# Introduction to Ionospheric Radar Remote Sensing

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# outline

- What is radar?
- Why use radar to study the ionosphere?
- What are the basics of ionospheric radar techniques?

# What is radar?

- a mature acronym (lower case!) for RAdio Detection And Ranging
- the name of a class of technologies for remotely sensing point targets (like airplanes) and volume targets (like weather) by analyzing the scatter of radio wave illumination

# Why use radar?

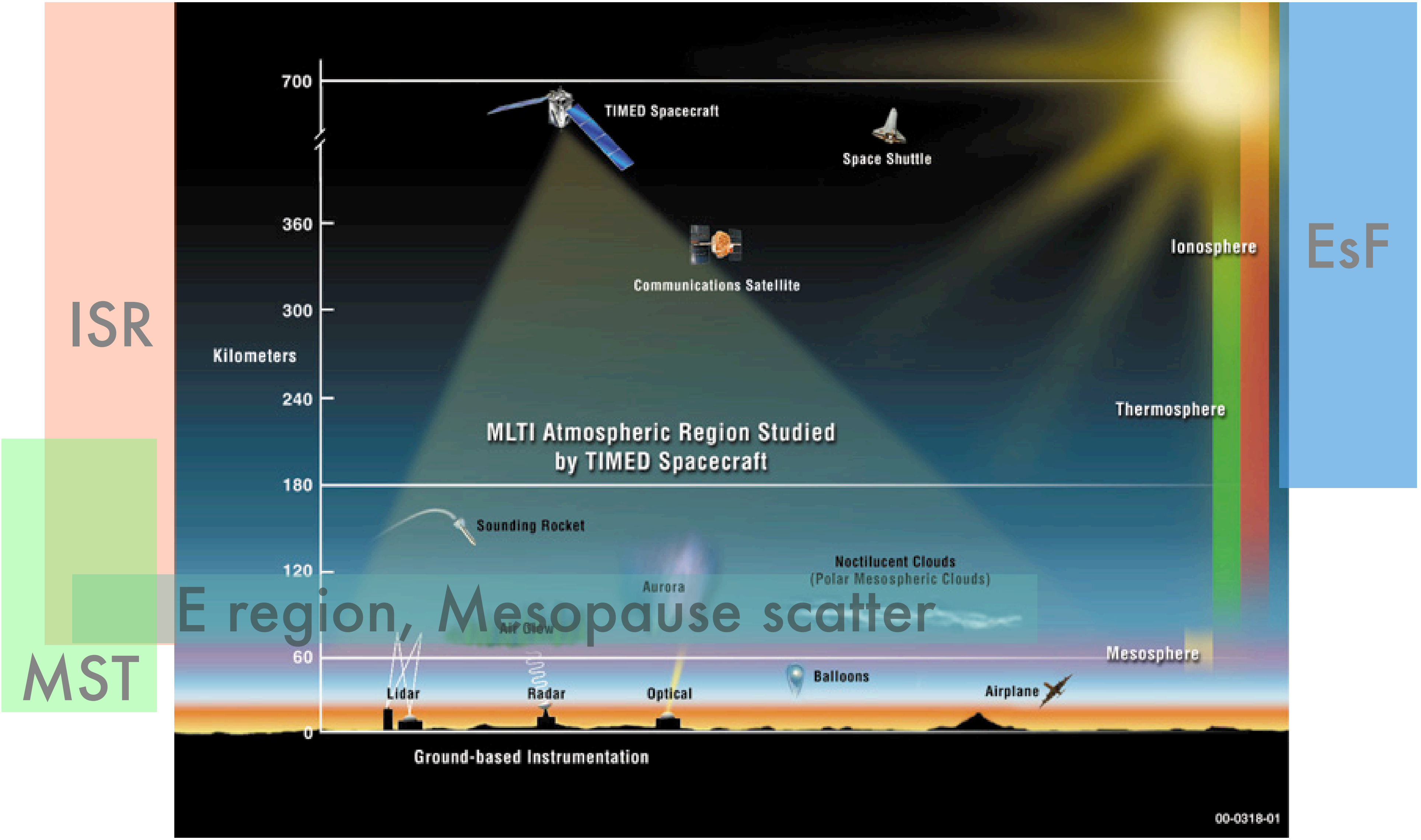
- as an alternative to *in situ* measurements (point vs. volume average)
- to probe particular parameters
- for very long observations over a fixed point on the Earth's surface

# High Altitude Radar Applications

- Incoherent (Thomson) Scatter: ion composition, concentration, temperature, drifts
- Coherent Scatter (plasma turbulence): plasma physics, and convection tracer, interferometry & imaging
- MS(L)T scatter (meso-, strato-, lower thermosphere): winds & waves (MLT region very tough for *in situ*!)
- Ionosondes (not really discussed here): plasma concentration profiling (bottomside only)

# From TIMED mission

http://www.timed.jhuapl.edu/WWW/science/images/00-0318-01large.gif



# Radar Basics

- Amplitude Information - how easy is it to detect?
- Spatial Information - where is it, and how big?
- Time, Frequency Information - how does it change or move?

# But what is the scatter from?

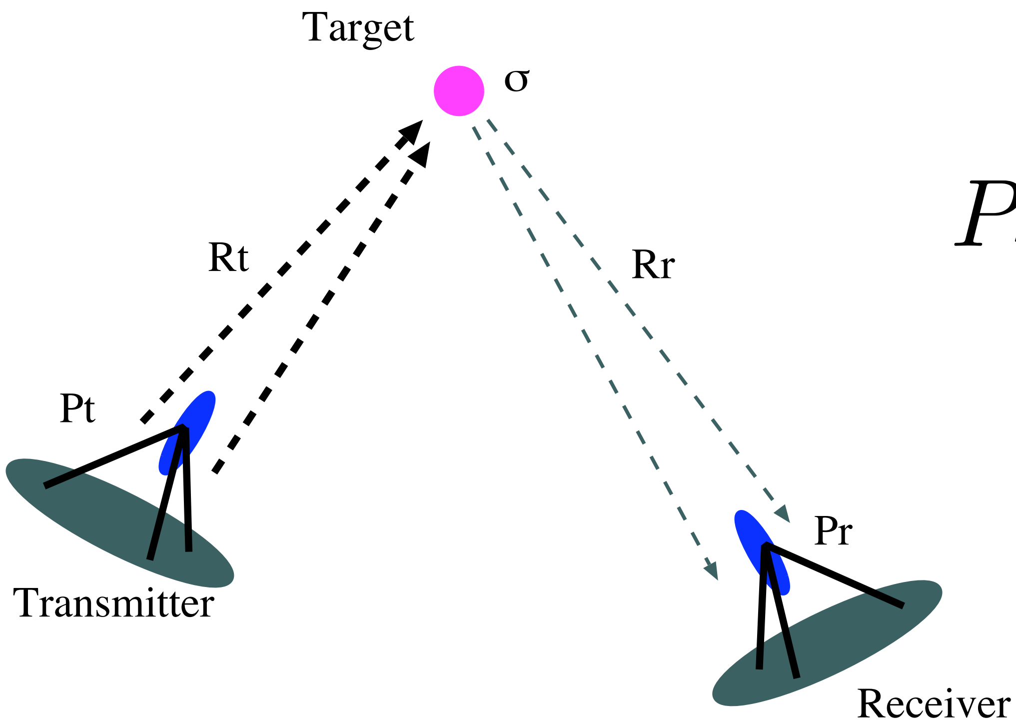
- Bragg Scatter: responsible for coherent and incoherent scatter.

