CEDAR 1992

Probing the Upper Atmosphere and Ionosphere with Large Radars

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Target audience:

Bright graduate students who don't know much about radars but have inquiring minds

Goal of this talk:

To give you some idea of

1. What radars are good for
2. How they differ from lidars (the uses of phase coherence)
3. Some basic radar concepts and techniques

More specifically, we will try to cover (pretty fast), or at least mention

1. The radar equation

2. The difference between scattering from hard and **SOFT** (main emphasis) targets

3. Some properties of soft targets; e.g.,

   - Range dependence of the scattered signal strength

   - The Bragg condition – why the radar picks out a single spatial Fourier component of the refractive index fluctuations in a random medium

   - Over- vs under-spread and why it matters; range and frequency aliasing

   - Statistical ideas – why one sample isn't enough even if the signal-to-noise ratio S/N is very large

4. Some radar techniques; e.g.,

   - FFT analysis of the Doppler spectrum from under-spread targets (Easy to do. Can measure very small Doppler shifts, for example 1 Hz, even if the pulse bandwidth is 1 MHz.)

   - ACF analysis of the spectrum from overspread targets (Not so easy. The price of beating the Fourier uncertainty principle is the addition of radar "clutter", or signals from unwanted ranges that act like noise.)

   - Pulse compression (How to turn a long low power pulse into a short high power one with the same number of joules.)

   - Radar interferometry (How to locate strong scatterers precisely within the scattering volume.)

5. Incoherent scatter

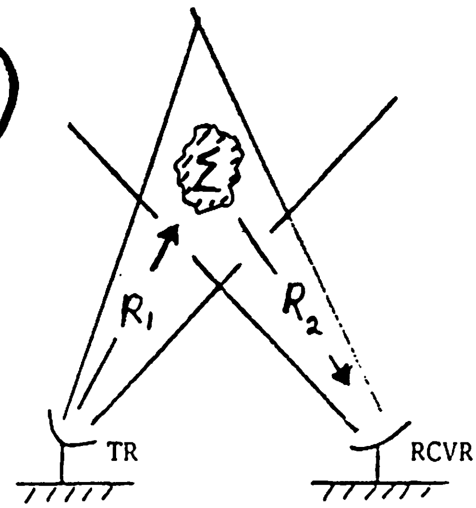
   The **very** weak scatter from purely thermal fluctuations (the irreducible minimum level) in plasma density. For a plasma in thermal equilibrium, the scattered power and signal Doppler spectrum depend in a quantitatively known way on the plasma density, temperatures, ion composition, drift velocity, etc.

   So by measuring the power spectrum, or more likely the signal autocorrelation function (ACF), we can determine most of the important plasma parameters via least squares fitting to the theory.

RADAR EQUATION

$$P_{rec} = \left(\frac{P_t G_t}{4\pi R_1^2}\right)\left(\Sigma\right)\left(\frac{A_{rec}}{4\pi R_2^2}\right)$$

incident power density	total scattering X-section	fraction received



FOR A SINGLE TRANSMIT-RECEIVE ANTENNA (PULSED RADAR)

$$P_{rec} = P_t \frac{G A_{eff}}{(4\pi R^2)^2}\,\Sigma$$

AND

$$G = 4\pi A_{eff}/\lambda^2 \qquad \text{(ANTENNA THEORY)}$$

SO

$$P_{rec} \sim P_t \frac{\lambda^2 G^2}{R^4}\,\Sigma \;\sim\; P_t \frac{A_{eff}^2}{\lambda^2 R^4}\,\Sigma$$

WHAT IS Σ ? [SOFT vs HARD TARGET]

WHAT IS G OR A_{eff} ? [NEAR FIELD vs FAR FIELD]

HARD TARGET

DOES NOT FILL BEAM - e.g. PLANE, MISSILE, SATELLITE

Σ INDEPENDENT OF RANGE

HENCE $$P_{rec} \sim R^{-4} G^{2}$$

SOFT TARGET

FILLS BEAM - e.g. SCATTER FROM ATMOSPHERE, IONOSPHERE

$$\Sigma = \sigma_{\substack{\text{per unit} \\ \text{volume}}} V_s$$

AND

$$V_s \simeq \Omega R^2 \ell \simeq \frac{4\pi}{G} R^2 \ell$$

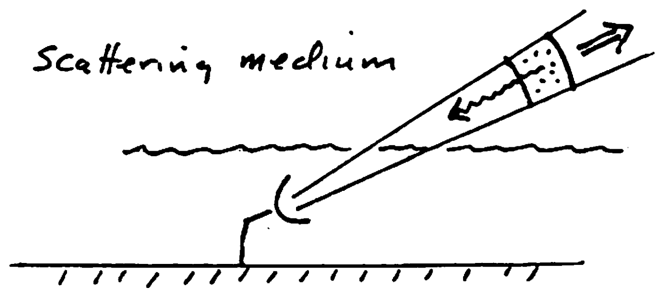
WHERE

$$\ell = \text{MIN [PULSE LENGTH} = C\tau/2\text{ , LAYER THICKNESS]}$$

HENCE

$$P_{rec} \sim \frac{\lambda^2 G \sigma \ell}{R^2} \sim \frac{\sigma \ell A_{eff}}{R^2}$$

What is a "soft" target?



"Soft" target fills the beam. (Hard target does not.)

<u>Radar equation</u> (far field case):

$$\frac{P_r}{P_t} = \left(\frac{G_t}{4\pi r^2}\right)\sigma_{target}\left(\frac{A_{eff}}{4\pi r^2}\right) \sim \frac{G_t A_{eff}}{r^4}\,\sigma_{target}$$

But $\sigma_{target} \sim (\text{beam area})(\text{pulse length}) \sim \frac{r^2}{G_t}\,\tau_{pulse}$

$$\Rightarrow \frac{P_r}{P_t} \sim \frac{A_{eff}\,\tau}{r^2} \qquad \left(\text{vs } \frac{A_{eff}^2}{\lambda^2 r^4} \text{ for hard target}\right)$$

Born approximation always valid for cases of interest

i.e. single (weak) scattering only,

scatter doesn't alter (attenuate) incident beam

Goal: Determine the statistical properties of the scattering medium.

Method: Measure the statistical properties (power spectrum or auto-correlation function) of the scattered signal, which is a Gaussian random variabl

Signal statistics vs medium properties

Straightforward to show that (for a plasma)

$$\underbrace{\langle E_s(t)\, E_s^*(t+\tau)\rangle}_{\text{Signal ACF}} \sim \langle \Delta N(\underline{k},t)\,\Delta N^*(\underline{k},t+\tau)\rangle$$

$$= \iiint \langle \Delta N(\underline{r},t)\,\Delta N(\underline{r}+\underline{r}',t+\tau)\rangle e^{i\underline{k}\cdot\underline{r}'}\, d^3\underline{r}'$$

(N = electron density)

$\underline{k} = \underline{k}_{incident} - \underline{k}_{scattered}$

$\rightarrow 2\underline{k}_{inc}$ for backscatter

(Bragg condition)

Fourier transforming in time gives

$$\underbrace{\langle |E_s(\omega_0+\omega)|^2\rangle}_{\substack{\text{Power spectrum}\\ \text{of received signal}\\ \omega = \text{Doppler shift}}} \sim \underbrace{\langle |\Delta N(\underline{k},\omega)|^2\rangle}_{\substack{\text{Power spectrum of}\\ \text{electron density "waves"}}}$$

