Wide Field Searches for Radio Transients

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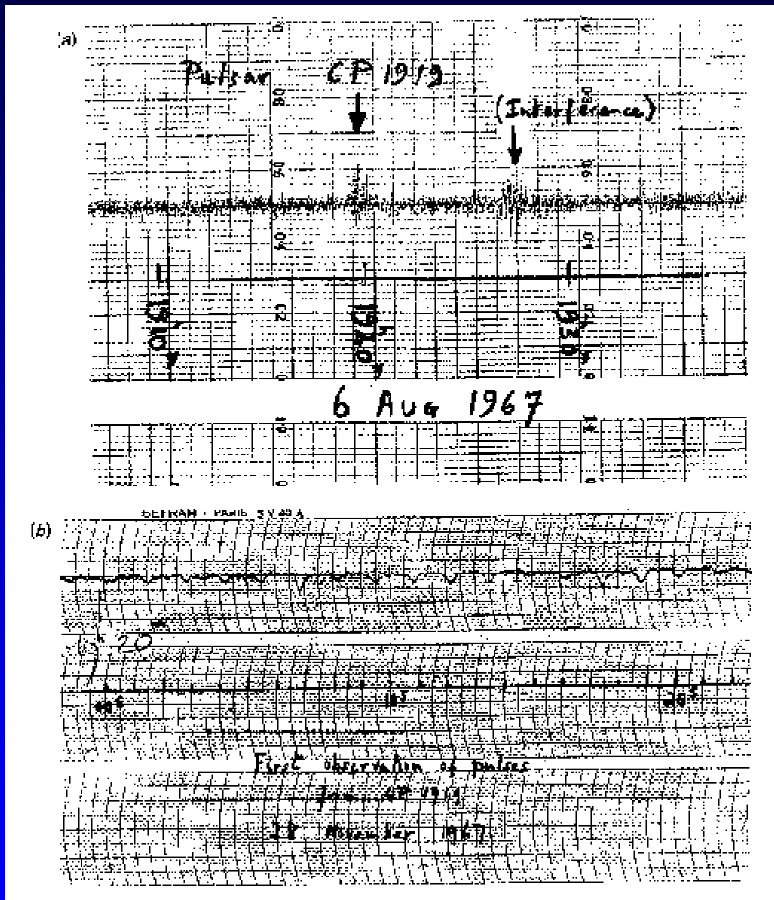
Time-Domain Radio Astronomy

- **Historically – and understandably – we tend to think of astronomical events unfolding over very long time scales**

- **So, discovery of astronomical events occurring over shorter timeframes tends to be a surprise.**

- **Examples:**

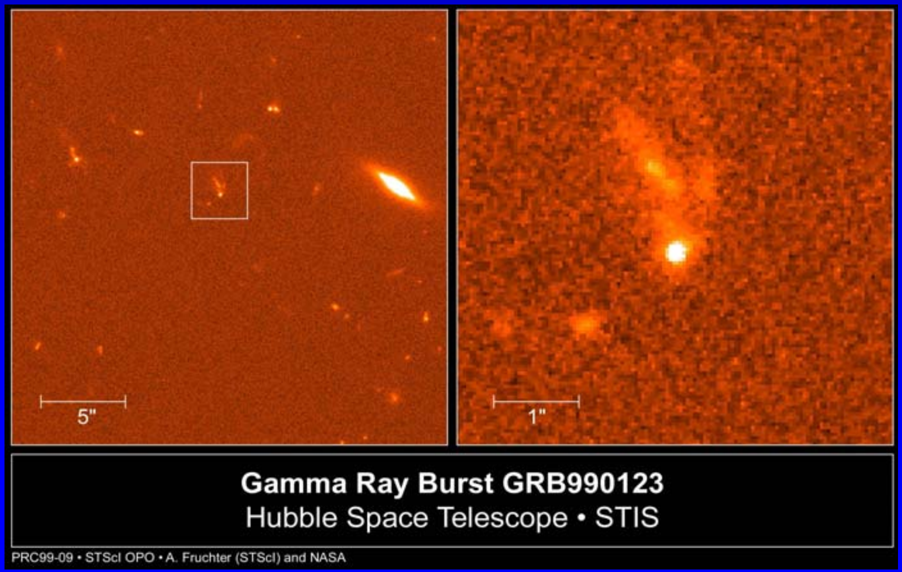
Pulsars



- **Pulsed emission from neutron stars was predicted, but unexpected**
- **Ironically, the Crab was discovered not by the periodic emission, but rather from its “giant pulses”**
- **A giant pulse is a rare (<1%) pulse of > 1000 times the mean intensity. Only a few pulsars are known to make them**
- **GP searches may outperform periodicity searches for detecting certain classes of pulsars**

Gamma Ray Bursts (GRBs)

- **Not anticipated before discovery**
- **Discovery completely by accident (by US DOD!)**
- **Only recently shown to be associated with extragalactic SNe**
- **A significant fraction can probably be detected via prompt (seconds-minutes) low frequency radio emission in the 10-1000 Jy range (Dessenne et al. 96, Balsano 98, Usov & Katz 00)**



Why Radio Transients Deserve More Attention

- **Short events imply extreme physics - Pulsars, GRBs are treasure troves of interesting science**
- **Since these were discovered by serendipity, it seems quite likely that a dedicated search would tend to reveal new sources of transient emission**
- **The transient "parameter space" (duration, rate, sky position, dispersion measure) is mostly unexplored since existing instruments are terrible for this.**
- **Maybe we should know what is going on in the 99.999…% of the radio sky we aren't currently observing…?**

Why Radio?

- Relatively unobscured sight lines
  (well, except for dispersion)

- Easy to obtain wide fields of view
  (>1 sr is no problem)

- Long wavelengths OK: Spatial resolution is not an issue. Ability to <u>localize</u> is not necessarily compromised.

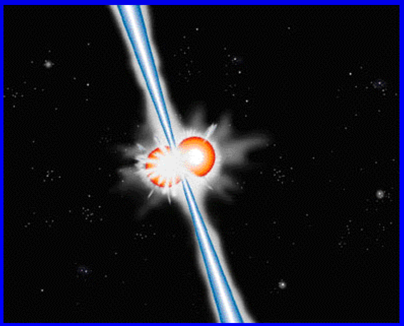
- Follow up to triggers at other wavelengths:
  γ, optical, LIGO, etc.

What Might We Expect to Find?

- **Exploding Black Holes**
  - **Extremely bright: Emission up to 10^{30} erg in last 0.1s (Hawking 74)**
  - **Rees (1977) postulates radio pulse resulting from expanding cloud of charged particles moving through magnetic field**
  - **1-1000 μs, few Jy, rate?**
  - **Searches by Meikle 1977, Phinney & Taylor 1979. Null result.**

What Might We Expect to Find?

- **Merging Neutron Star Binaries**
  - **Estimated 100-1000 total NS-NS (+ NS-BH) in Galaxy**
  - **Low frequency emission in the Jy range possible (Hansen & Lyutikov 2001)**
- **Merging Neutron Star – Black Hole Binaries**
  - **Probably more prevelant (Bethe & Brown 1998) but probably not as bright NS-NS (Hansen & Lyutikov 2001)**



What Might We Expect to Find?

- **Extrasolar jupiters**
  - **Narrowband (10's of kHz), Jy’s at 20 MHz, fractions of a second**
- **Type I SNe prompt emission**
  - **~10 ns, due to rapid expansion of conducting envelope of white dwarf through magnetic field (Colgate et al. 72, Colgate 75)**
  - **Search by Meikle & Colgate 78, null result**

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  - **Search by Meikle & ... gate**

Plus all the other stuff we don't know about yet!

Some Recent, Current, & Planned Searches

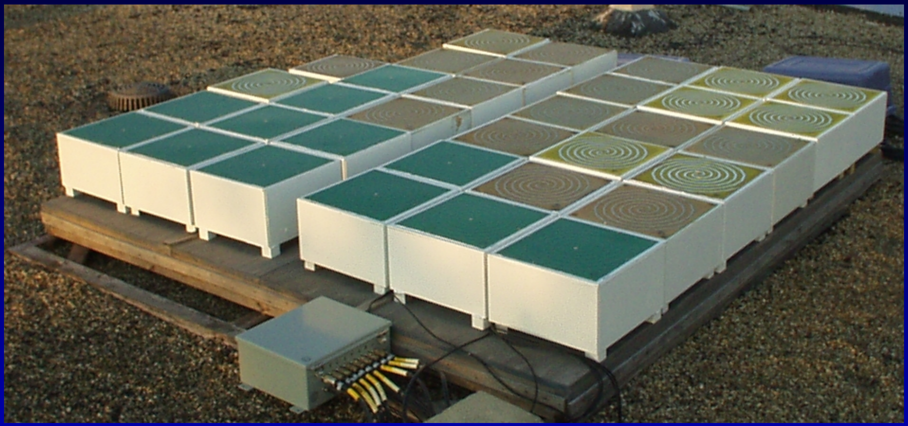
- **FLIRT (Balsano 99)**
  - **Primarily searching for GRB prompt emission**
  - **74 MHz phased array, 1000 m^2, triggered**
  - **No confirmed detections above a few kJy; one possible**