$$\lambda_{radar} = 2\lambda_{scatter}$$

- Sharp changes in index of refraction: meteor scatter
- Total Internal Reflection (ionosondes)

# The Radar Equation

- Relates the received signal strength to transmitter power, antennas, distance, and target size

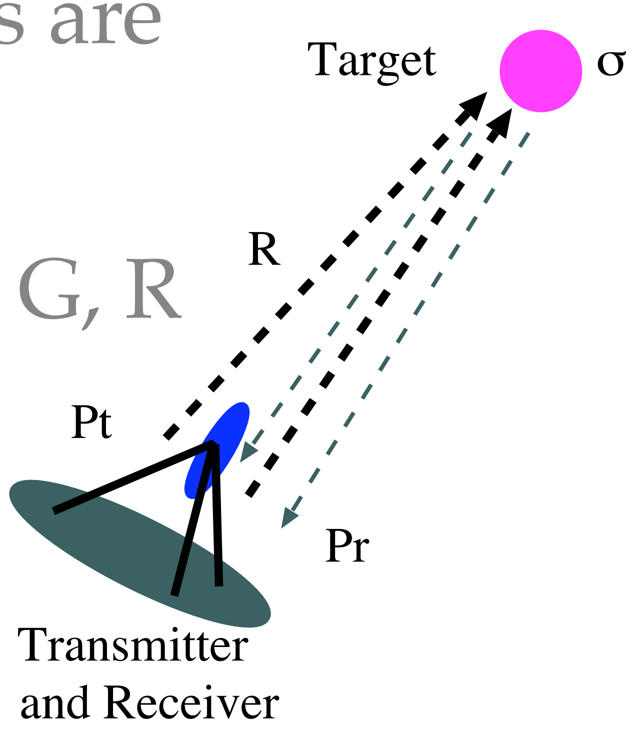



$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2}$$

# Monostatic Radar

- For many radars, the transmitter and receiver share one antenna. Such radars are said to be "monostatic."
- Almost all ionospheric radars are monostatic.
- Simpler radar equation: only G, R

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



# Signal to Noise Ratio

- The Received power Pr can seem very small ... but is it?
- Compare the received power to competing signals:
  - environmental signals/sky noise
  - system noise
  - clutter -- unwanted signals from our transmitter
  - jamming -- other transmitters

# Signal to Noise Ratio (2)

- often lump everything into Tsys
- note that the clutter power scales with the transmitter power Pt
- mitigation by quieter electronics, low antenna sidelobes, careful bandwidth control, and appropriate waveforms

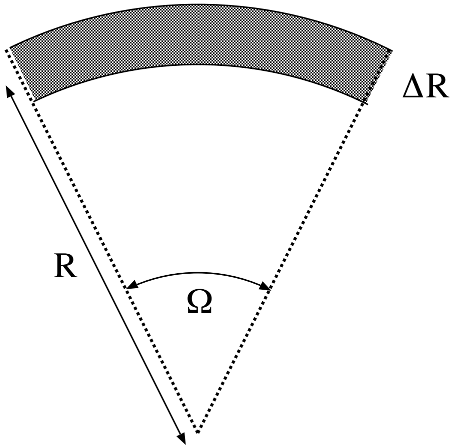
$$P_n = k_B T_{sys} B + k_B T_{sky} B + \alpha P_t + P_j$$

# What about the target?

- The target size $\sigma$ tells you how easy it is to detect
- Has units of area (bistatic radar cross section) (N.B. Physics definition of "differential cross section" is scaled "per steradian")
- Many ionospheric targets are volume scatterers ...

# Scattering Cross Section

- How much target do you see (monostatic)?
  - Antenna Beam Shape
  - Range Resolution
  - Volume Scattering Cross Section $\sigma_v$ has area/volume units




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

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

# Radar Equation for Volume Targets

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

- Signal proportional to Megawatt-Hectares
- Signal proportional to range resolution
- Signal inversely proportional to R^2 (not R^4)
- ... However some targets are inverse R^3, R^4, or R^8 (!)

# Rough Comparison ...

| Instrument | approx Pt A (MW Hectares) | Tsys+sky (K) |
|---|---|---|
| Arecibo | 10 | 100 |
| JRO | 10 | 20,000 |
| MH | 0.3 | 100 |
| Sondrestrom | 0.1 | 100 |
| AMISR | 0.3 | 300 (?) |
| EISCAT UHF | 0.1 | 100 |
| EISCAT Svalbard | 0.2 | 100 |
| MU | 0.8 | 10,000 |
| MRR | 0.0001 | 2000 |

# Incoherent Scatter Target

- For an F peak ionization (1E12 per cubic meter), and
- At a slant range of 500 km, and
- And a range resolution of 1 km, and
- For a Millstone Hill-like transmitter + antenna ...