(Radar selects a specific $\underline{k}$, a single spatial Fourier component)

Often written as $\sigma(\underline{k},\omega) \sim \langle |\Delta N(\underline{k},\omega)|^2\rangle$

Similarly, for fluctuations in the neutral atmosphere due to CAT etc

$$\sigma(\underline{k},\omega) \sim \langle |\Delta\epsilon(\underline{k},\omega)|^2\rangle$$

Note: $\langle\,\rangle \Rightarrow$ averaging needed even if $S/N \gg 1$

Statistics and Errors

Signal and noise are both Gaussian random variables

We have to estimate their statistical properties

(e.g. mean power, power spectrum $\overset{F.T.}{\Longleftrightarrow}$ ACF)

per unit volume

$$\underset{\text{(soft target)}}{\text{Signal power}} \equiv S \propto P_{trans.} \frac{A_{ant}\, \sigma_{medium}}{R^2} \tau_{pulse}$$

$$\text{Noise power} \equiv N = K_{Boltz}\, T_{system}\, B_{receiver}$$

For "matched" filtering (gives max S/N)

we often (but not always) have

$$B_{rec} \simeq \frac{1}{\tau_{pulse}}$$

$$\Rightarrow \frac{S}{N} \propto \tau_{pulse}^2 \propto (\Delta R)^2$$

range resolution

Using many samples of the signal, we form an <u>estimator</u> of the true signal power, or ACF, etc

For example,

$$\widehat{S+N} = \frac{1}{K}\sum_{i=1}^{K} |V_i|^2_{\text{(transmitter on)}} , \quad \hat{N} = \frac{1}{K}\sum_{1}^{K} |V_i|^2_{\text{(trans. off)}}$$

$$\hat{R}(\tau) = \frac{1}{K}\sum_{i=1}^{K} V(t_i)V^*(t_i+\tau) \Rightarrow \rho(\tau) = R(\tau)/R(0)$$

Easy to show that $\langle \hat{N} \rangle = N$ (unbiased estimator)

<u>Mean square errors in the estimate</u>:

$$\delta_x^2 \equiv \left\langle \left(\frac{\hat{X} - X}{X}\right)^2 \right\rangle \simeq \frac{1}{K}\left(\frac{S+N}{S}\right)^2 \underset{\text{const} \sim \Theta(1)}{A}$$

where $X = S, \rho(\tau)$, or whatever

K = number of <u>independent</u> samples used in the estimator

$\Rightarrow$ Use tradeoffs between K and S/N wisely

$\langle \; \rangle \Rightarrow$ ensemble average ($\simeq$ time average) in the above

Measurement Techniques

Depends upon whether target is

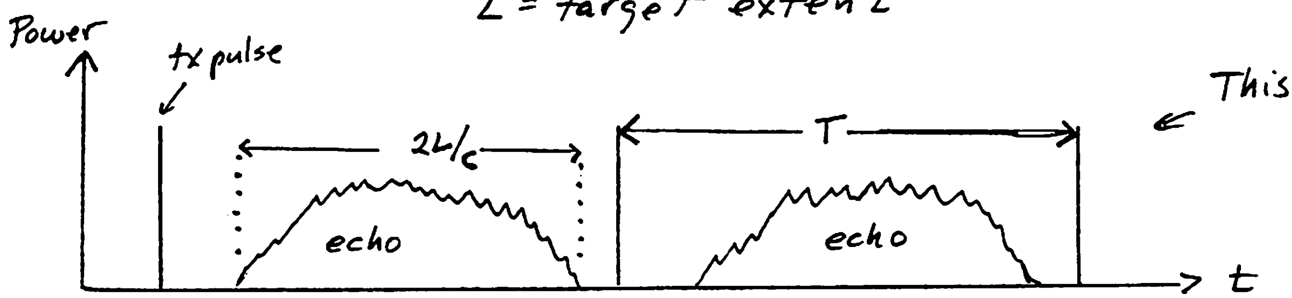
Underspread or Overspread

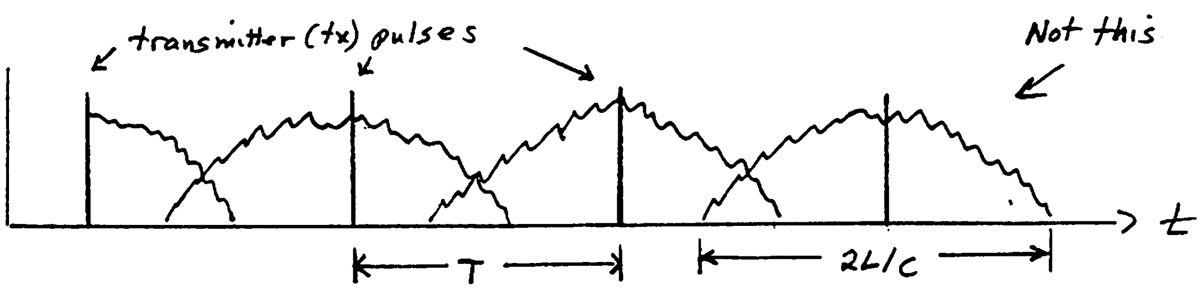
<u>Underspread</u>: Range and frequency aliasing both easily avoided

<u>Overspread</u>: Not so easy!

To avoid <u>range aliasing</u>, need $T = \underbrace{IPP}_{\text{interpulse period}} > 2L/c$

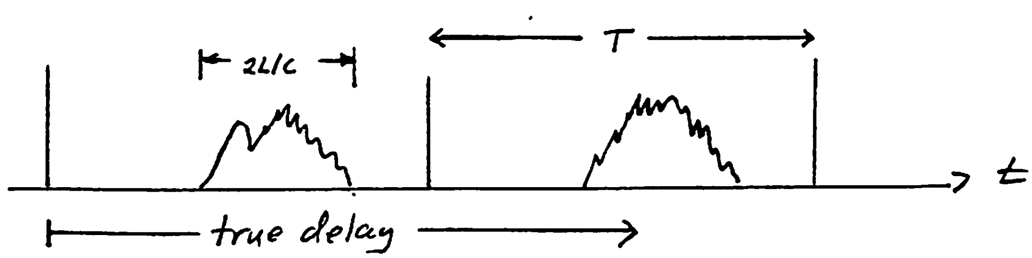
L = target extent





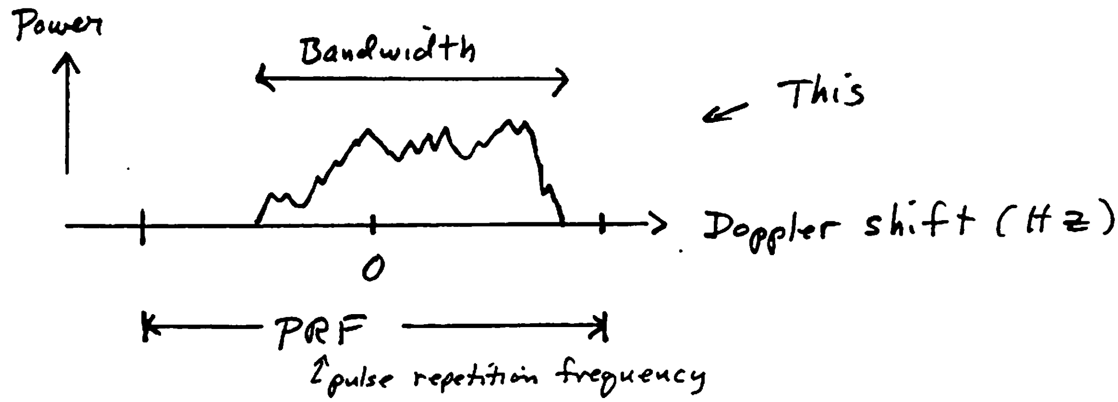
Ok if echo is "second time around" - as long as you know this is the case (which you usually do)