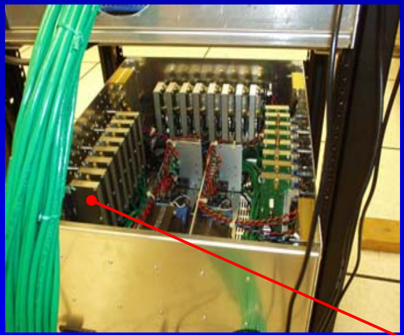
- **Benz & Paesold 1998:**
  - **Searching for GRB prompt emission & exploding black holes**
  - **3 x 7 m dishes with 40-1000 MHz sweeping receivers, 1 MHz BW, and .25 s sweep time**
  - **No detections - 100 kJy**

- **STARE (Katz et al. 2003)**
  - **1.4 sr field of view , 3-way anticoincidence**
  - **0.125 s – a few minutes, 611 MHz x 4 MHz**
  - **No detections above 27 kJy at Zenith**

- **Summary: Nothing "interesting" above current sensitivity limits of 10's of kJy's**

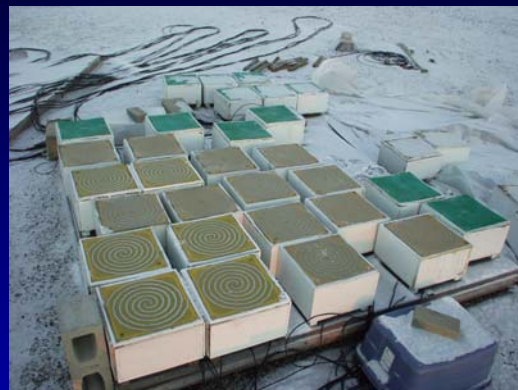
Argus



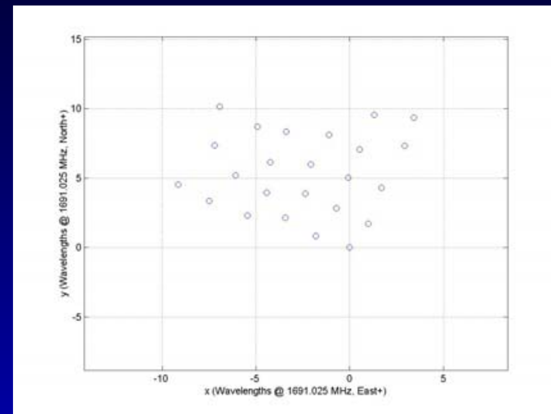


- N = 24 element array, ~1 sr FOV
- 1200-1700 MHz tuning
- T_{sys} ~ 215 °K per element
- Fully coherent PC-based processing
- Sensitivity ~ 24 kJy at zenith in 0.2 s
- No confirmed extrasolar detectons - yet. (All detections so far attributable to RFI)
- Work continues
- ~(US$1K)N not including PC cluster-based backend; Cost scales linearly with B (up to B=14 MHz) and N (no upper bound)

All-Sky Imaging at L-Band Using Argus



Argus Array (N=24)



Phase Center Geometry at 1691 MHz

Image field of view is the entire sky!

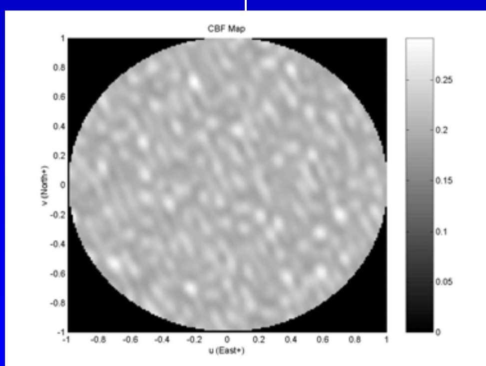
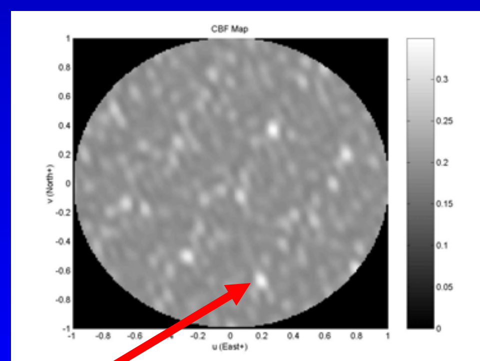
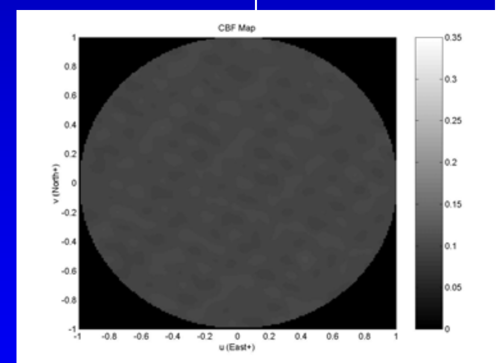


Image **before calibration**



GOES-12
(Other bright spots are aliases
arising from redundant subnyquist
spacings)

After calibration using just
one near-field noise source



Same procedure applied to adjacent (signal free) channel

Detecting Transients Using an Array

- **Optimal Strategy:**
  - **Search over directions of arrival (DOAs)**
  - **For each DOA, form a beam**
  - **Process each beam output through the appropriate matched filter**
- **Drawbacks of Optimal Strategy:**
  - **Only finite number of DOAs can be searched - cusping loss**
  - **Requires very good calibration, so as to form proper beams**
- **Alternative Approach:**
  - **Compute the spatial covariance (cross correlations, or "visibilities")**
  - **Analyze the associated eigenvalues for a detection**
- **Drawbacks of Alternative Strategy:**
  - **Poor performance for noise-dominated scenarios (like RA)**
  - **High computational cost for large arrays; $O(N^3)$ at least**
- **But desirability of avoiding calibration hassles makes this interesting…**

Calibration-Less Detection Algorithm

TXE

(Time-Gate, Cross-Correlate, Eigenanalysis)

1. Divide the data record up into L blocks of M array output vectors (snapshots) each.
2. For each block l, compute the $(N^2 + N)/2$ non-redundant cross-products between elements, summing over the M results per block. This results in L observations, each summarized by a covariance matrix $\mathbf{R}^{(l)}$.
3. Compute $\lambda_1^{(l)}$, the primary (largest) eigenvalue of $\mathbf{R}^{(l)}$ for each block, using SVD or the Power Method.
4. Compute $d_l = \lambda_1^{(l)}/(\mathrm{Tr}\{\mathbf{R}^{(l)}\} - \lambda_1^{(l)})$ for each block. d_l expressed in standard deviations σ from the mean across the remaining blocks.
5. A detection is declared if d_l for any block is greater than some threshold.
6. The steering vector associated with a detection is the eigenvector of $\mathbf{R}^{(l)}$ associated with $\lambda_1^{(l)}$ for the block l in which the detection occurred.

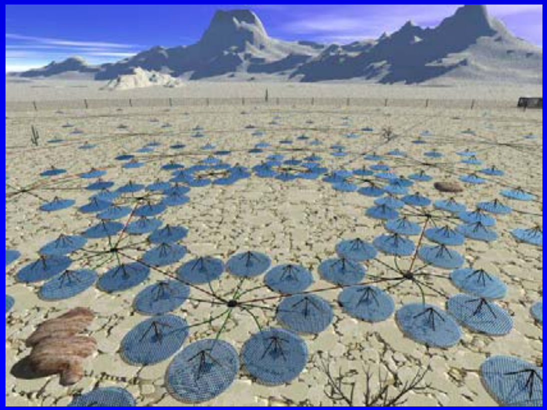
Provides robust detection of pulses with no need to calibrate array

Performance is not quite as good as beamforming at max beam gain, but better than BF at half-beam gain (i.e., likely beam crossover points) for sufficiently long integration

Computation burden (using Power Method in place of TXE) is about the same as beamforming

