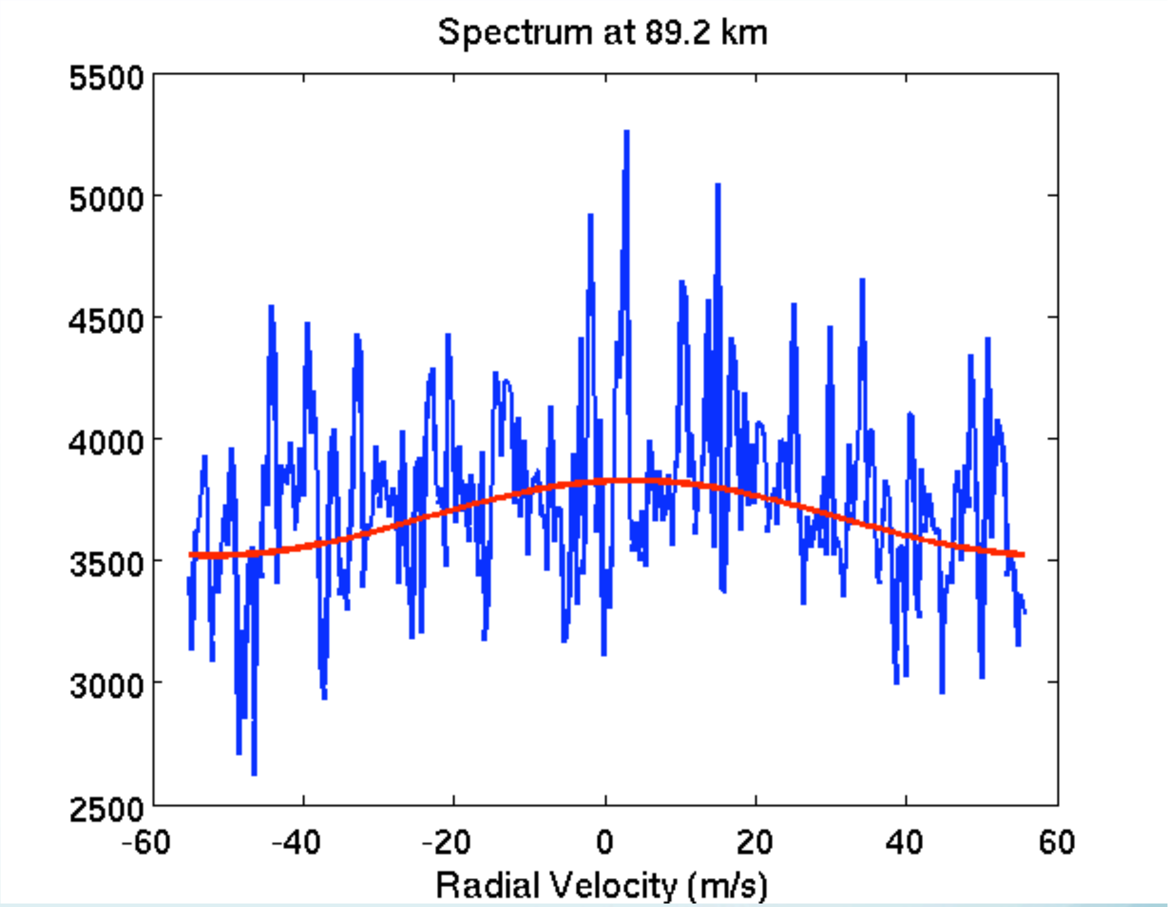
Aliasing

- Long tails of the spectra will alias
- When fitting, fold the model to compensate