the scattering cross section is about the size of a pencil eraser

# Range Estimation

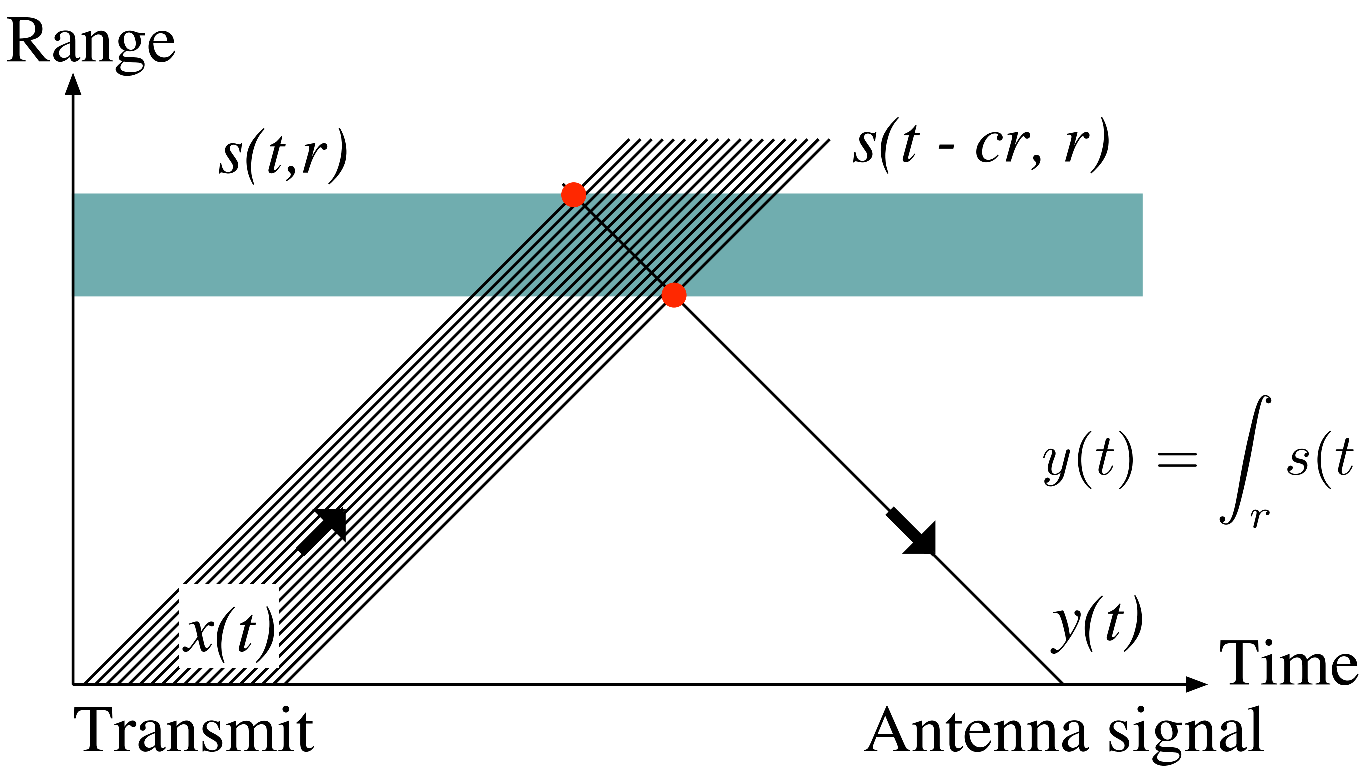
Range is estimated from time of flight

- speed of light = 3 x 10^8 m/s
- speed of radar = 1.5 x 10^8 m/s
- ... or 150 km/ms

The E region is 1 ms away
The F region is 3 ms away
The Plasmasphere is 10 ms away

# The scattered signal

- target interrogated in space-time
- antenna signal y(t) is further processed...




$$y(t) = \int_r s(t - cr, r)x(t - 2cr)\, dr$$

# Range Resolution

- The antenna signal *y(t)* is passed through the impulse response of the receiver *h(t)*
- If the scatterer is a point target, then the final receiver output *z(t)* is the convolution of *y(t)* and *h(t)*

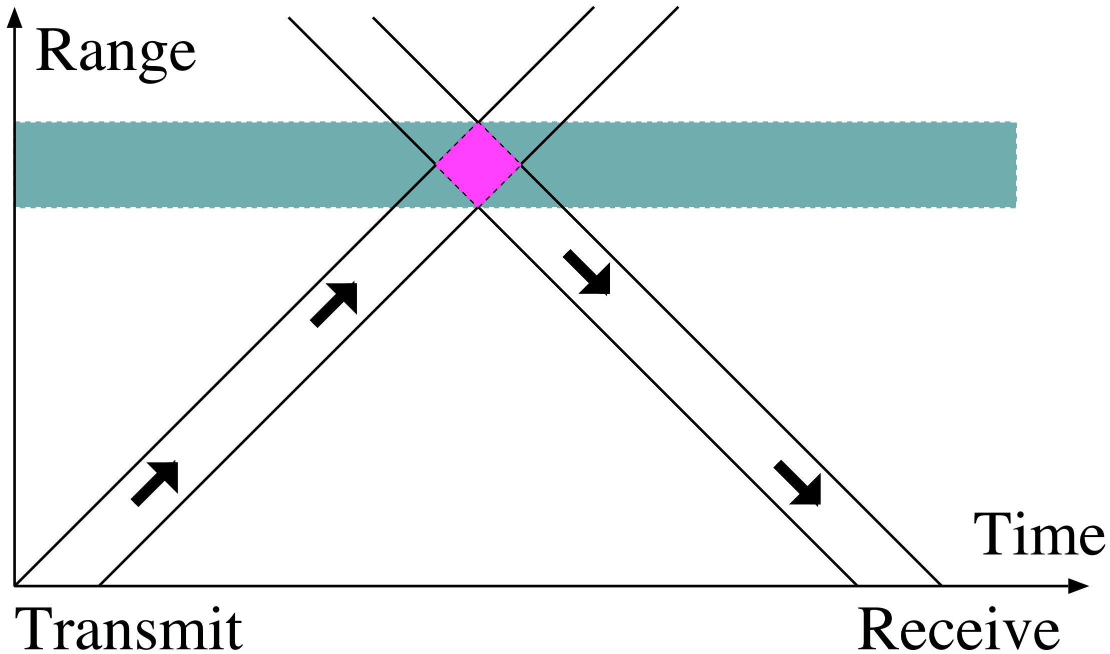
$$z(t) = \int_{\tau} y(t-\tau)h(\tau)\, d\tau$$

# Range-Time Diagram

Range Resolution for a simple, matched pulse

$h(t) = x^*(t)$

is triangular weighting of possible ranges




Transmitters look forward in time
receivers look backward

# Radar Postulates

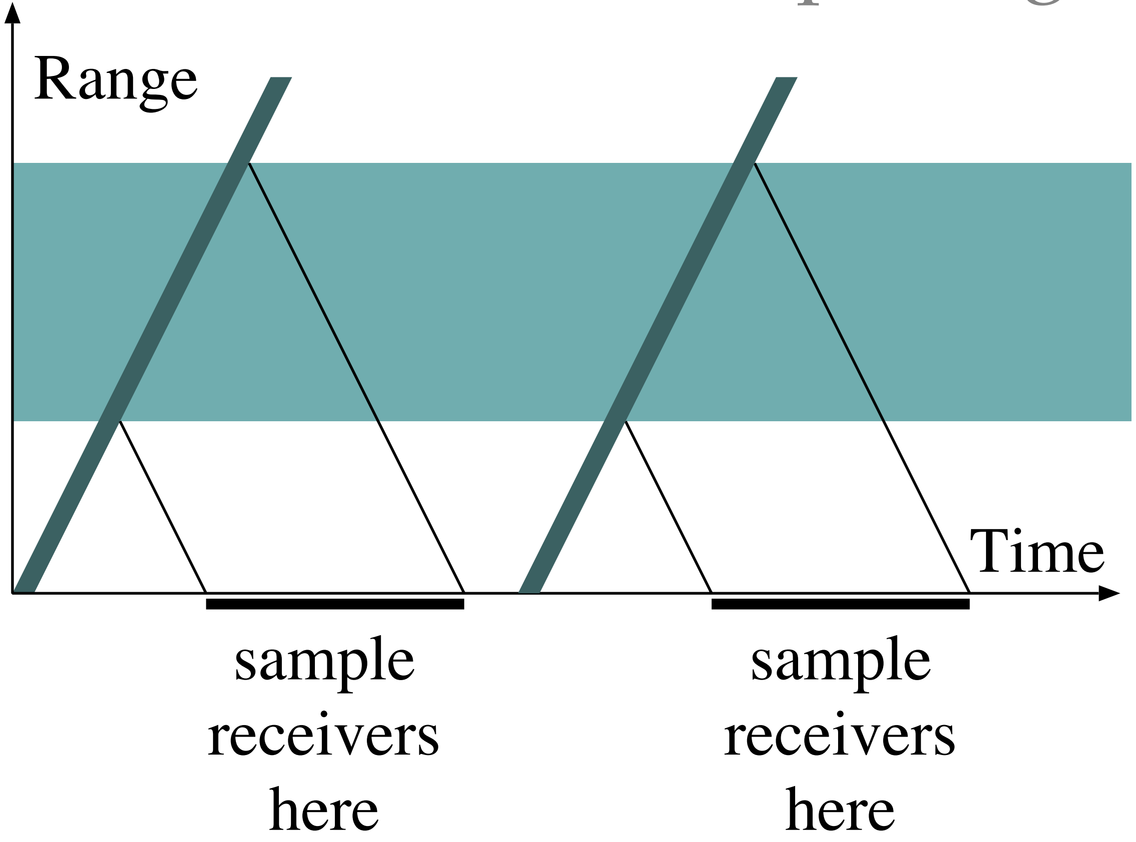
- **Volume independence**: The signal scattered from different places is statistically independent (true down to a few meters)
- **Stationarity**: The signal scattered from a particular place is statistically stationary (true down to a few seconds; perhaps a few minutes)