LOFAR / ASM

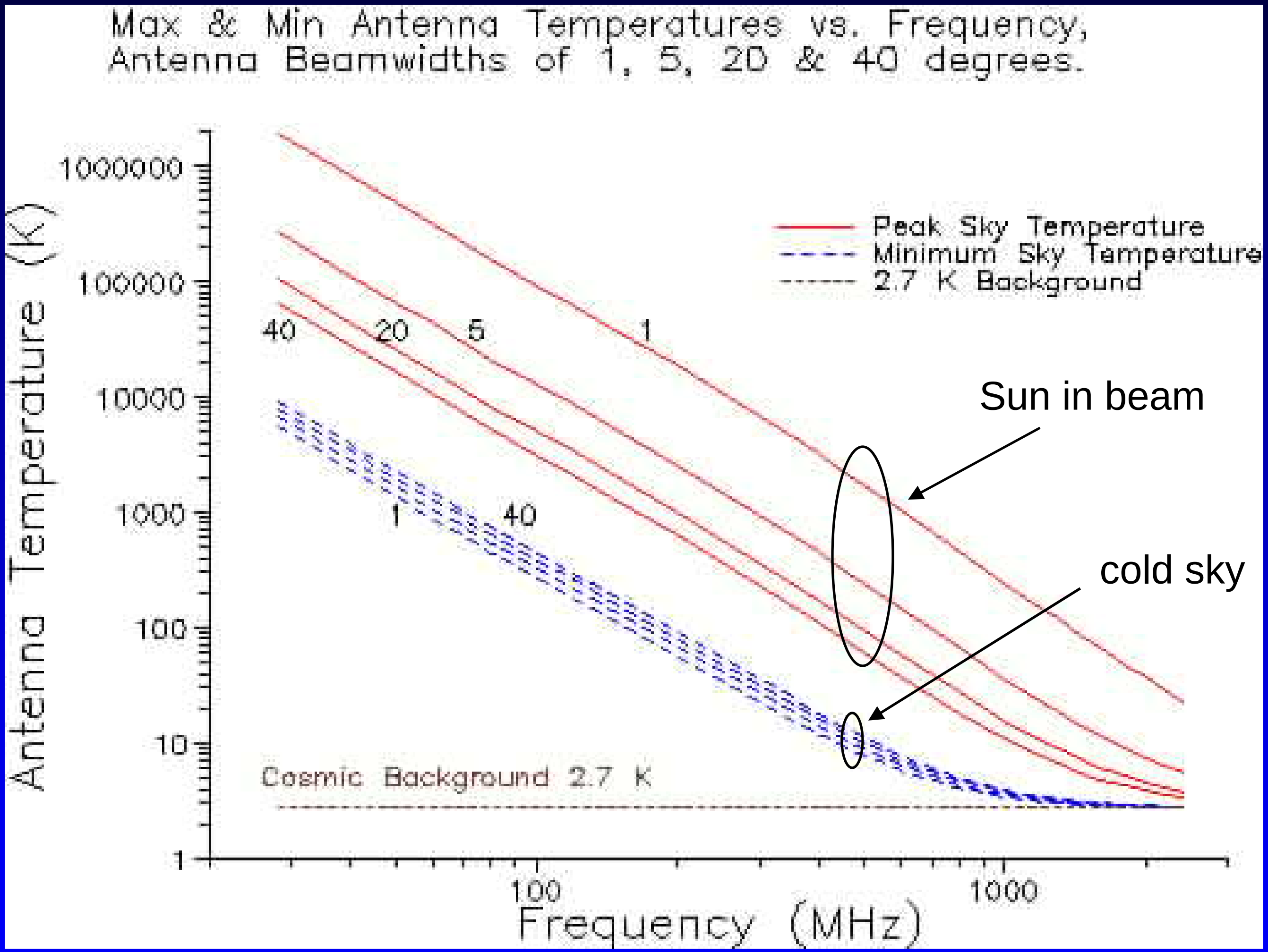
- **Central 25% of collecting area available for “All Sky Monitor”**
- **~1 sr sky image from Fourier-transformed visibilities + selfcal**
- **10-240 MHz tuning**
- **4 MHz x 0.5 s (very well suited to “slow” transients)**
- **ASM adds only about $1.5M to system cost**
- **Status?....**



Desirable Features of a New Transient Instrument

- **Continuous monitoring of > 1 sr, indefinitely**
- **Max 100's of Jy in 1 s (100x improvement over previous efforts)**
- **Bandwidth a tradeoff between sensitivity to dispersed pulses and RFI avoidance; ~10 MHz reasonable**
- **6 kHz x 10 ms time-frequency resolution (counter dispersion)**
- **Multiple sites for anticoincidence**
- **Frequency**
  - **> 300 MHz**
    - Avoid being sky noise limited
    - Avoid worst of the man-made RFI
    - Simplify de-dispersion
  - **< 1500 MHz**
    - Effective aperture of arrays goes as λ^{-2}, Beamwidth of filled aperture as λ^{-1}
    - Low cost per element
  - **Simultaneous multiple frequency bands for confirmation / RFI discrimination**
    - E.g., 1.4 GHz x 20 MHz + 611 MHz x 4 MHz + 38 MHz x 500 kHz

Sky Noise Considerations



Graphic courtesy D. Emerson, NRAO

Directivity is Bad

- The time required to search a solid angle of 1 sr is
  $$T = (\tau + T_{point})\, \Omega_0^{-1}$$
  where τ is the time required to achieve the desired sensitivity, and Ω_0 is the instantaneous beam solid angle

- L-Band Search #1
  - 140 2.3 m dishes cover 1 sr at 1.4 GHz (T_{point}=0)
  - Uncooled front ends T_{sys} = 100 K (A_e/T_{sys} ~ 0.02 m^2/K) yields ~ 200 Jy in 1 s
  - “Pile of parts” cost ~US$140K

- L-Band Search #2
  - Arecibo (Ω_0 ~5 μsr) searches 1 sr at 1.4 GHz
  - A_e/T_{sys} ~ 2250 m^2/K; yields ~ 200 Jy in ~80 ps
  - But > 185,000 pointings are required! -> hours to cover 1 sr

- If source is not on continuosly for entire time it takes to complete search, probability of detection is dramatically degraded

Directivity is Bad

- The time required to search a solid angle of 1 … is

  $$T = (\tau + T_{point}) \Omega \ldots^{-1}$$

  wh… is the time req… d to ach… e desired sensitivity, a… is the ins… ous … olid angl…

- L-Band Search #1
  - 14…
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- If source is not on continuosly for entire time it takes to complete search, probability of detection is dramatically degraded

> **Penalty is high for attempting search with sensitivity greater than necessary:**
> **<u>Filled aperture</u>: Slows down**
> **<u>Array systems</u>: Becomes expensive**

RFI Mitigation Techniques - Passive

- **Require coincidence at multiple widely-separated sites ("Anticoincidence")**
- **Require dispersion (since RFI should have DM~0)**
  - **Discriminates against nearby sources**
  - **Some RFI has "apparent DM" > 0**
- **Require large bandwidth or associated detections in multiple frequency bands**
  - **Discriminates against sources with steep spectrum**
- **Require angle of arrival well above horizon**
  - **Aircraft reflections**
  - **Discriminates against Galactic Center when oberving from high lattitutes**
- **Summary:**
  - **No "magic bullets"**
  - **Nevertheless, these are essential techniques and perhaps all that is needed for searches of moderate senstivity at many existing observatory sites**

RFI Mitigation Techniques - Active

- **Blanking**
  - **Value in transient detection is to avoid periods of known RFI activity**

- **Spatial Nulling**
  - **Essentially blanking in the "angle domain" – requires calibration, but probably useful against satellites**

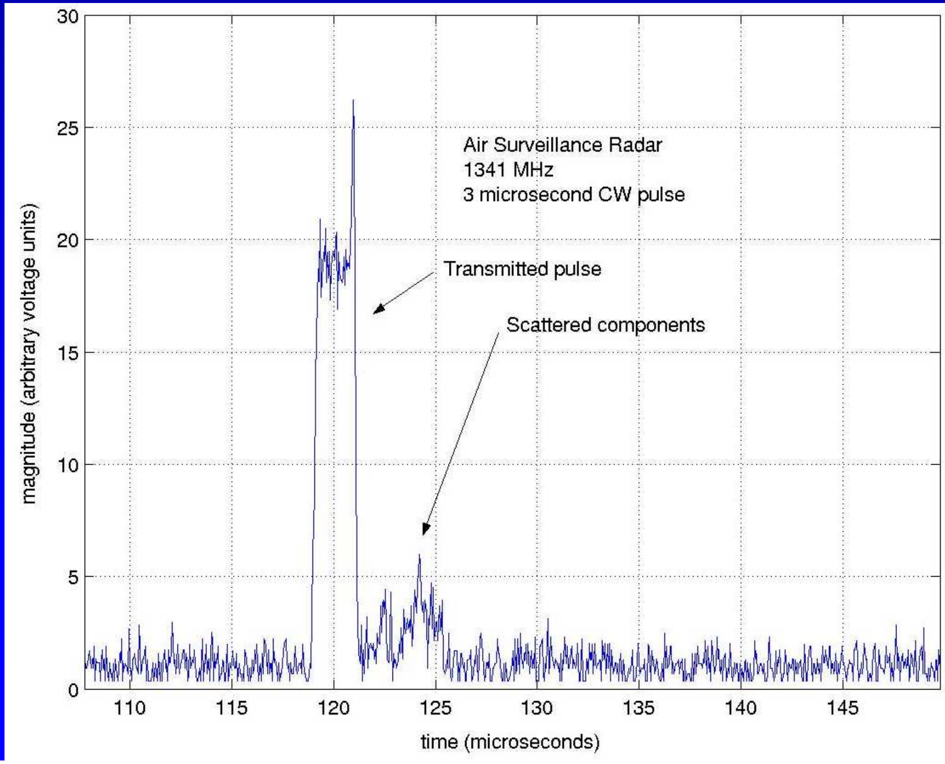
- **Canceling**
  - **When you find yourself wanting to blank all the time!**