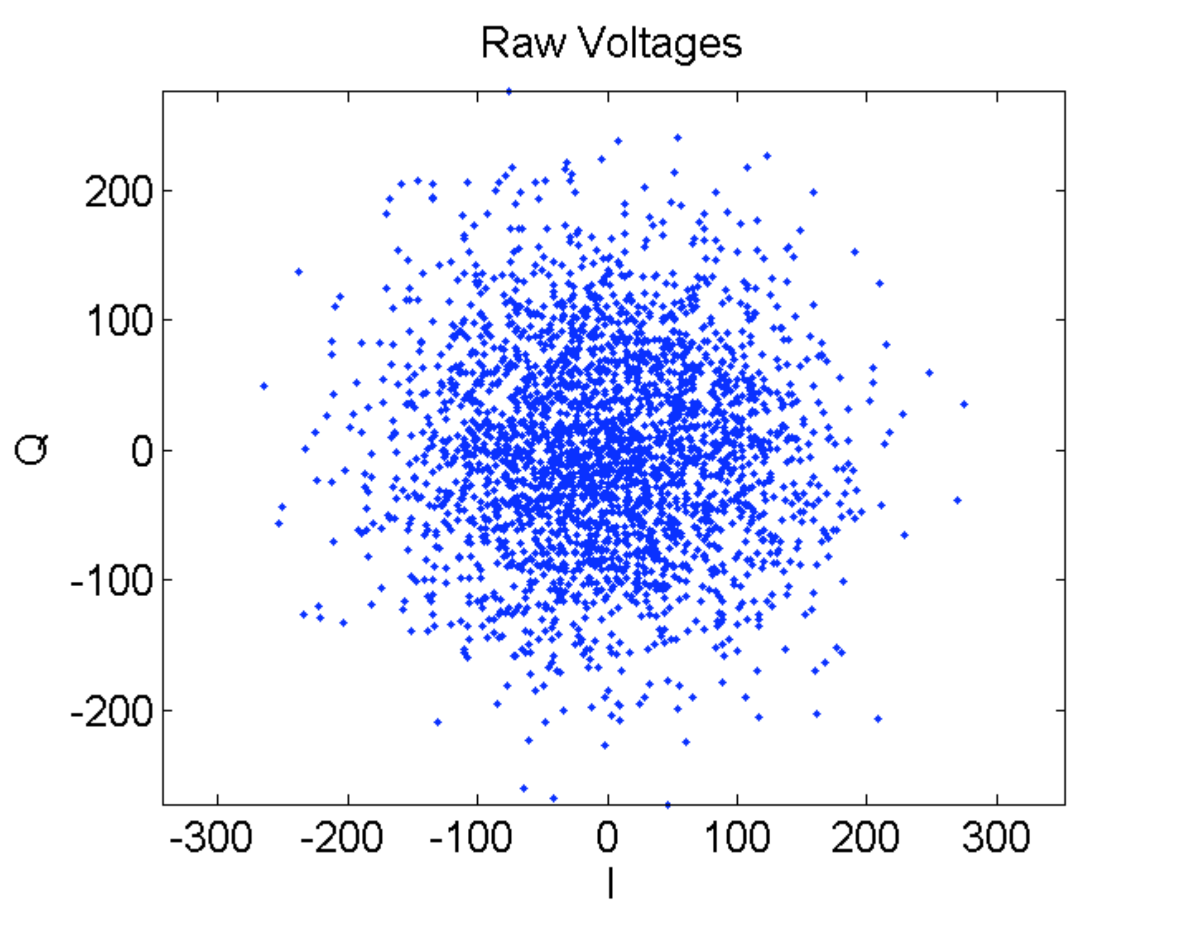
Aliasing

- Aliasing is more severe at higher altitudes
- Underspread processing is not appropriate



Statistics of Radar Signals

Received voltage is a Gaussian random process



Statistical Quantities

Definitions

- Variance (Power): $P = E[|V|^2]$
- Autocorrelation: $R(\tau) = E[V^*(t)V(t+\tau)]$
- Power Spectrum: $S(\omega) = \int_{-\infty}^{\infty} R(\tau)\exp(-i\omega\tau)d\tau$