$$\langle s(\vec{r}_1, t_1) s^*(\vec{r}_2, t_2) \rangle = R(t_1 - t_2; \vec{r}_1)\, \delta(\vec{r}_1 - \vec{r}_2)$$

*statistically stationary* means that the statistics are not a function of time, not that the process is constant

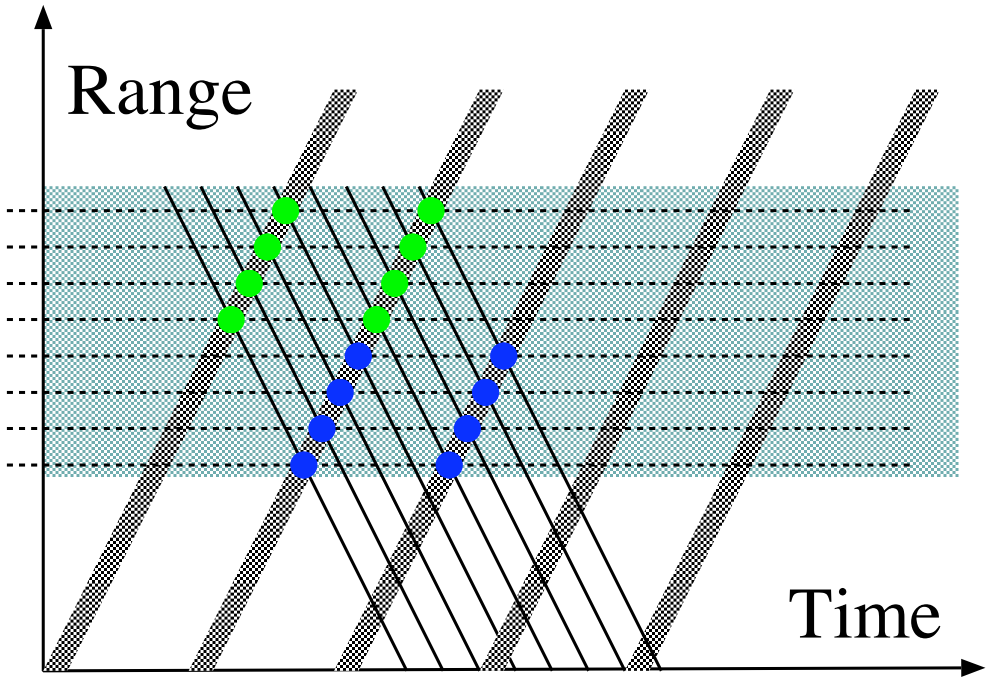
# Range Ambiguity

- Radar Pulses need to be far enough apart so that that all the signal has returned before the next pulse goes out:



# Range Ambiguity

- If the radar pulses are too close together, then signals from different ranges will show up in the receiver at the same time:




Note that the transmitter buries some received signals

# Target Bandwidth

- The target amplitude fluctuates due to target turbulence.
- The target amplitude fluctuates due to mean motion (Doppler Shift)

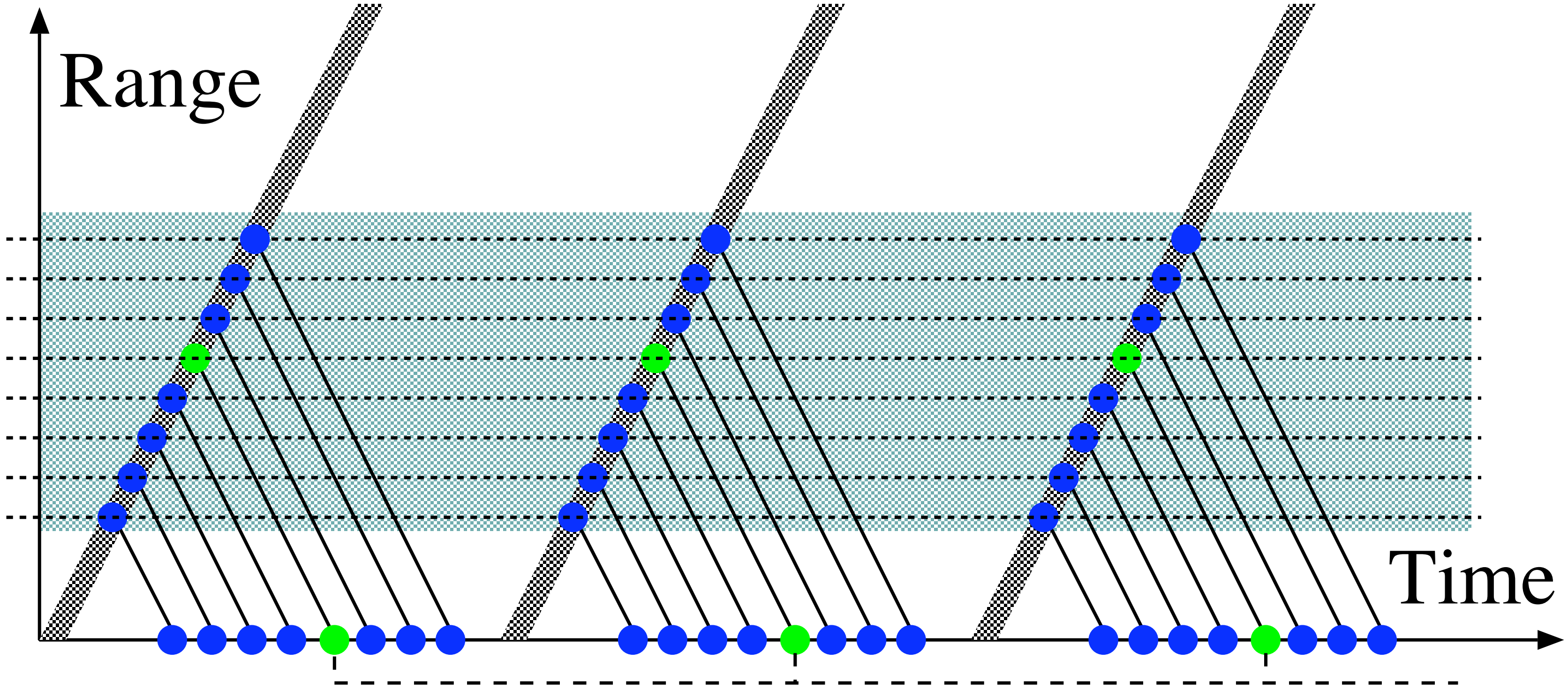
$$e^{-j[\omega t - k(r_0 + vt)]} \rightarrow e^{-j[(\omega - kv)t - kr_0]}$$

$$\Delta\Omega = -kv = -2\pi\frac{v}{\lambda} \quad \text{one way}$$

$$\Delta f = -2\frac{v}{\lambda} \quad \text{two way}$$

# Time Series Analysis

- First Spectrum Estimation Idea: Periodogram: Time Series, Window, FFT, square, average.