Case Study: L-Band Radar

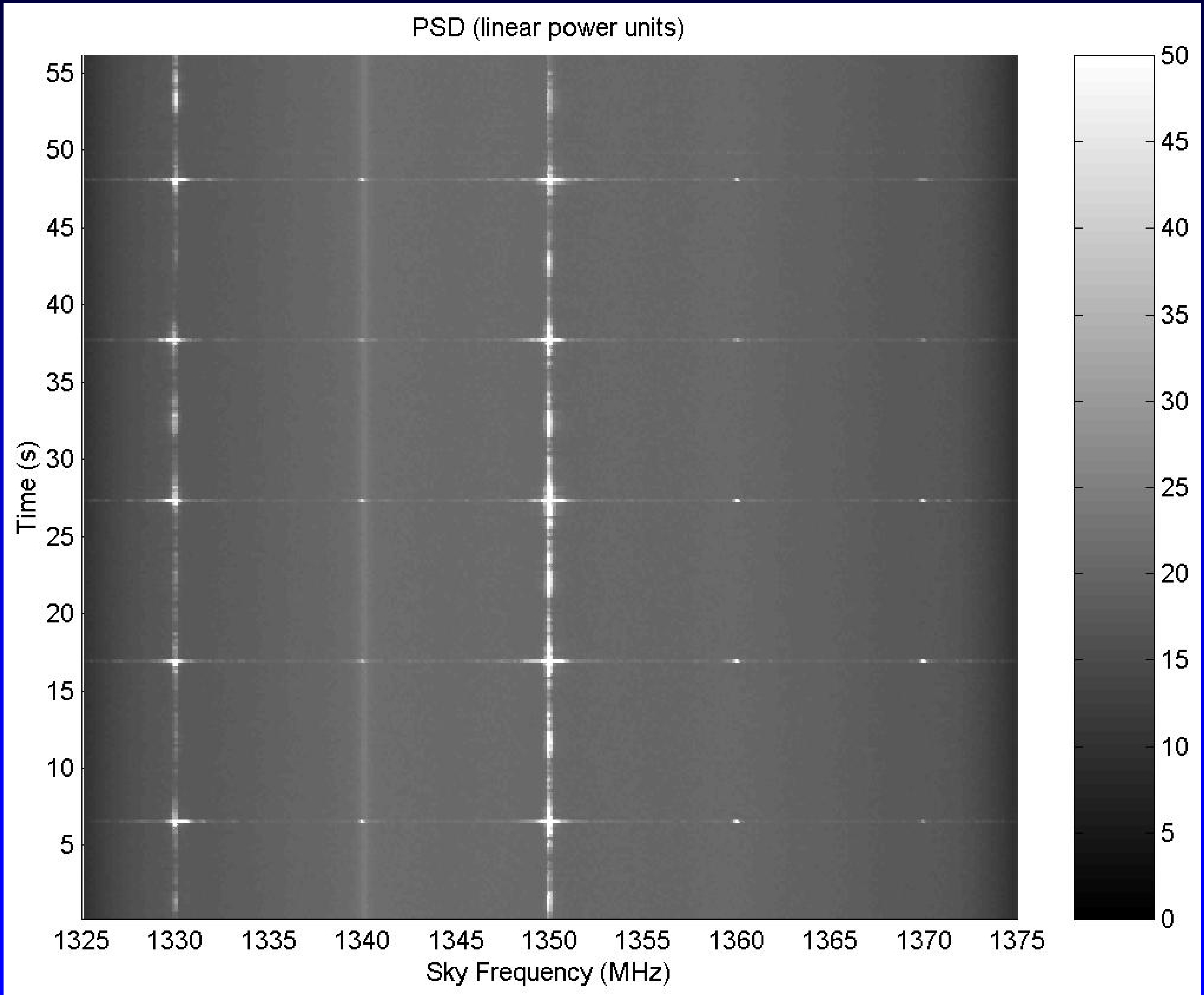
- **The band 1215-1400 MHz is important for:**
  - **Spectroscopy of redshifted HI**
  - **Continuum & Pulsar work**
  - **Earth climate & geophysical studies: Brightness temperatures infer ocean salinity, soil moisture, ...**

- **AND this entire band is allocated primarily to aviation radars!**

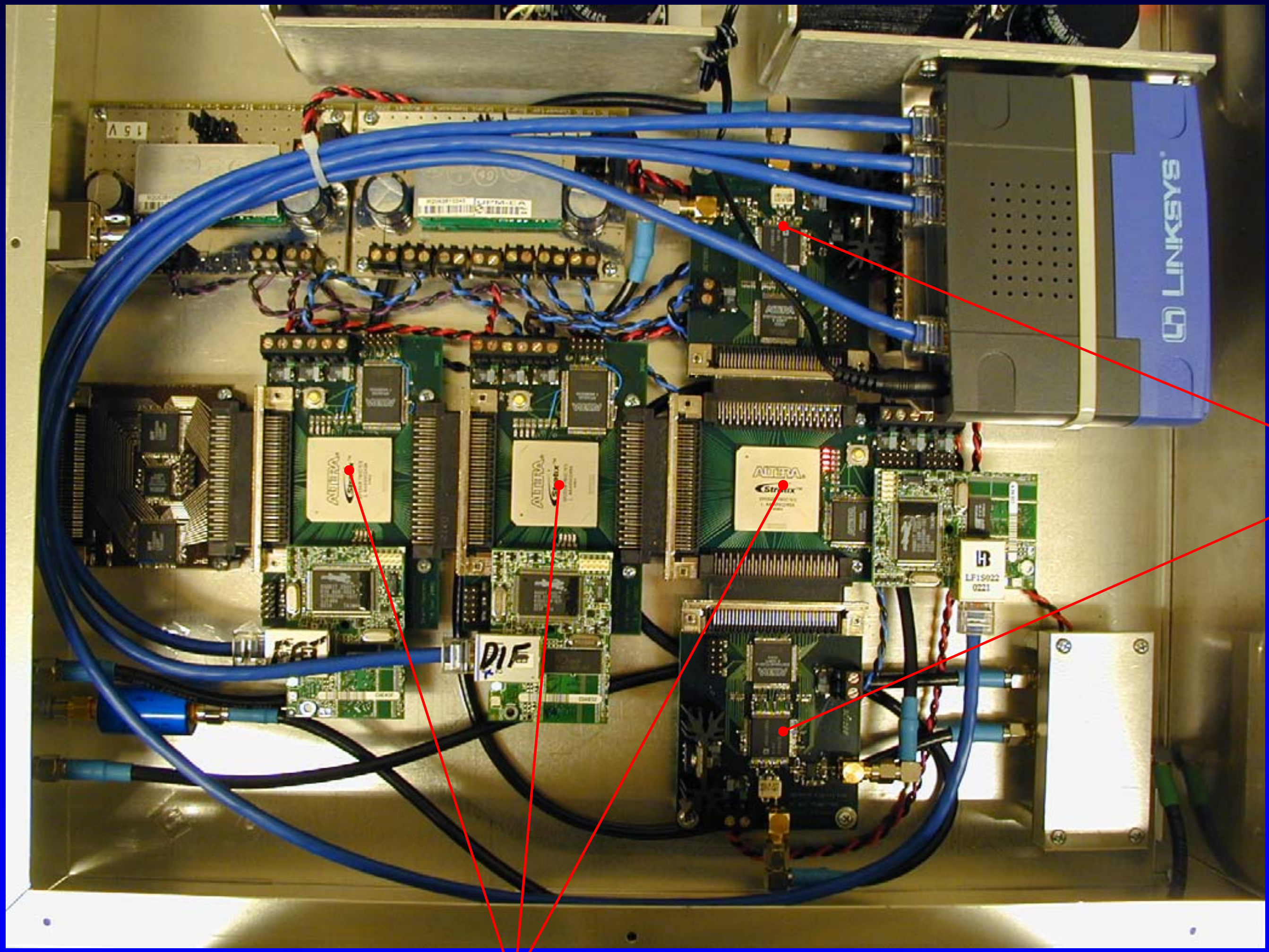
Waveform:	**Fixed-frequency (CW) or chirped, & pulsed**
Pulse length:	**2-400 μs**
Pulse spacing:	**1-27 ms (typical duty cycle ~0.1%)**
Bandwidth:	**~1 MHz**
Tx pwr:	**10^3 - 10^6 W**
Antenna:	**Highly directional, rotation rate ~10 s**



What Arecibo Sees:



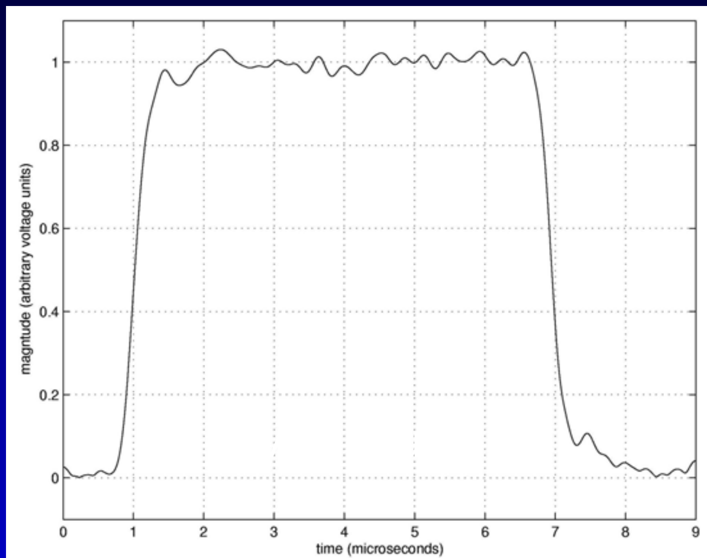
OSU NASA/IIP Wideband Digital Receiver

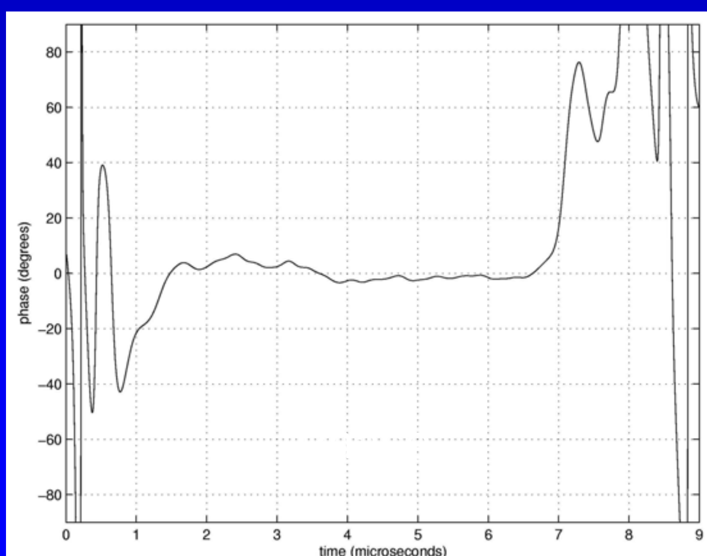


200 MSPS A/Ds

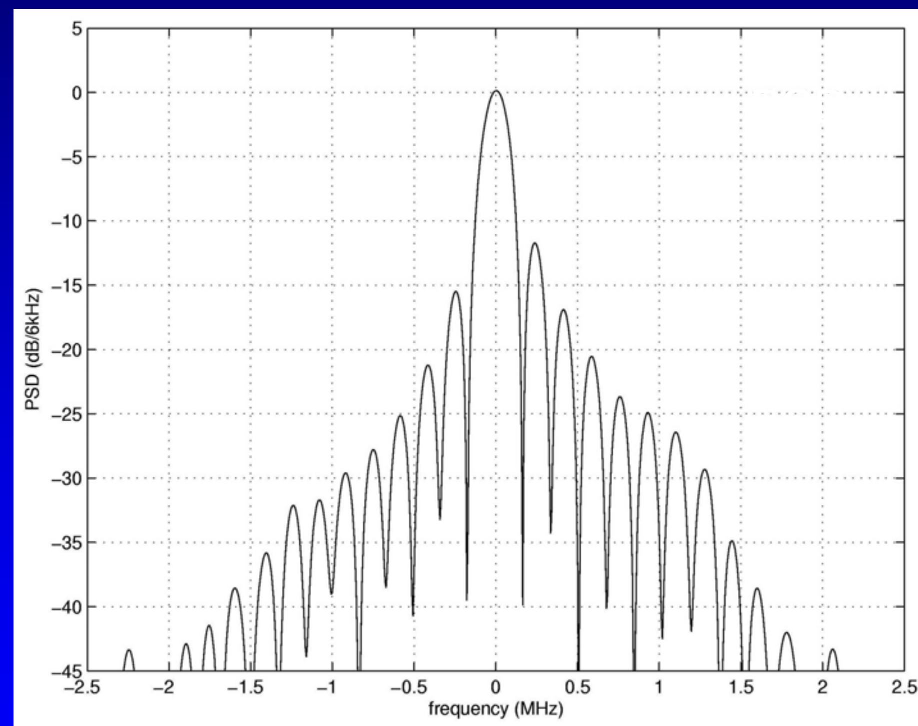
FPGAs implementing Receiver, FFT, RFI Mitigation, PC Interface

Measured Radar Waveform Characteristics



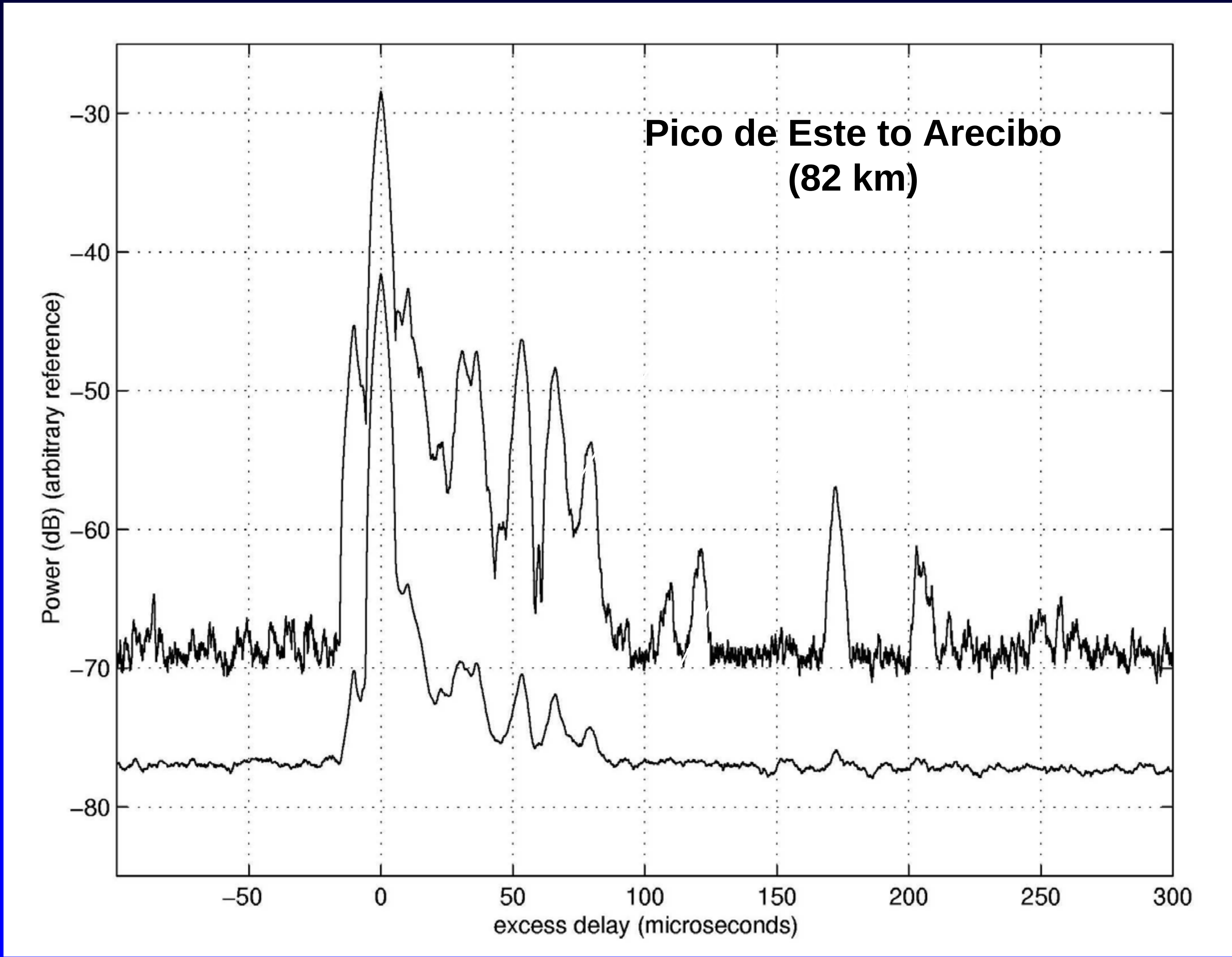


Derived Transmit Pulse Waveform
(Based on receive data taken at Arecibo and lots of post processing)



Ellingson & Hampson (2003), *ApJS*, **147**, 167.

Derived Channel Impulse Response



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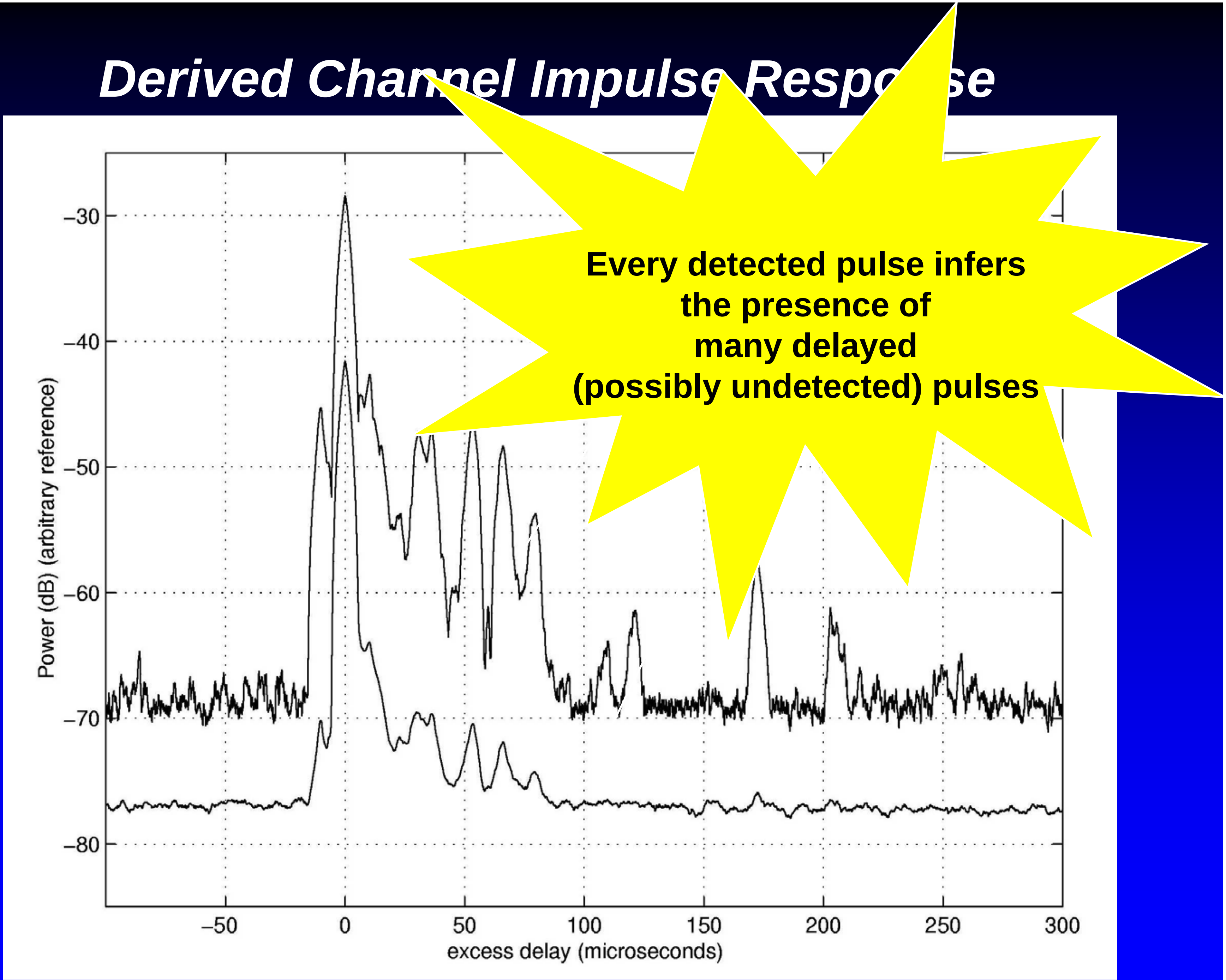


Ellingson & Hampson (2003), *ApJS*, **147**, 167.