Estimators

$$\hat{P} = \frac{1}{K}\sum_{i=1}^{K}|V_i|^2$$

$$\hat{R}(\tau) = \frac{1}{K}\sum_{i=1}^{K}V_{i1}V_{i2}^*$$

$$\hat{S}(\omega) = DFT\{\hat{R}(\tau)\}$$

Variance of Estimators

$$\hat{S} = \hat{P} - N$$

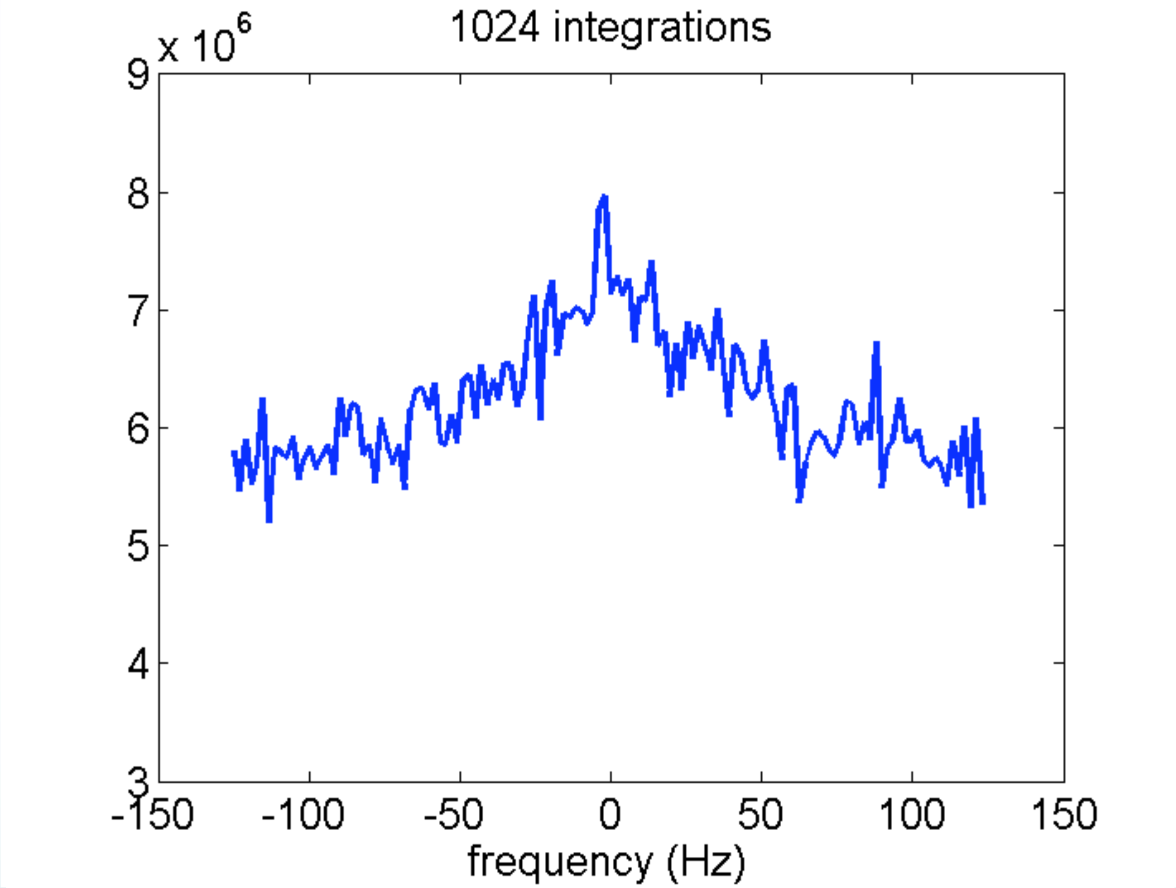
$$\delta\hat{S}^2 \approx \delta\hat{P}^2 = \frac{(S+N)^2}{K}$$

$$\frac{\delta\hat{S}^2}{S^2} = \frac{1}{K}\frac{(S+N)^2}{S^2}$$

$$\frac{\delta\hat{S}}{S} = \frac{1}{\sqrt{K}}\left(1 + \frac{1}{SNR}\right)$$

- Strive for SNR=1
- Little benefit from SNR>1
- A single estimate has over 100% error
- Some amount of incoherent integration is always necessary