<u>i.e.</u>

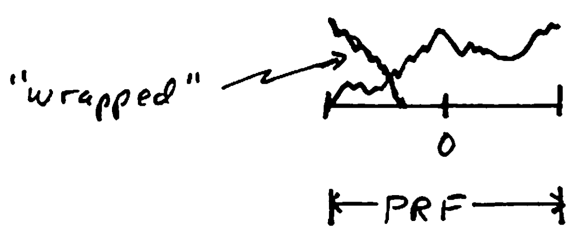


To avoid <u>frequency aliasing</u>,

need $PRF = \frac{1}{IPP} >$ Doppler bandwidth



Not this



So we want to satisfy 2 conditions:

1) $IPP > 2L/c$

2) $PRF >$ Doppler BW

or $IPP = \frac{1}{PRF} < \frac{1}{\text{Doppler BW}}$

$$\Rightarrow \frac{2L}{c} \overset{?}{<} IPP < \frac{1}{BW}$$

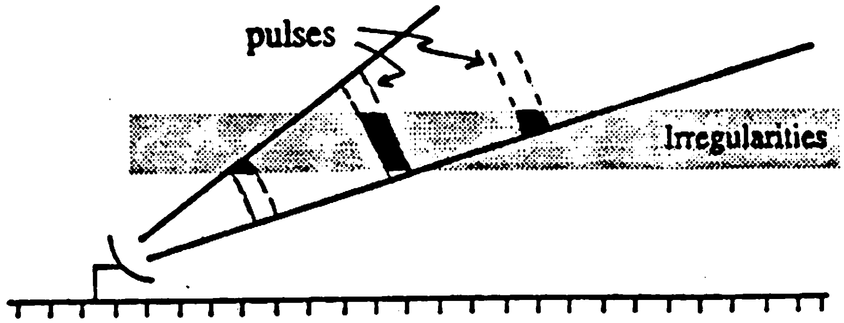
$$\Downarrow$$

$$\frac{2L}{c} \overset{?}{<} \frac{1}{\text{Bandwidth}}$$

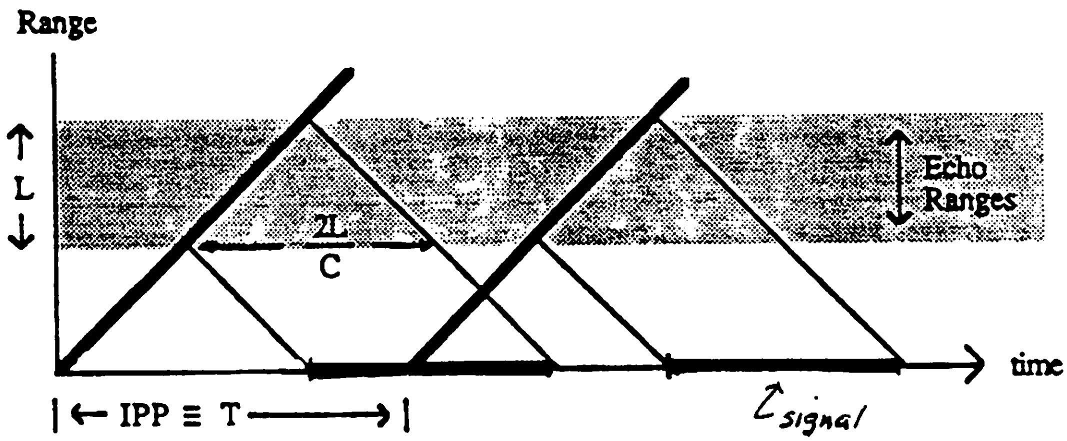
Yes $\Rightarrow$ Underspread target; easy to deal with

No $\Rightarrow$ Overspread target; harder to deal with, but can be done

Range and Frequency Aliasing Problem



Pulses too close together ⇒ Range ambiguities

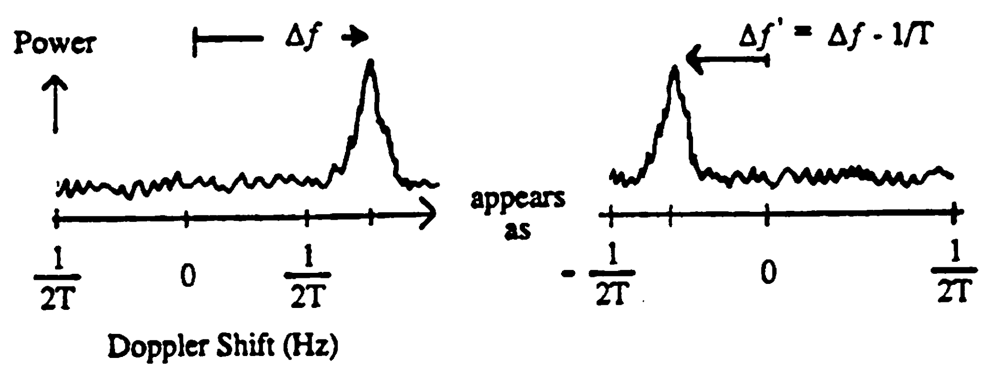


- Need $T > 2L/c$ (as shown) to avoid ambiguity.

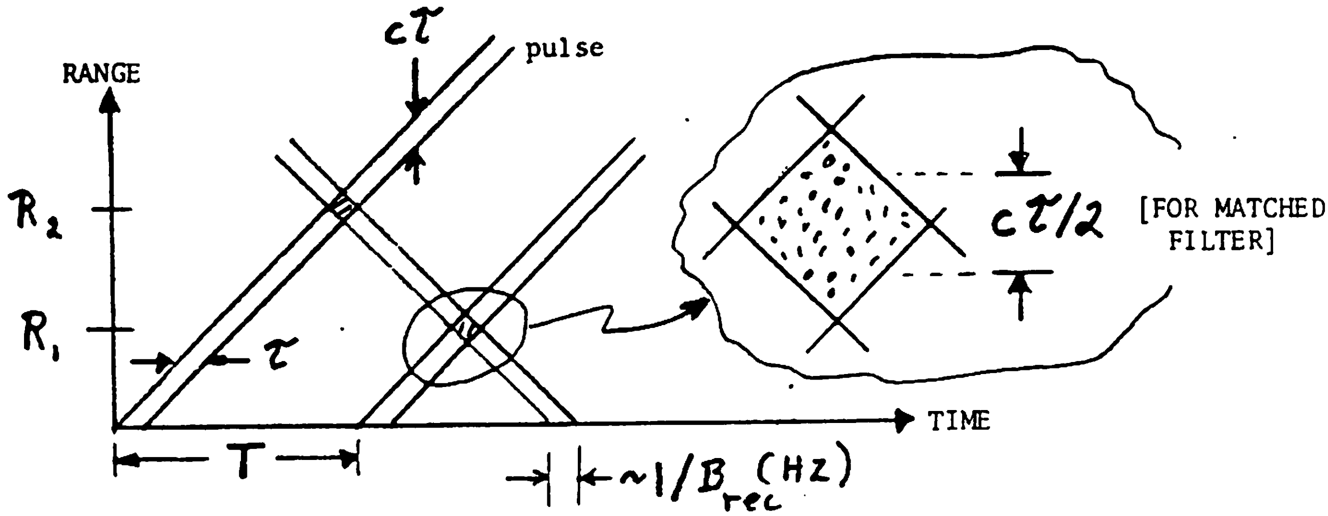
- But we also need $T < 1/2|\Delta f|$ to avoid frequency aliasing. (Δf = echo Doppler shift)