Pulse Blanking $\rightarrow$ Pulse Canceling

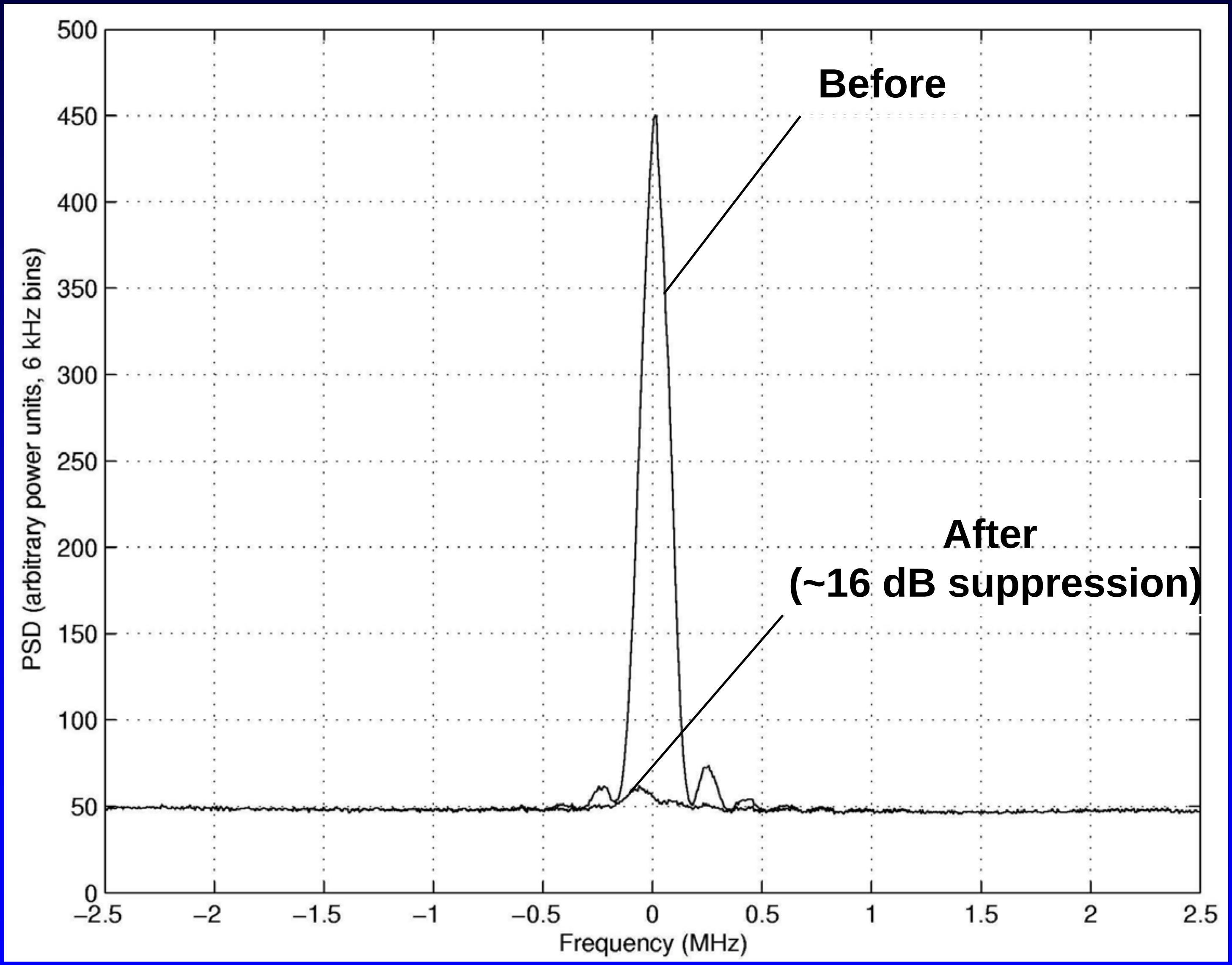
- **Pulse blanking works great for continuum and spectroscopy work**

- **Blanking is problematic for transient searches**
  - **Tampering with noise statistics affects detection performance**
  - **Holes in the time series complicate analysis by disrupting the otherwise ergodic characteristics of the noise**
  - **Possibility of blanking interesting transients?**

- **In dealing with these things, we would really like to be able just to "look through" the interference**

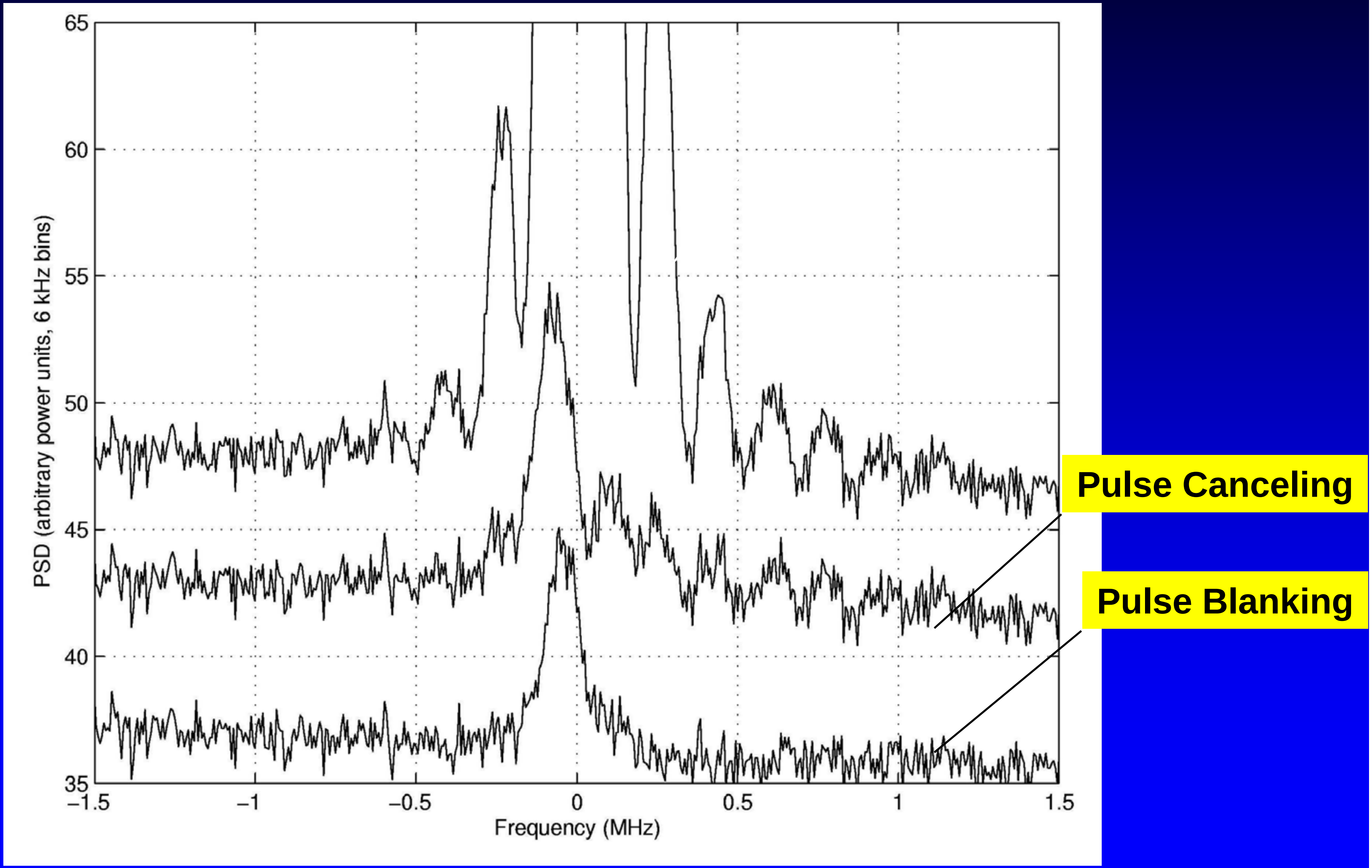
- **Possible answer is *Pulse Canceling*: Estimate and subtract pulses, as opposed to simply blanking**

Pulse Canceling at Arecibo



Ellingson & Hampson (2003), *ApJS*, **147**, 167.