# Periodogram

- Works fine when you can sample at or above the Nyquist Rate
- Doesn't work when you cannot sample at the Nyquist Rate! (Overspread)
- (May be too much work if the target evolves slowly. (Strongly Underspread))

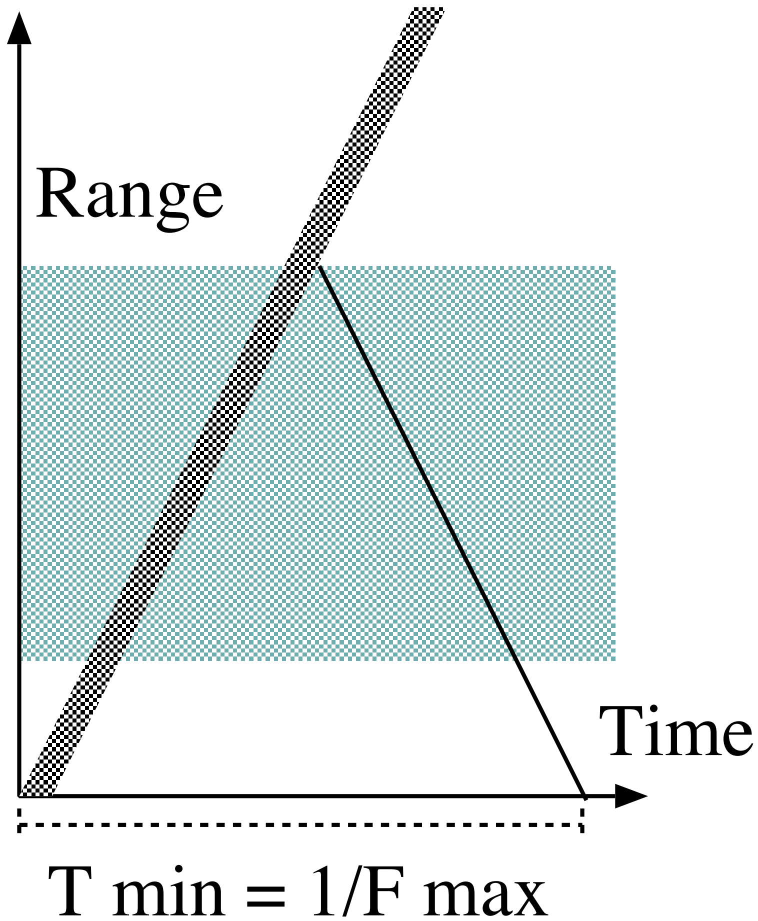
# Overspread Targets

- For a target with total bandwidth $B$, you must IQ sample at a rate $F$ exceeding $B$.
- For a target which could be as far away as $R_{max}$, the radar pulses must be at least $2 R_{max}/c$ apart.

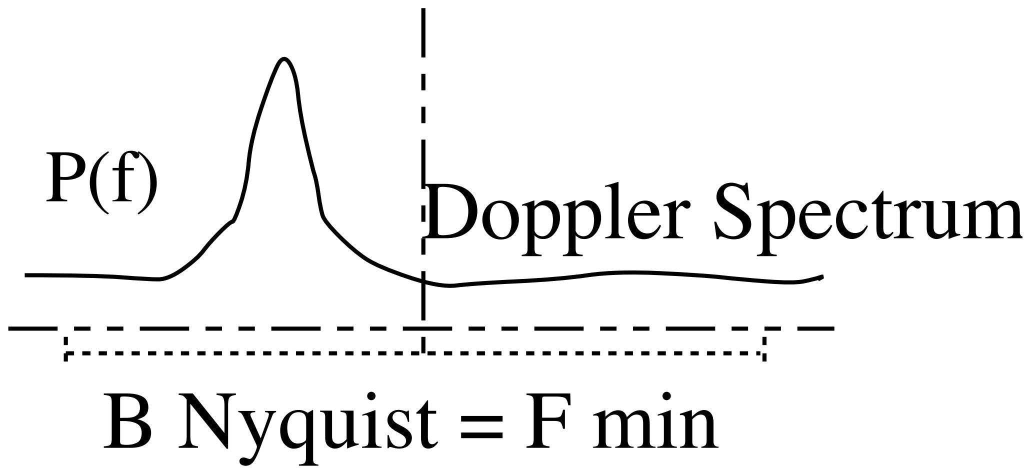
# Overspread Targets

- Competition between Distance and Bandwidth

$$B < F < \frac{c}{2R_{max}}$$




$$B\frac{2R_{max}}{c} < 1$$



# Overspread Targets

- 450 MHz incoherent scatter: B 2R_max/c = (40 kHz)(10 ms) = 400 >> 1 **overspread**
- 50 MHz auroral scatter: B 2R_max/c = (1 kHz)(6 ms) = 6 > 1 **overspread**
- 50 MHz PMSE: B 2R_max/c = (10 Hz)(1 ms) = 1/100 << 1 **underspread**

# Overspread Targets

- You can either get the slant range right and get the spectrum wrong (by undersampling), or
- You can get the spectrum right (from several ranges) but get the range wrong.
- Hmmm.