  i.e., need $|\Delta f| < 1/2T < c/4L$

- If ***not*** true ⇒ target *echo is aliased in frequency*



RANGE RESOLUTION AND AMBIGUITY



MATCHED FILTER: RECEIVER GATE WIDTH ($\sim B^{-1}$) = PULSE DURATION

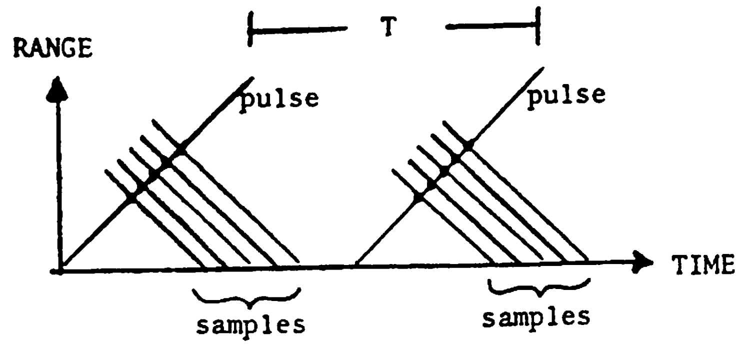
AMBIGUITY: SIGNALS RECEIVED SIMULTANEOUSLY FROM R_1, $R_2 = R_1 + CT/2$, ETC

RESOLUTION: $\delta R \simeq \text{MAX}\ [C\tau/2,\ CB_{rec}^{-1}/2] \simeq C\tau/2$ FOR MATCHED FILTER

TO AVOID OVERLAPPING ECHOES, NEED $P_s(R_2) \ll P_s(R_1) \longrightarrow$ LARGE T

BUT FOR STATISTICAL REASONS AND TO AVOID FREQUENCY ALIASING, WE WANT SMALL T

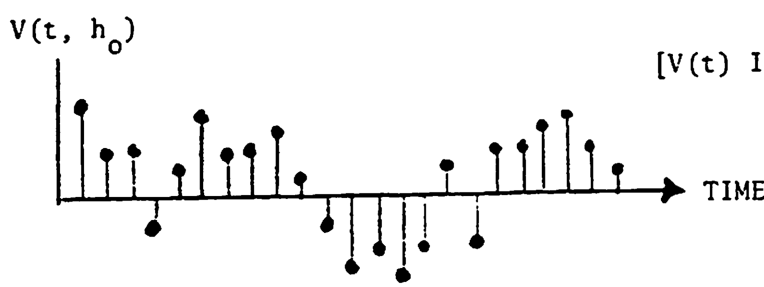
SAMPLING AND FREQUENCY ALIASING



LEADS TO SAMPLE ARRAY

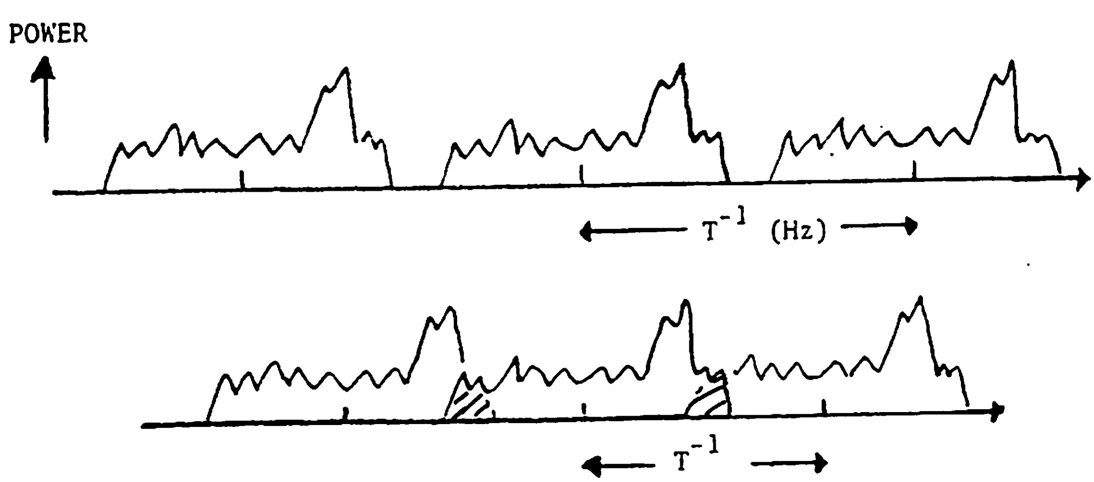
pulse \ range	0	1	...	n
0	$V(t_o, h_o)$	$V(t_o+\delta t, h_o+c\delta t/2)$	...	$V(t_o+n\delta t, h_o+nc\delta t/2)$
1	$V(t_o+T, h_o)$	$V(t_o+T+\delta t, h_o+c\delta t/2)$	...	⋮
⋮	⋮	⋮		⋮
m	$V(t_o+mT, h_o)$	⋮	...	$V(t_o+mT+n\delta t, h_o+nc\delta t/2)$

EACH COLUMN CONVERTED TO FFT FOR A PARTICULAR ALTITUDE



[V(t) IS OFTEN A COMPLEX NUMBER]

$\Downarrow |FFT|^2$



[UNALIASED]

[ALIASED]

Undersread

Examples
- Echoes from Venus (slow rotation)
- Scatter from stratospheric and mesospheric irregularities
- Scatter from auroral irregularities (sometimes)

Simple techniques work fine, e.g.