Pulse Canceling vs. Pulse Blanking



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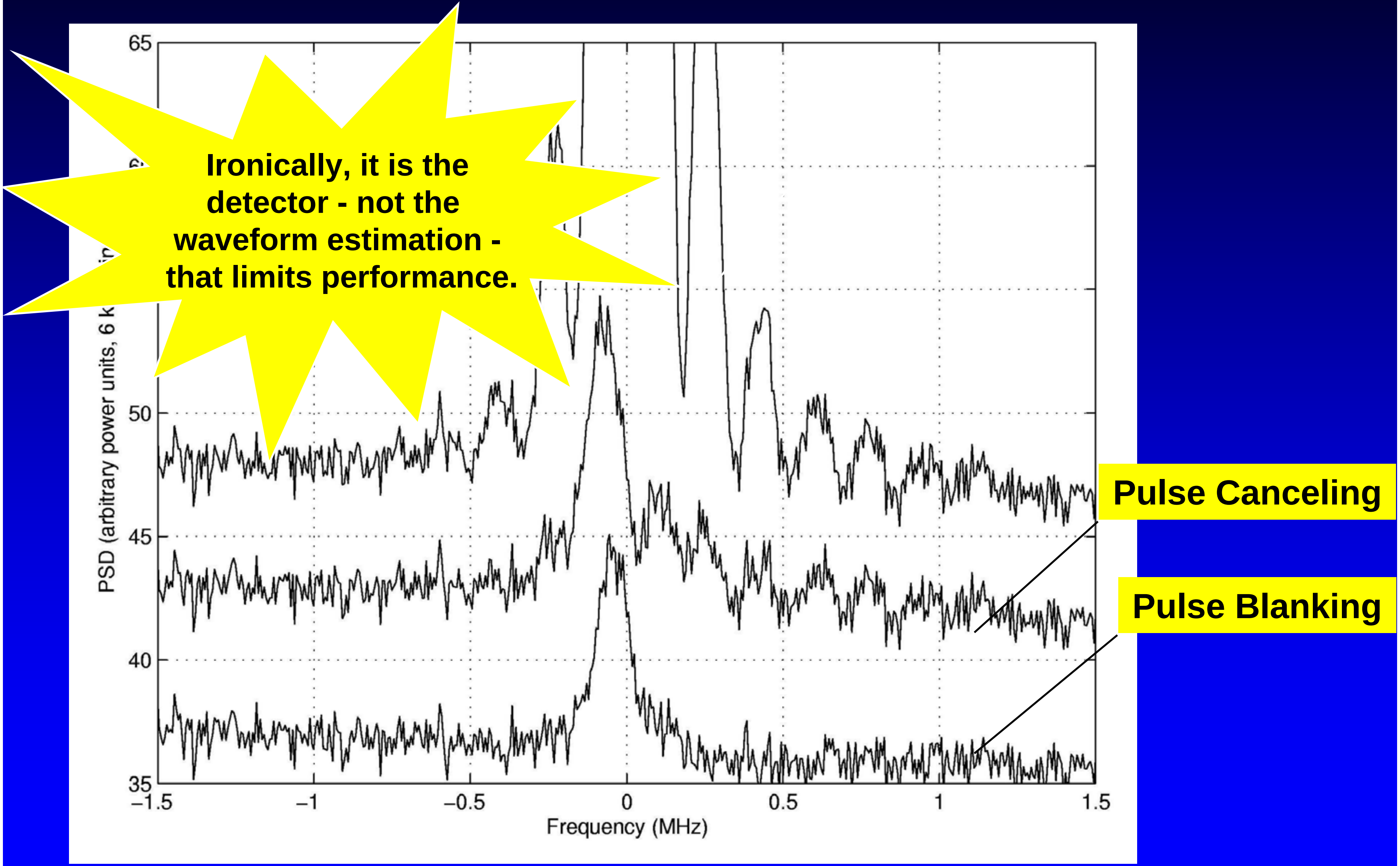
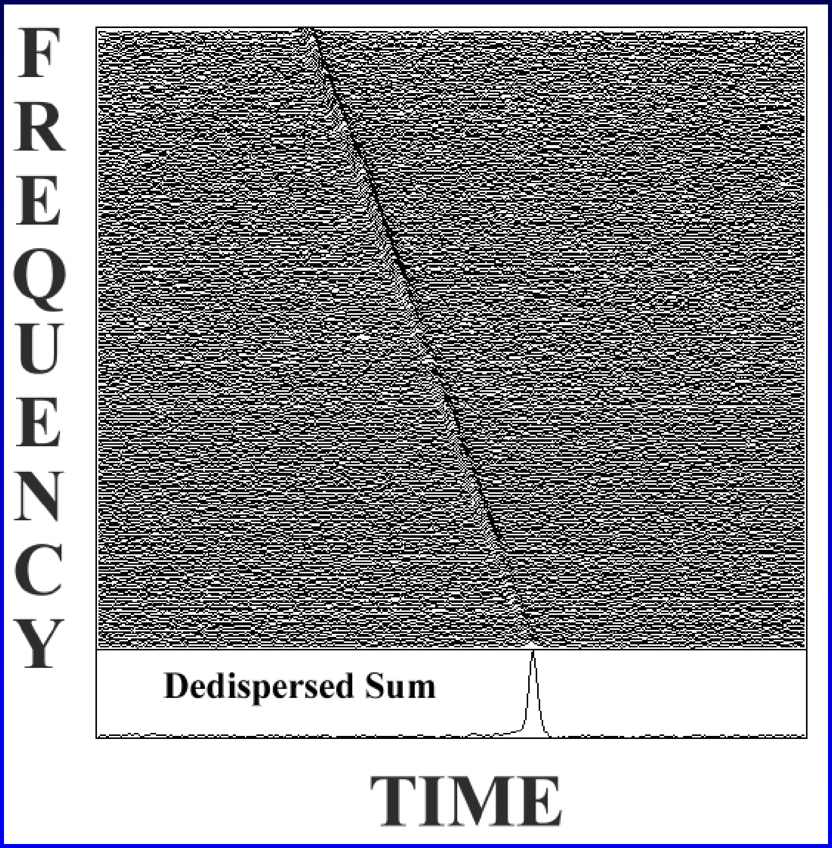


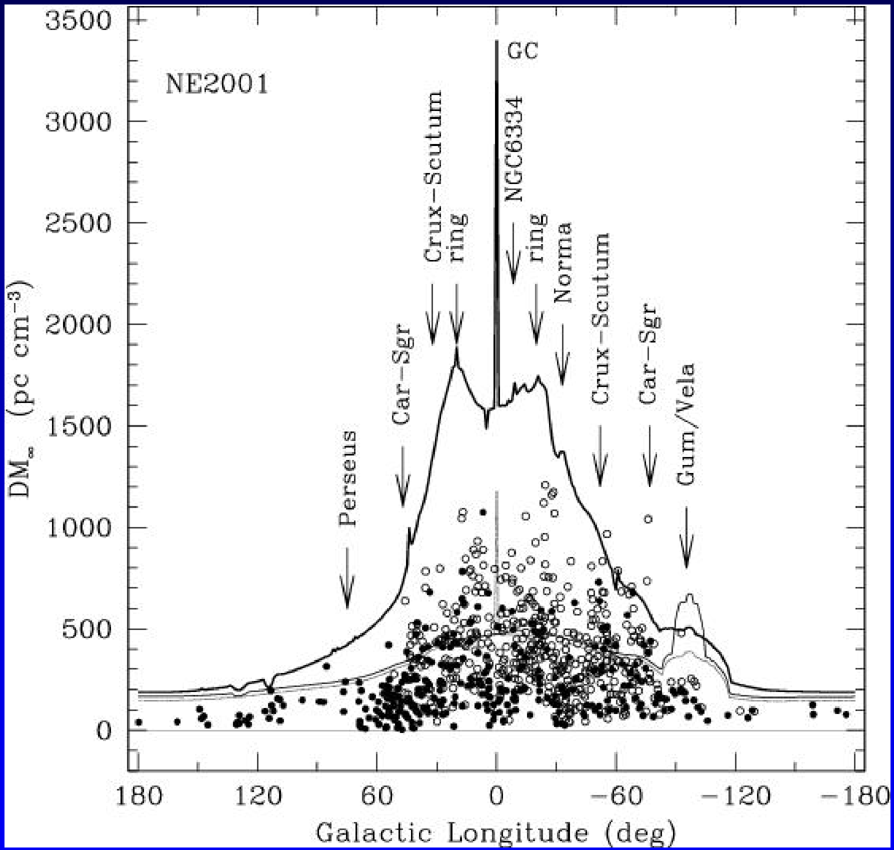
Ellingson & Hampson (2003), *ApJS*, **147**, 167.

Will a Radar Pulse Blankers/Cancelers "Eat" Astrophysical Pulses?