# Weiner-Khinchine Theorem

- or ... you could remember that the autocorrelation function R($\tau$) and the power spectrum P(f) are a Fourier Transform pair

$$R(\tau) = \int \exp(j2\pi f\tau)P(f)\, df$$

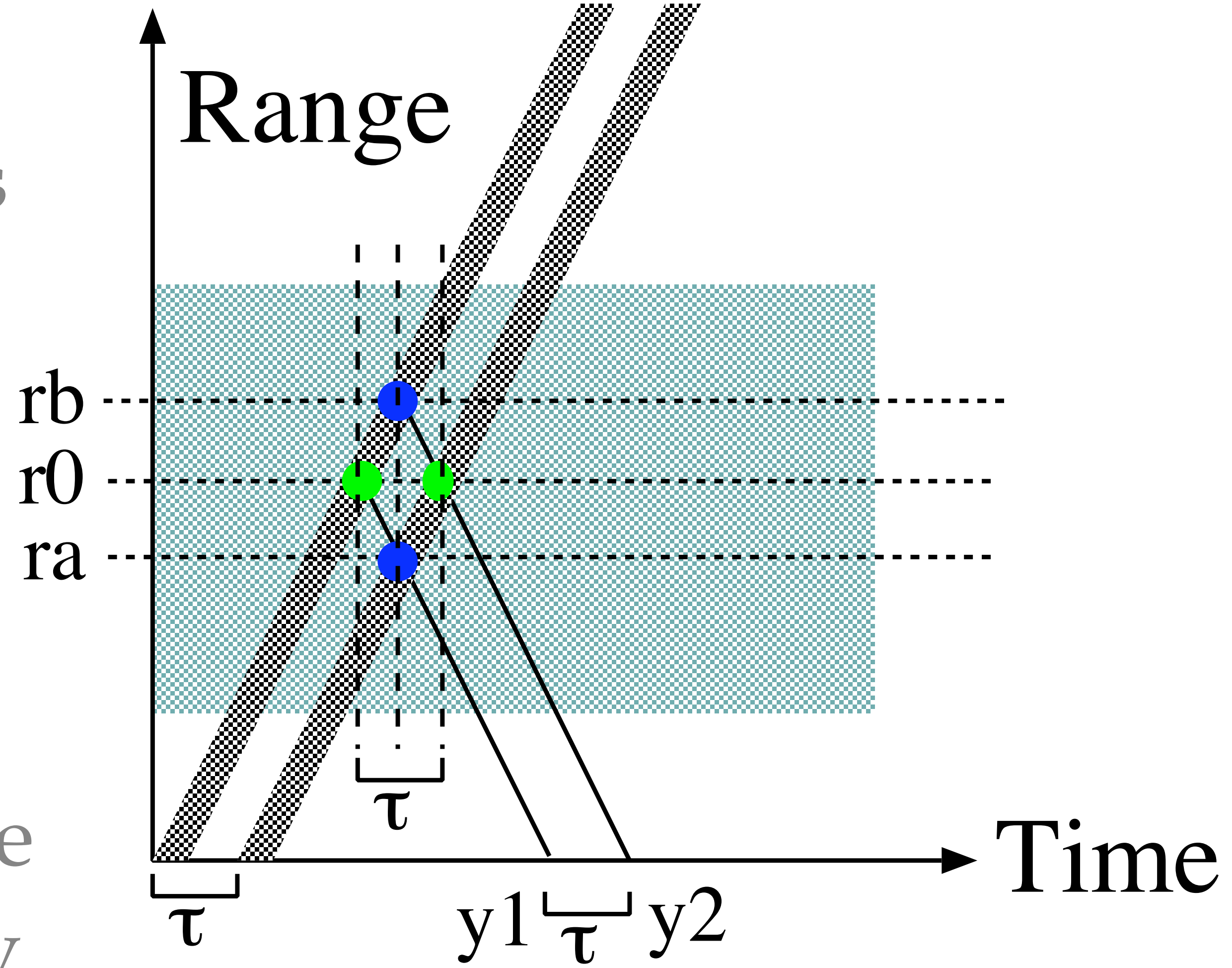
Idea: estimate the Autocorrelation Function first

# ACF estimation

- Assemble sums of immediate products
- Handle range clutter by relying upon “Radar Postulates.”
- Double Pulse; MultiPulse; Alternating Codes; Coded Long Pulse ... lovely and intricate waveforms.
- Probably the best possible waveforms are now known (!)

# The Double Pulse

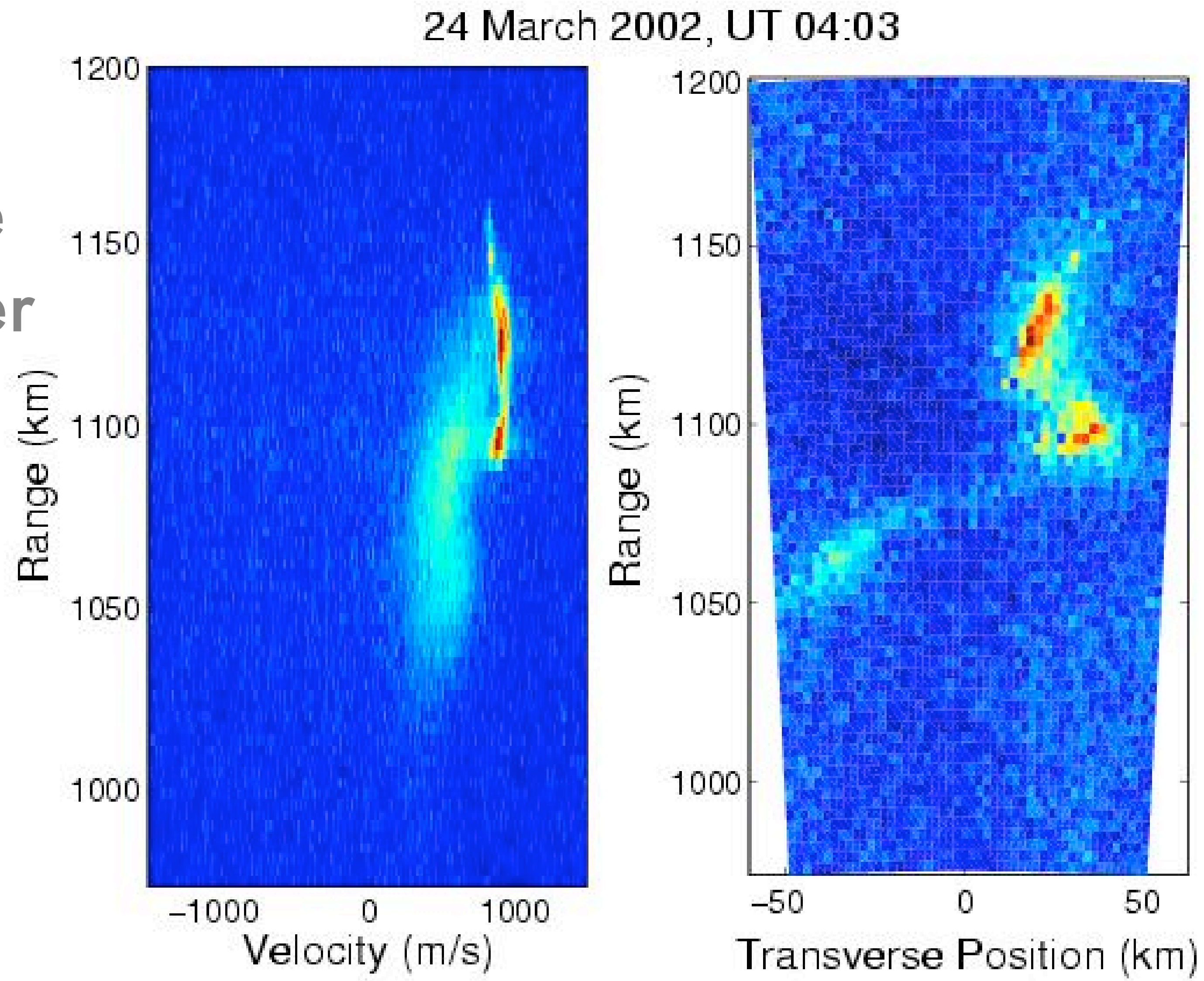
- Immediately multiply samples y2 and y1*
- Accumulate similar products
- Behold! an unbiased estimate of R($\tau$) for r0 only



# (Interferometry)

- Interferometry works the same way in space as multipulse codes work in time.
- Collect estimates of target angular correlation function
- Then Fourier-like Transformation back to real image (i.e. power spectrum)
- Statistical Inverse Theory...