1) Transmit evenly spaced train of pulses
2) Sample and digitize at each range of interest
3) Compute FFT for each range and avergge the power spectra

Also available and useful:

1) Coherent integration (this has various definitions)
2) Pulse compression using complementary code pairs (Golay codes), which have no range sidelobes

These work only if the medium correlation time $\gg$ IPP

e.g., the stratosphere, for which

$\tau_{correl} \sim$ few $\times 10^{-1}$ s

$\gg$ IPP $\sim$ 1 ms perhaps

Overspread

Examples:

Incoherent scatter from random thermal fluctuations in the ionosphere

Radar echoes from Mars

Radar echoes from the aurora (sometimes)

Techniques now are not so simple

Measure ACF using multipulse schemes (adds clutter)

Pulse compress with Barker (or longer) codes, but be careful about code length (must be $<$ or $\ll$ τ_{correl})

Combine both of the above

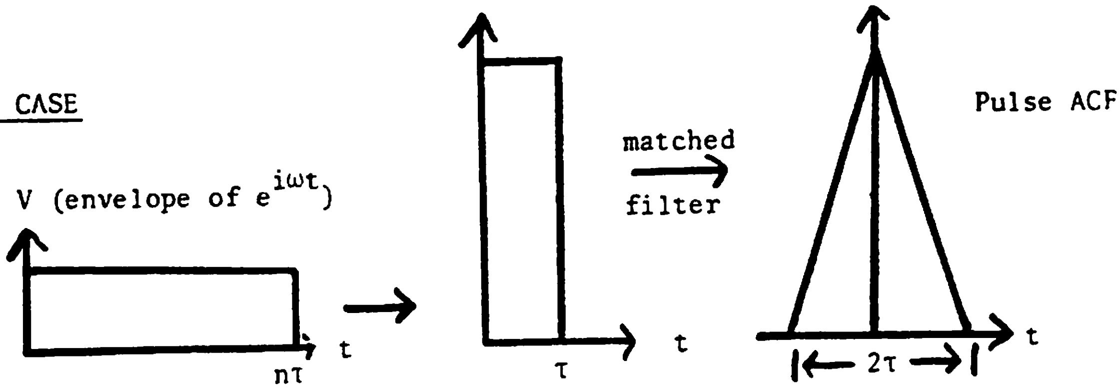
For mildly overspread (e.g. auroral case), can replace the usual power spectrum with double-pulse cross spectrum that unravels mild frequency aliasing

All of these could be used also for underspread targets, but usually are not

Radar interferometry is also a powerful technique for improving spatial resolution for either class of target

PULSE COMPRESSION

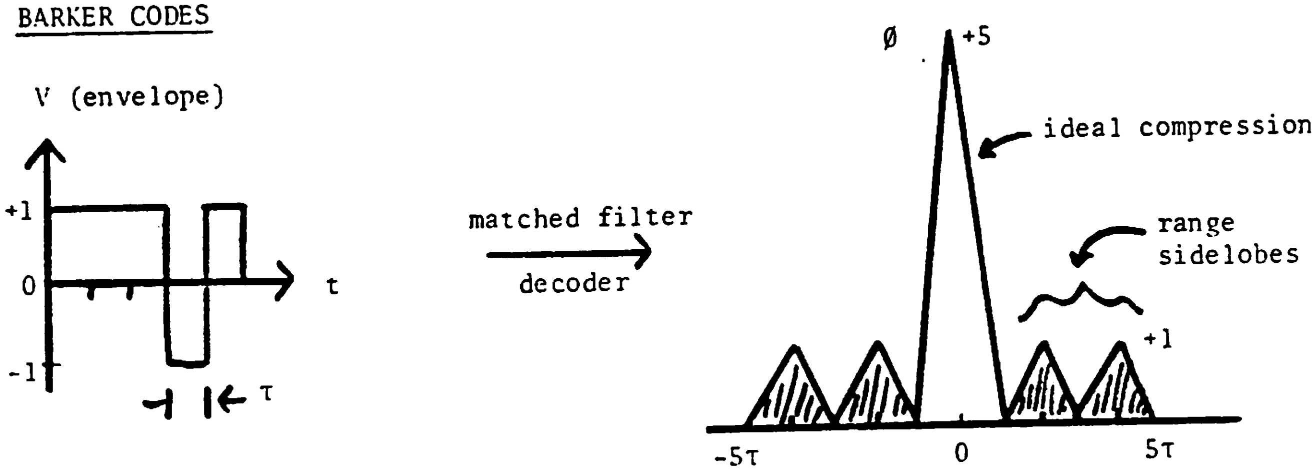
IDEAL CASE



CAN USE FREQUENCY "CHIRPING" OR PHASE CODING

IN PRACTICE USE BINARY PHASE CODING AND DECODE WITH COMPUTER OR SPECIAL PURPOSE DIGITAL OR ANALOG DEVICES

BARKER CODES



Ø = AMBIGUITY FUNCTION (FOR NO DOPPLER)

= VOLTAGE FROM SMALL STATIONARY TARGET

= ACF OF CODE

TARGET MUST REMAIN COHERENT FOR $n\tau$ (UNCOMPRESSED DURATION)

GROUND CLUTTER DURATION $\geq$ UNCOMPRESSED PULSE

MAX COMPRESSION WITH BARKER CODE (UNITY SIDELOBES) IS 13:1 (n=13)

OTHER LONGER SIMILAR NON-CYCLIC CODES AVAILABLE

e.g., n= 28 $\longrightarrow$ MAX SIDELOBE OF 2

Pulse Compression (con't)

All forms of pulse compression rely on careful use of phase information.

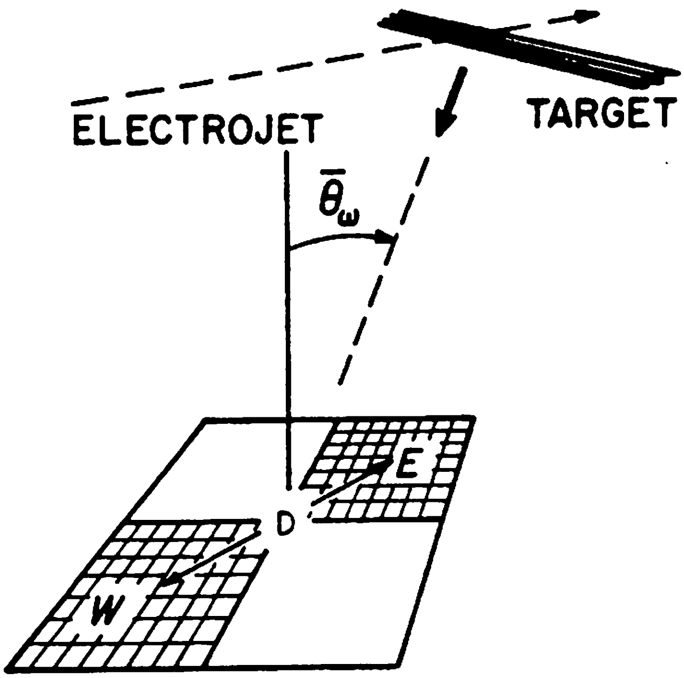
Hence, unknown significant Doppler shifts and/or phase decorrelation (soft targets) will seriously distort/destroy the compression. (These effects are described by the full radar "ambiguity function".)