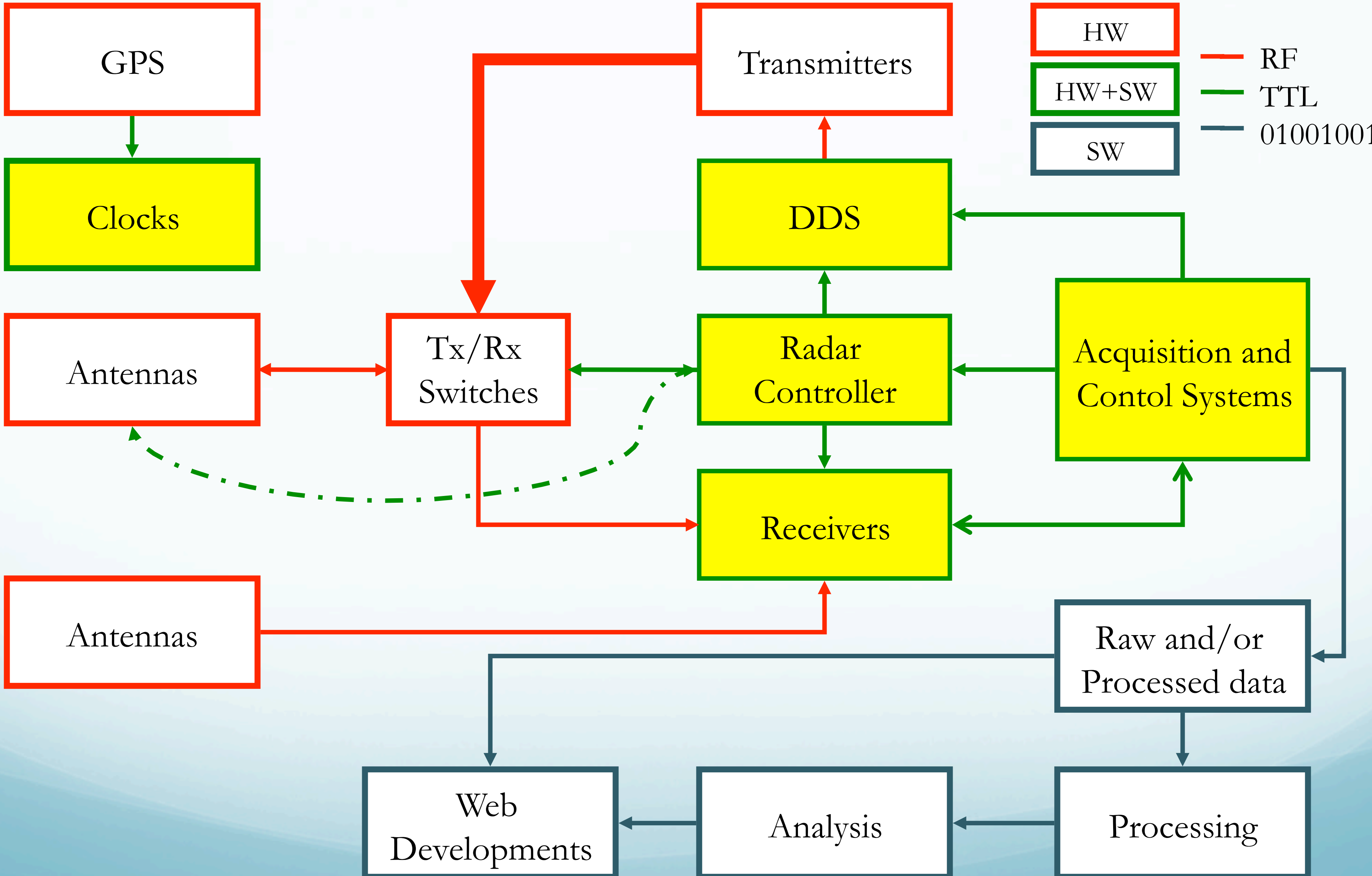
Incoherent Integration



Useful Links

- ISR Student Workshop (CEDAR 2006)
  - http://cedarweb.hao.ucar.edu/workshop/archive/2006/agenda_2006.html
- 2nd AMISR Science Planning workshop
  - http://www.amisr.com/meetings/2008/
- Incoherent scatter radar book by Farley and Hagfors, in progress.