# MRR interferometry




Range Doppler

Range Azimuth Image

from Melissa Meyer

# Pulse Compression

- Consider 1 MW ISR transmitter looking straight up; 3000 km pulse spacing (20 ms between pulses). Want 600 m range resolution (pulse length = 0.004 ms)
- Average Transmitter power is

Pave = (1 MW)(0.004 ms)/(20 ms) = 200 W

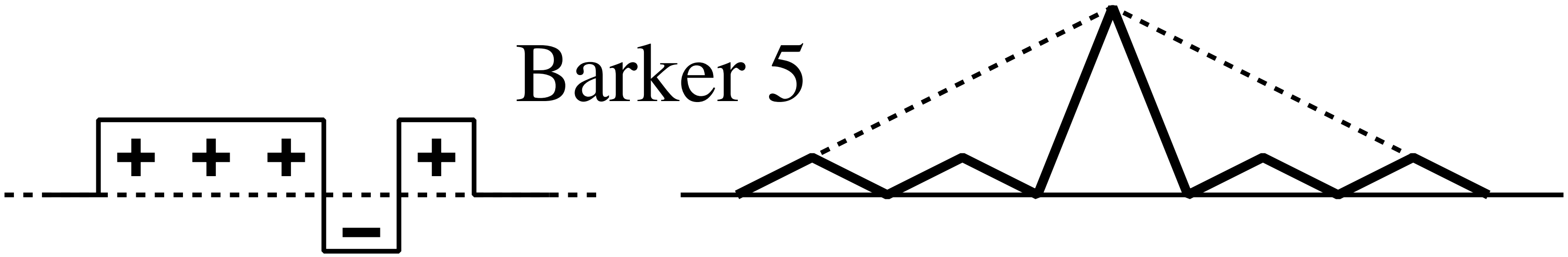
200 Lousy Watts from a 1 MW Transmitter!

# Pulse Compression

- Q: Can we make a long, low amplitude TX pulse look like a short, high amplitude TX pulse?
- A: Yes, by using special waveforms with nice correlation properties.
- Remember: resolution is from TX waveform convolved with RX impulse response.

# Barker Codes

- Binary Sequences with "almost perfect" range sidelobes
- Exist for length 2, 3, 4, 4, 5, 7, 11, 13 **only**
- They look like "chirps"
- Long "pretty good" codes can be found



# Pulse Compression

- For low ambiguity targets “complementary codes” have perfect (zero) sidelobes.
- Modern practice includes sampling the TX waveform as well, to account for its imperfections: amplitude droop, chirp.
- Extremely interesting stuff!

# Random Codes

- Q: “What waveforms have an autocorrelation function that looks like an impulse?
- A1: the impulse function
- A2: white noise

Long, random waveforms achieve very good pulse compression!

# Random Codes

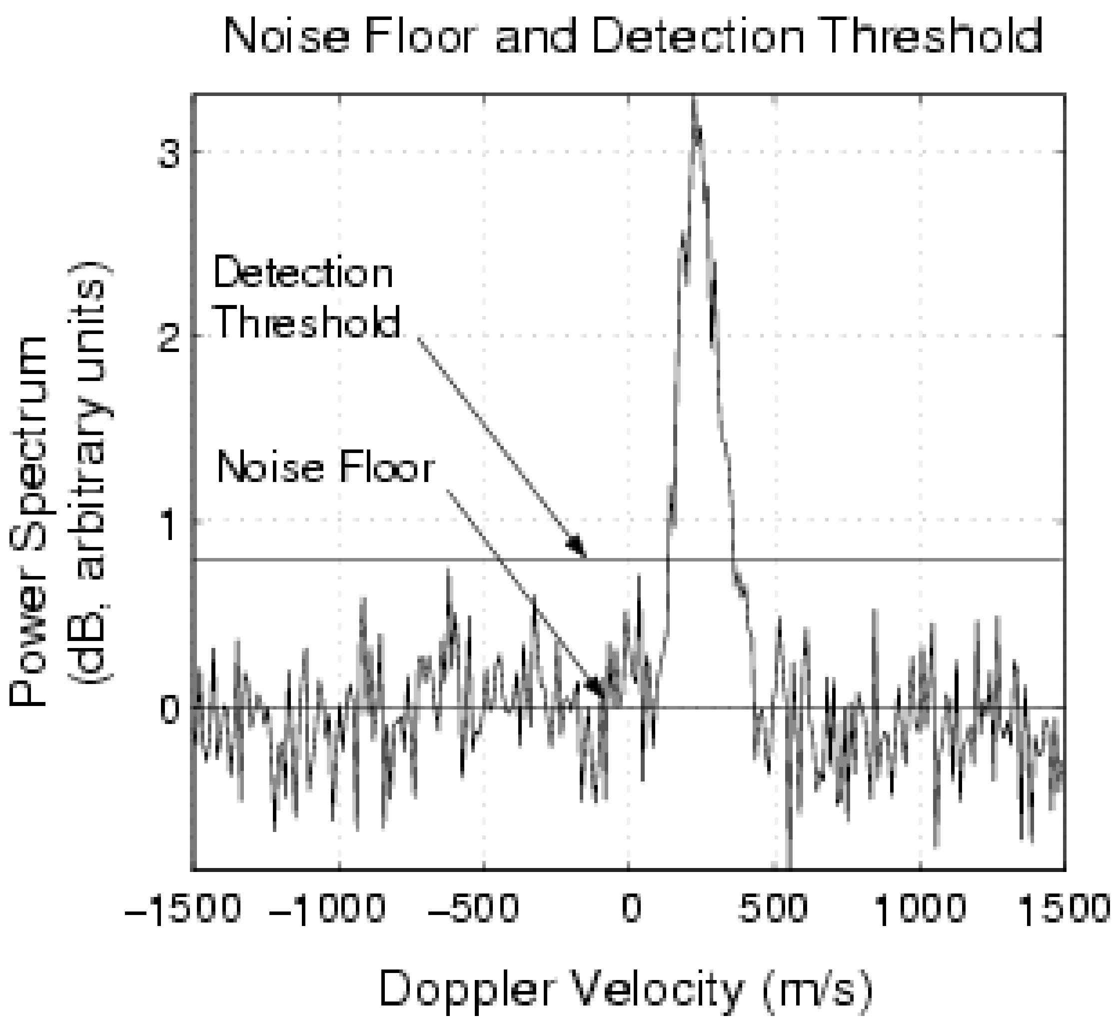
- Developed by Hagfors (radar astronomy) and Sulzer (Thomson Scatter). Performance quite similar to Alternating Codes (Lehtinen et al) but (IMHO) Random Codes are easier to understand.
- 100% duty cycle “sort of random” codes used in FM passive radar.