For highly coherent, underspread targets, many other (than Barker) coding schemes are possible, some of which are very long and give very high compression ratios.

e.g. Complementary code pairs

cyclic codes

RADAR INTERFEROMETRY
(Equatorial Geometry)



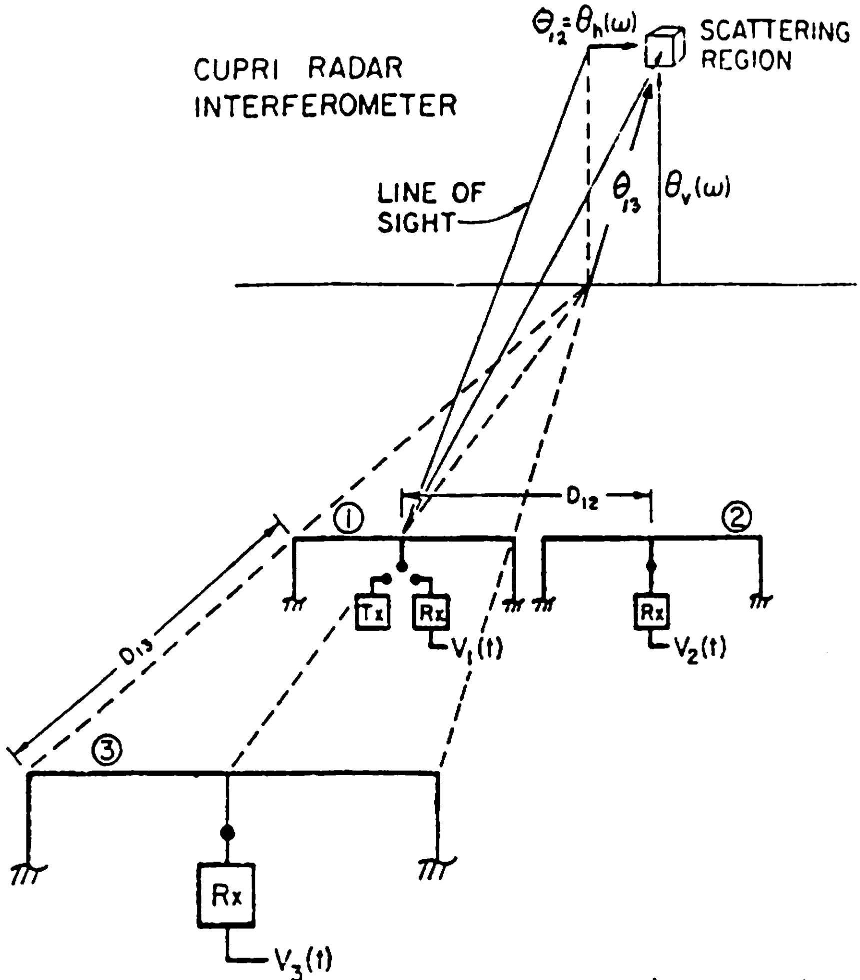
The geometry of the electrojet interferometer. The entire Jicamarca 50-MHz array was used for transmission, but the scattered signals were received separately on the east and west quarters, whose phase centers are separated by the distance *D* which is 208.2 m. The field-aligned "target" is assumed to occupy a small range of angles centered about the small mean angle θ_ω, and the subscript ω refers to the Doppler shift of the echo.

<u>Simplest Situation</u> (Single Target)

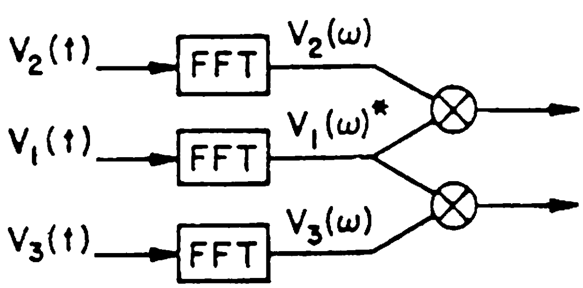
Suppose
$$V_E = V_{01} e^{i\omega t}$$
$$V_W = V_{02} e^{i\omega t - ikD\sin\theta}$$
$$(k = 2\pi/\lambda \text{ radar})$$

Then
$$\frac{\langle |V_E V_W^*| \rangle}{\langle |V_E|^2 \rangle \langle |V_W|^2 \rangle^{1/2}} = e^{ikD\sin\theta} \Rightarrow \theta \text{ and } d\theta/dt \Rightarrow \text{velocity}$$

In other words, the time delay between the arrival of the signal at the E and W antennas $\Rightarrow$ a phase shift which $\Rightarrow$ θ. This idea can be extended to multiple targets with different Doppler shifts.



$$S_{12}(\omega) = \frac{\langle V_1(\omega)V_2^*(\omega)\rangle}{[\langle|V_1(\omega)|^2\rangle]^{1/2}[\langle|V_2(\omega)|^2\rangle]^{1/2}} = e^{ikD\bar{\theta}_\omega} \text{ (for } \theta << 1)$$



$$S_{12}(\omega) = |S_{12}|\, e^{i\phi_{12}} = \langle e^{ikD_{12}\sin\theta_{12}} \rangle$$

$$S_{13}(\omega) = |S_{13}|\, e^{i\phi_{13}} = \langle e^{ikD_{13}\cos\theta_{13}} \rangle$$

$$\langle e^{ikD\theta} \rangle \approx \int e^{ikD\theta} \langle |\Delta N(2k,\omega,\theta)|^2 \rangle \, d\theta$$

- For point targets, this is simply 2-D direction finding.
- For distributed targets, each baseline provides one point on the complex spatial ACF, which is the FT of the angular power spectrum.
- In both cases, the information is provided for each Doppler shift separately.

$$|S(\omega)| \cong e^{-(1/2)k^2D^2(\delta\theta_\omega)^2} \equiv \text{coherence} \Rightarrow \text{size}$$

$$\phi(\omega) = kD \left\{ \begin{array}{c} \sin \bar{\theta}_\omega \\ \\ \cos \bar{\theta}_\omega \end{array} \right\} \equiv \text{phase} \Rightarrow \text{position}$$

In the auroral case the 2-D, orthogonal baseline data can be combined to give contour plots which roughly indicate the shape of the scattering center.

Measuring the ACF of an overspread target (e.g. "incoherent" scatter)

How do we manage to (apparently) violate the Fourier Uncertainty Principle?

We use the fact that signals from disjoint scattering volumes are completely <u>uncorrelated</u>.

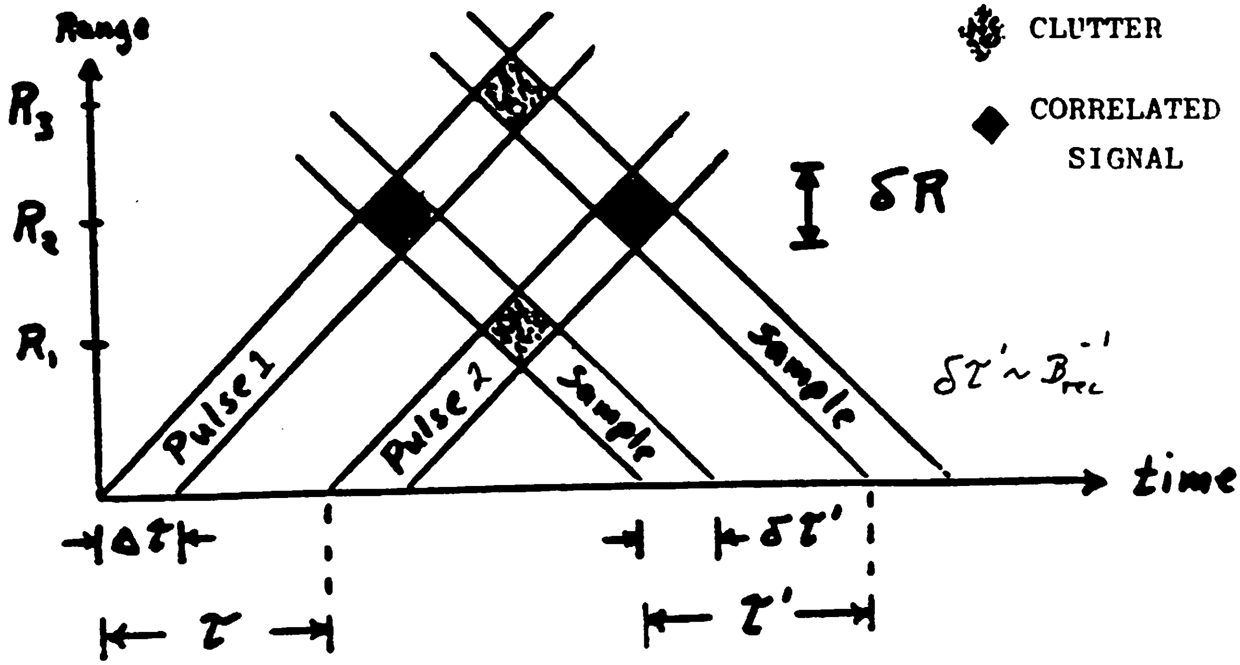
<u>The price for this</u>:

We add "clutter" (C), or unwanted signal from other ranges, to the noise. This clutter is averaged out, but it increases the statistical errors

$$\delta_x^2 \rightarrow \sim \frac{1}{K}\left(\frac{S+N+C}{S}\right)^2$$

ACF (continued)

DOUBLE OR MULTIPLE PULSE

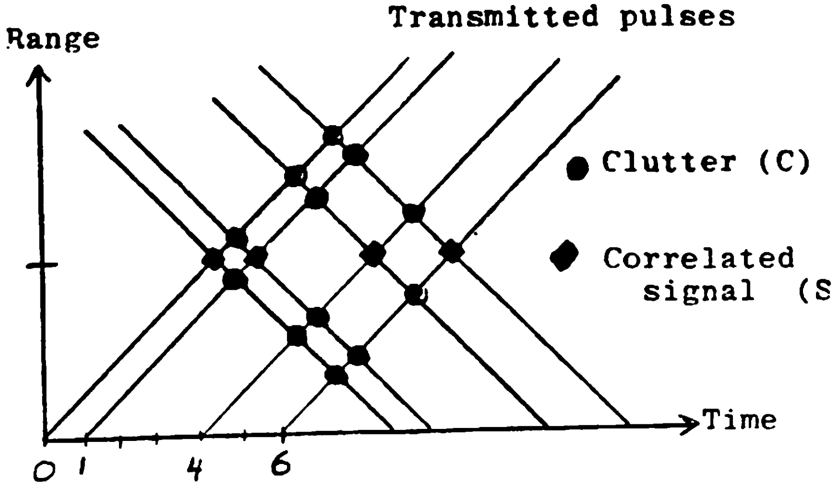


- SAMPLE PRODUCTS $\rightarrow \langle V(R_2,t)V^*(R_2,t+\tau')\rangle \longrightarrow \rho(R_2,\tau')$
- TRANSMIT (CYCLICLY) DIFFERENT SPACINGS AND SAMPLE AT ALL RANGES TO DETERMINE COMPLETE $\rho(R,\tau')$
  OR USE MULTIPLE τ, τ', AS WE SHALL SEE
- GOOD RANGE AND LAG RESOLUTION POSSIBLE
- CLUTTER (ECHOES FROM UNWANTED RANGES) ADDS TO NOISE
- CAN HAVE $\tau \neq \tau'$ AND/OR $\Delta\tau \neq \delta\tau'$ (UNMATCHED FILTER)
  BUT NOT RECOMMENDED (LIKELY TO GIVE SYSTEMATIC ERRORS)
- "MUST" HAVE $\tau \geq \Delta\tau + \delta\tau'$

$\Rightarrow$ CLUTTER ECHOES CAN BE ELIMINATED IF PULSES 1 AND 2 HAVE ORTHOGONAL POLARIZATIONS (WITH MATCHING RECEIVER SYSTEM)

ACF (continued)

HIGHLY DESIRABLE TO EXTEND
THIS IDEA TO
MULTIPLE PULSES



- EXAMPLE: 4 PULSES AT $t = 0, 1, 4, 6$ PRODUCES
  lags = 0, 1, 2, 3, 4, 5, 6
  ↑ not useful - range aliased
- IN GENERAL: n PULSES → $n(n-1)/2$ DIFFERENT LAGS
- SOME "MISSING" LAGS FOR $n > 4$
- CLUTTER POWER $\sim$ $(n-1)$ x SIGNAL POWER
- SAME ADVICE AS IN DOUBLE PULSE CASE FOR
  τ vs τ', $\Delta\tau$ vs $\delta\tau'$, τ vs $\Delta\tau + \delta\tau'$
- BEST TO MAKE n AS LARGE AS POSSIBLE, CONSISTENT WITH THE VARIOUS CONSTRAINTS OF PULSE LENGTH, ETC., IF COMPUTER CAN HANDLE THE INCREASED PROCESSING

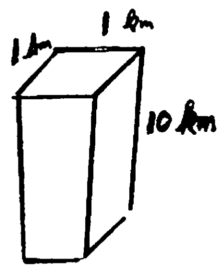
  STATISTICS IMPROVE EVEN THOUGH CLUTTER INCREASES — ESPECIALLY IF $S/N \ll 1$ AND HENCE $C \lesssim N$
- CANNOT USE ORTHOGONAL POLARIZATION TECHNIQUE TO ELIMINATE CLUTTER
- CANNOT USE MULTIPLE FREQUENCIES EITHER (ELIMINATES CLUTTER, BUT ALSO SIGNAL!)
- SAME IDEA USED IN "NON-REDUNDANT" ANTENNA ARRAYS FOR APERTURE SYNTHESIS. SOME REDUNDANCY OK IN ANTENNA ARRAY CASE, BUT NOT FOR RADAR ACF MEASUREMENT (GIVES RANGE ALIASING)

INCOHERENT SCATTER

What is it?

Extremely weak scatter from electrons that are as unorganized as possible (usually not totally "incoherent" in some sense - but don't worry about this refinement now).

How weak?

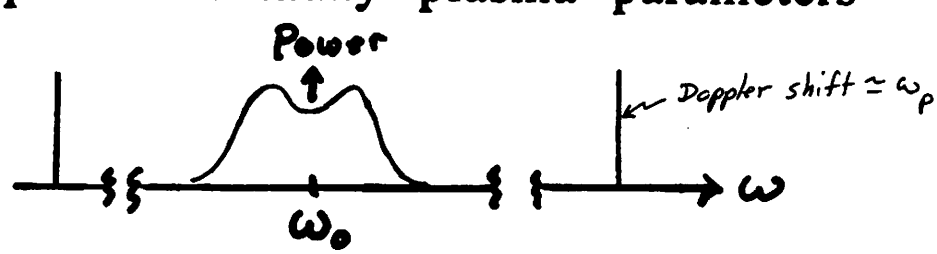


10 km^3 with 10^{12} electrons/m^3
$\Rightarrow$ radar cross section ~ 10^{-6} m^2
~ (1 mm)^2 !
(10^{-28} m^2 per electron)

But can be "easily" detected, nevertheless, with a powerful radar
(W.E. Gordon, K.L. Bowles, 1958)