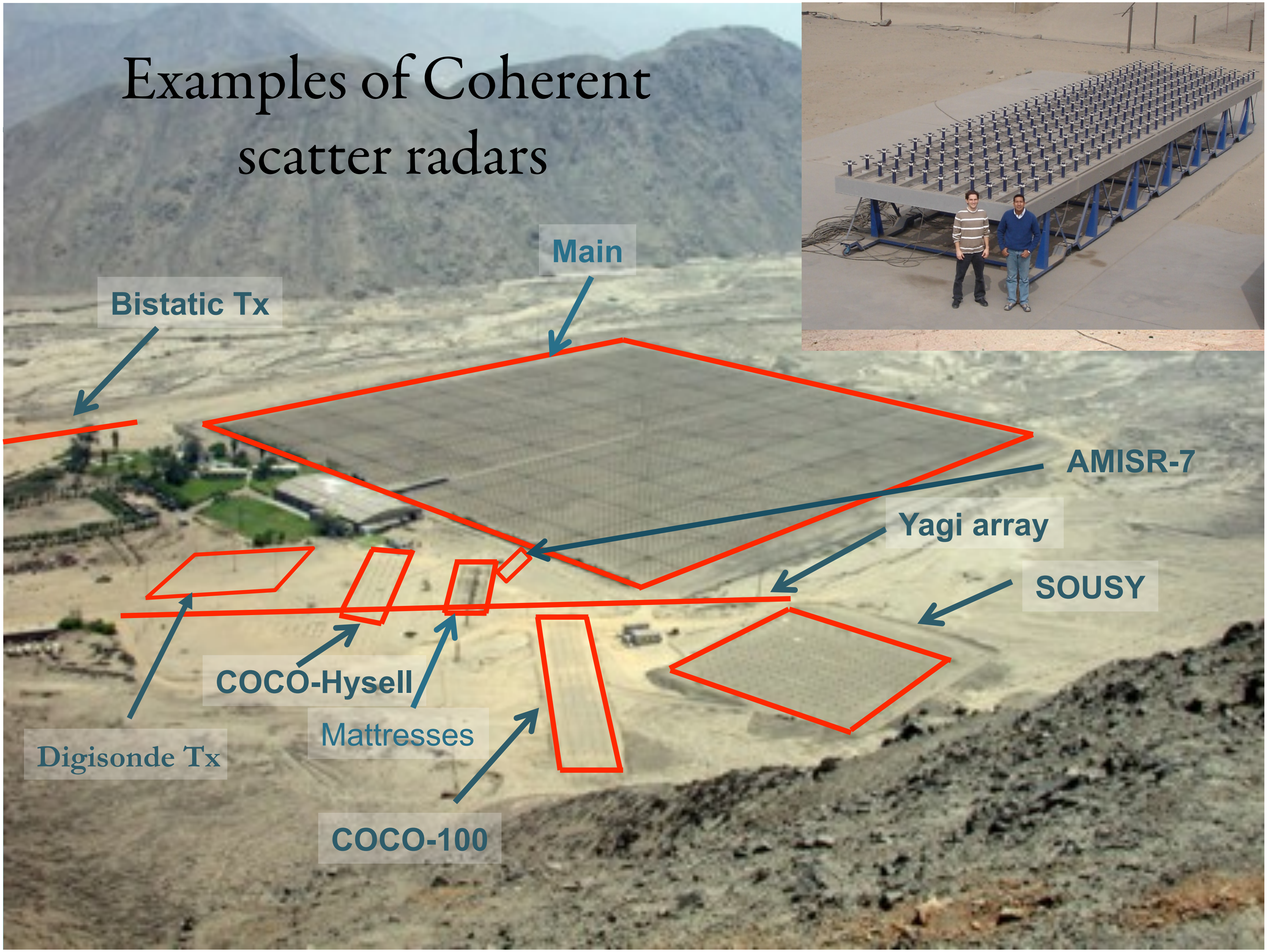
Radar: Block Diagrams



Incoherent Scatter Radars (1)

Incoherent Scatter Radars (2)

Examples of Coherent scatter radars



Additional considerations

- Coherent and incoherent signals are caused by refractive index fluctuations on the propagation path of transmitted radar pulses.
- At VHF and higher frequencies the scatter signal is so minor that there is no need to consider secondary scattering of the scattered signals or the extinction of a propagating pulse due to scattered energy.
- Linear superposition methods can be used to establish the relationship between scattered radar signal and the scattering medium [e.g., *Woodman,* 1991]