# Passive Radar

- FM broadcasts (100 MHz) have high average power (about 50 kW)
- FM broadcasts (usually) behave like band limited white noise, with bandwidth about 100 kHz, an autocorrelation time of about 0.01 ms, for an effective range resolution of 1.5 km.

# Power Spectrum in Passive Radar

MRR data from Melissa Meyer



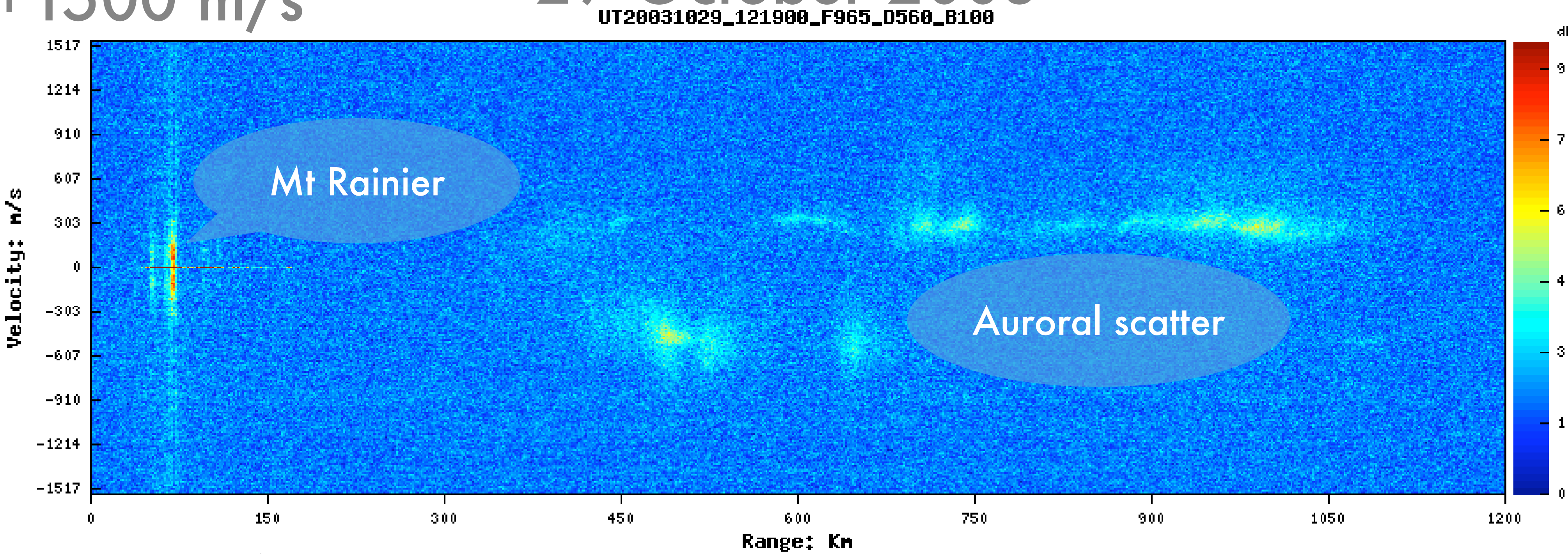

E Region Turbulent Scatter

96.5 MHz

# High Latitude E Region Turbulence

29 October 2003

+1500 m/s




-1500 m/s

300 km 600 km 900 km 1200 km

A 10 second average over 800 ranges, each of 1.5 km resolution, Doppler resolution of 12 m/s; 96.5 MHz (Rock and Roll)
see http://rrsl.ee.washington.edu/Data

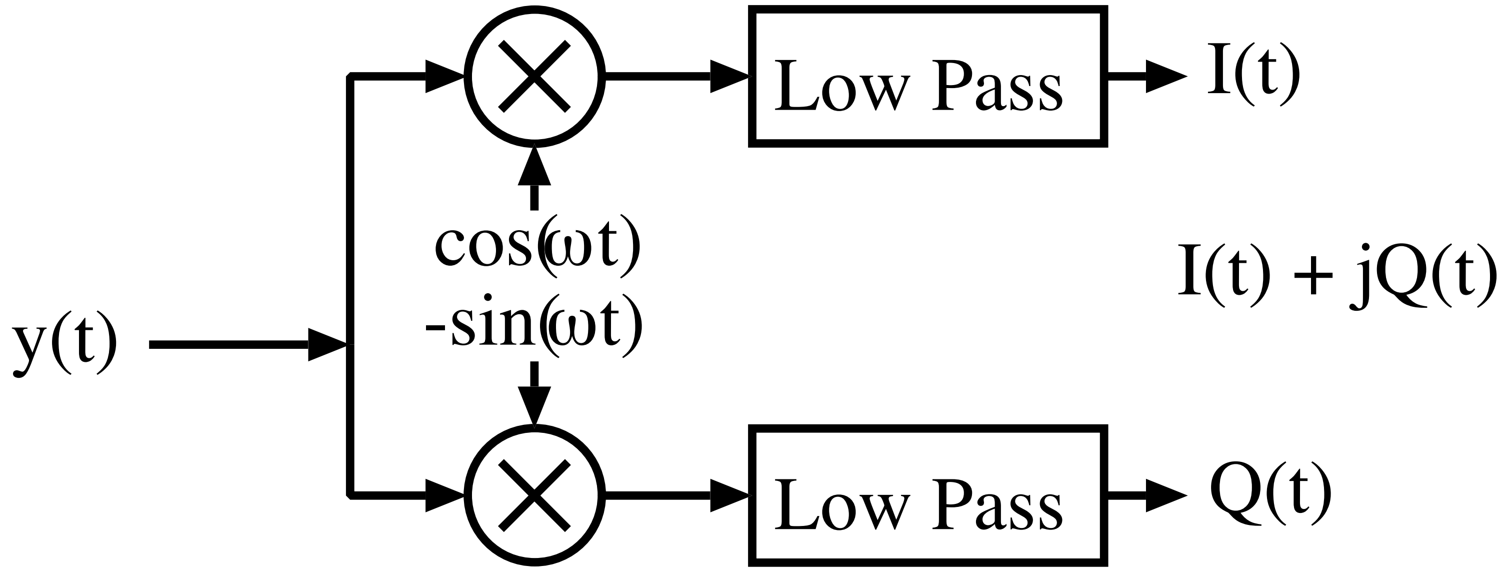
# In Phase/Quadrature

- Complex valued time series? Yep!
- Preserves the sign of the Doppler Shift
- Halves the Nyquist Sampling Rate (but doesn't halve the number of samples!)
- A bit of an analytic advantage with Isserliss' Theorem

$$\langle xy^* zw^* \rangle = \langle xy^* \rangle \langle zw^* \rangle + \langle xw^* \rangle \langle zy^* \rangle$$

# IQ Receiver

- Basically, multiply received signal by complex exponential, and preserve real and imaginary parts as separate signals.
- All "digital receivers" work this way.



# Thanks!



and
thanks
NSF!