Theory

- Linear plasma kinetic theory
- Thoroughly worked out
- Very rich - spectrum of scattered signal depends on many plasma parameters



- Shape and total power $\Rightarrow$ N_e, T_e, T_i, V_d, ... etc.
  ion composition (incl. negative ions)
  ν_{in}, differential ion drifts, currents ($V_e - V_i$,

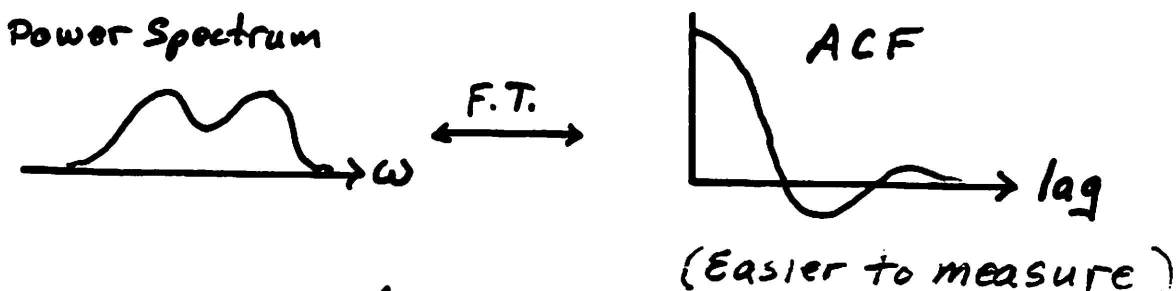
IS (continued)

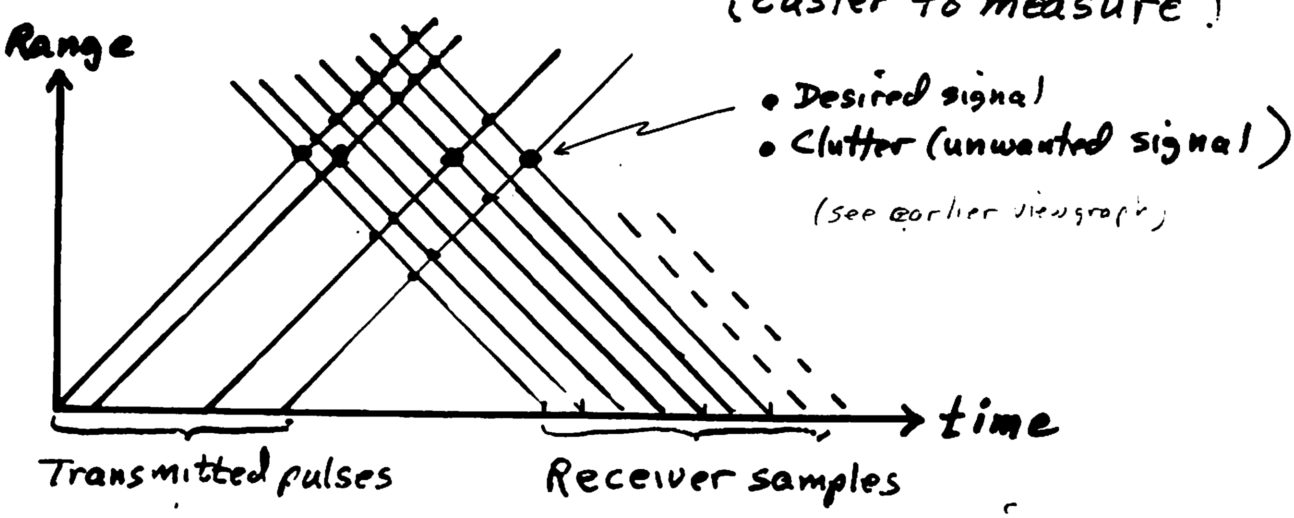
How do we do the measurements?

- We want good resolution in range, time, and frequency.
- But target is "overspread", i.e., we want

  Doppler BW $\leq$ IPP^{-1} $\leq (2L/c)^{-1}$, but BW $> (2L/c)^{-1}$

  (Nyquist) (Avoid echo overlap)
- A problem? Yes, but we can do clever things.





- Various coding schemes and lag sequences used
- Individual pulses may be "compressed" (e.g. Barker coding)

IS (continued)

Choice of lag spacing or further coding

+

statistical averaging

⇓

Range "clutter" (echoes from the "wrong" altitude) eliminated since echoes from different regions of space are *uncorrelated*

ERRORS

$$\epsilon^2 \simeq \left(\frac{S+N+C}{S}\right)^2 \frac{1}{K}$$

K = number of independent samples

S = signal power

N = noise power

C = clutter power

ANALYSIS

Least square fitting of theory to data

⇒ ionospheric parameters

Fit entire profile at one time? (OASIS program)

IS (continued)

Questions:

- Non-Maxwellian plasmas (high latitudes)?
- IS from unstable plasmas (high latitudes)?
  Yes, apparently, for **k** well inside stable regime.

What can we study using IS?

- Energy balance and Tn
- Photoelectron energy distribution, including arrivals from conjugate hemisphere
- Low and mid latitude winds, tides, gravity waves, TIDs
- **E** fields, conductivities, dynamo theories $\underline{V}_{d\perp} = \frac{\underline{E} \times \underline{B}}{B^2}$
- High latitude winds, ion drag, magnetospheric forcing
- Magnetospheric convection, response to changes in the IMF and solar wind
- F region trough dynamics
- Ion chemistry, composition transitions
- Ionosphere-magnetosphere coupling (fluxes of particles and energy)
- Ion drift vs neutral winds (airglow)
- High latitude heating events (natural)
- Artificial (HF) heating experiments

Altitudes Covered and Resolution for IS

h: ~ 80 km (even less sometimes)
to several $\times 10^3$ km

Δh: ~ 150 m (1 μs pulse) (F region, coded pulses)
to ~ 150 km (1 ms pulse) at high alts.

Δt: ~ few secs to ~ 1 hr

IS (continued)

- IS is the most powerful ground based technique for monitoring most of the important parameters of the ionosphere.

- Rapid improvements in DSP technology mean that we should soon be able to exploit the full potential of the method (years ago 90-99^{+} % of the data was sometimes wasted).

- There are many global IS observing programs associated with CEDAR, e.g.
  GISMOS (substorms)
  GITCAD (ionosphere-thermosphere coupling)
  LTCS (lower thermosphere coupling)
  SUNDIAL (not an acronym!)
  WAGS (gravity waves)
  CHARM (hydrogen)
  MISETA (equatorial)
  ATLAS

IS (continued)

RECENT TOPICS

- Non-Maxwellian ion distributions at high latitudes when drift velocity large.
- Can you observe IS looking along **B** while unstable waves are being generated with **k** nearly ⊥ **B**? Evidence seems to ⇒ Yes.
- Ionosphere is changing rapidly now with increasing solar activity.
- Digital data processing power improving rapidly. Cheap way to improve observatories.

NEW OBSERVATORIES?

USSR EISCAT receiving station (VHF)
Svalbard (Spitzbergen)? Japan? UK?
Resolute Bay, Canada?
Fairbanks, AK?
Indonesia? (Japan)
Other USSR observatories?

TIMETABLE?

- Any new high latitude radars should be ready by the time of the "Cluster" multi-satellite launch in ~ 1995 if at all possible.
- So time is pretty short.