- **Clearly, there is some risk of this for strong pulses which have low dispersion measures**
- **Actual risk can be determined as a function of strength and DM**

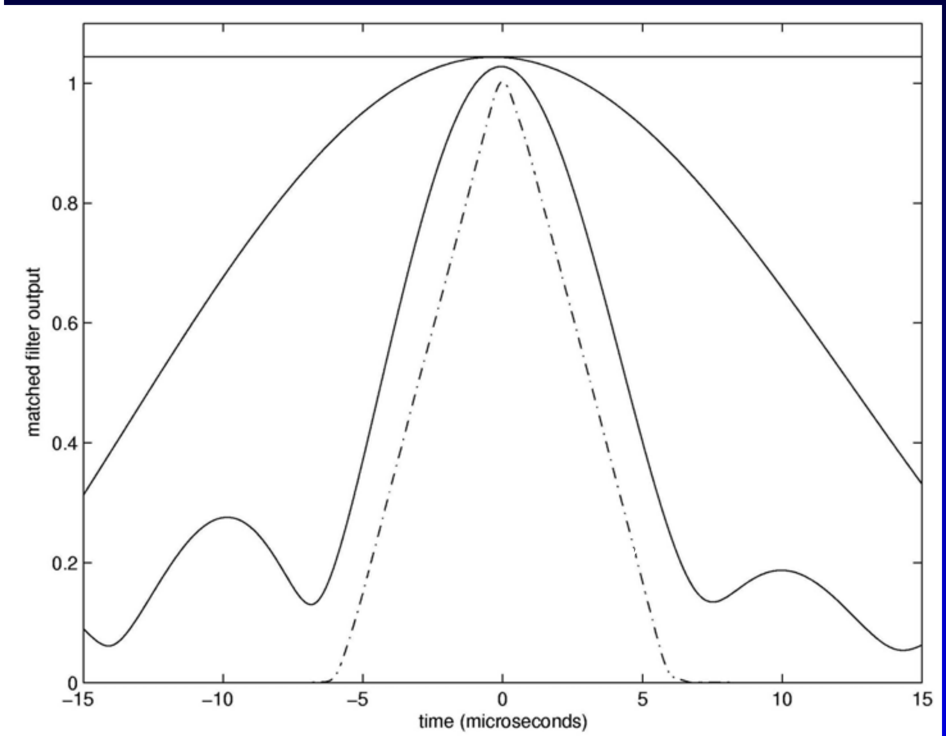
Asymptotic vs. Known Dispersion Measures

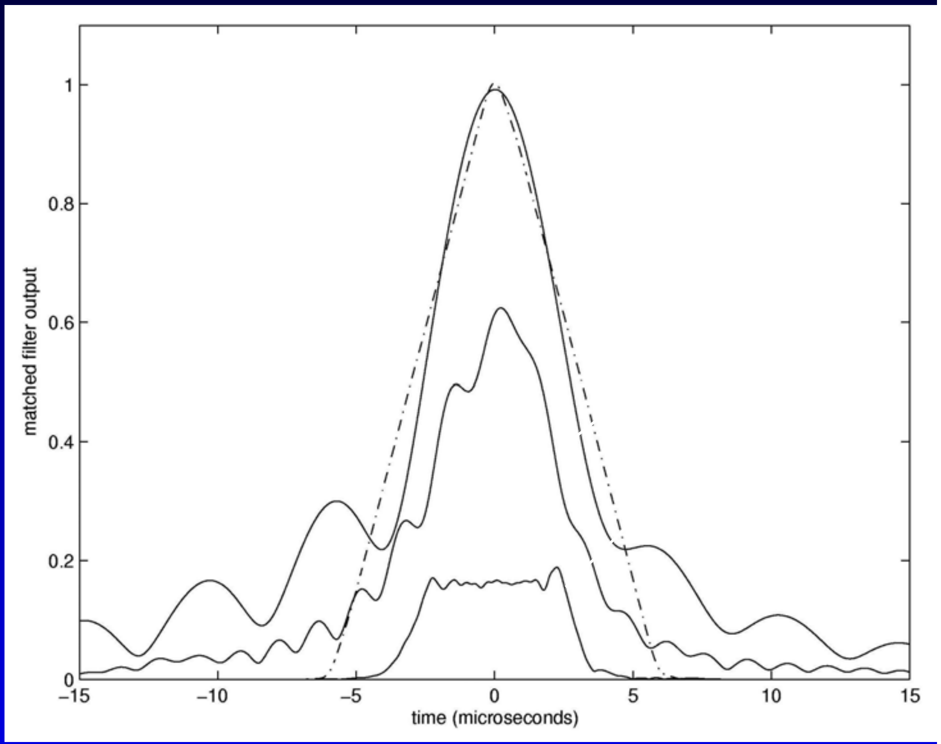


- **Extragalactic sources will experience asymptotic DMs**
  - **~ 1400 pc/cm^3 in the plane of the galaxy**
  - **~ 50 pc/cm^3 normal to the plane**
  - **Plus contribution from host galaxy**
- **Galactic sources will also be in this range, but are likely to be less luminous and therefore biased toward the low end**

Cordes & Lazio (2003)

Examples





<u>DM > 20 or so</u>: No problem if time above threshold is taken into account

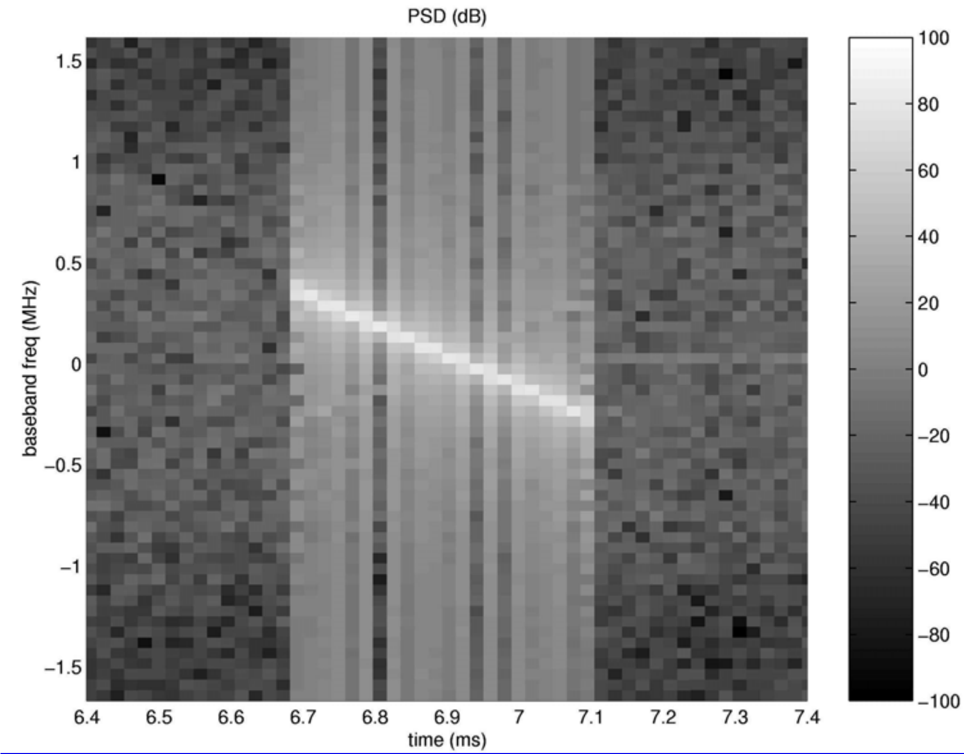
<u>DM < 20 or so</u>: Risk decreases with decreasing DM

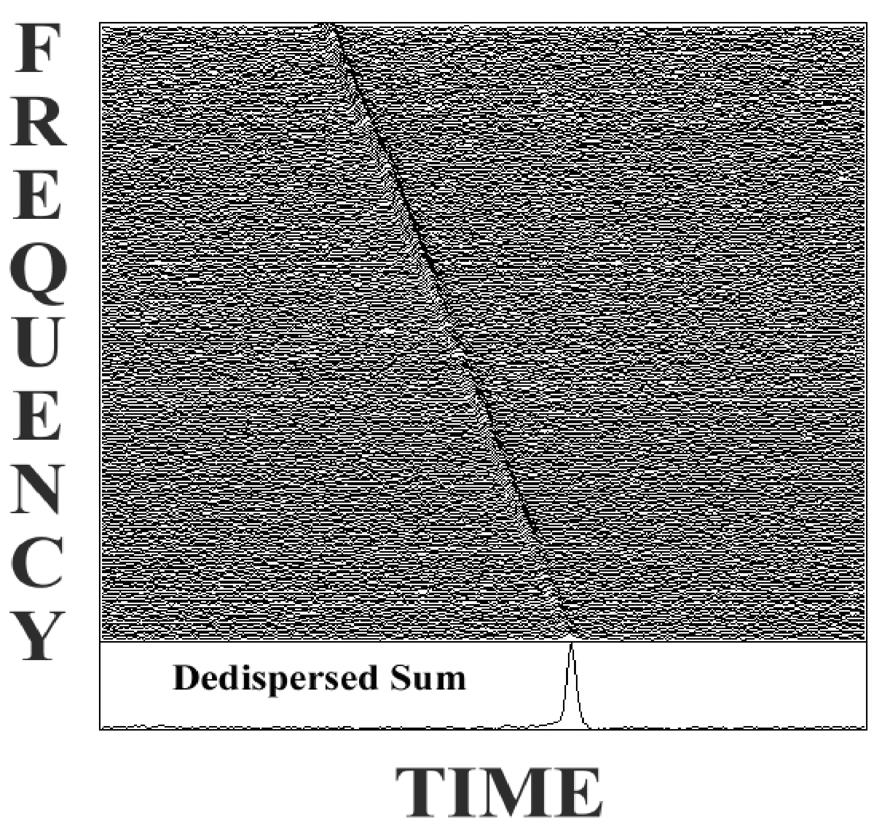
<u>DM ~ 20</u>: Dispersed pulse looks like radar at output of matched filter.
At Arecibo, dispersed pulses greater than about 0.1-1.0 Jy are detected.
For proposed instrument, this happens at about 10 kJy

<u>In general</u>: Risk is greatest when dispersed pulse exhibits the same time-frequency occupancy as radar pulse. (In this case, 7 ms x 150 kHz)

Ellingson & Hampson (2003), *ApJS*, **147**, 167.

Other Annoyances…



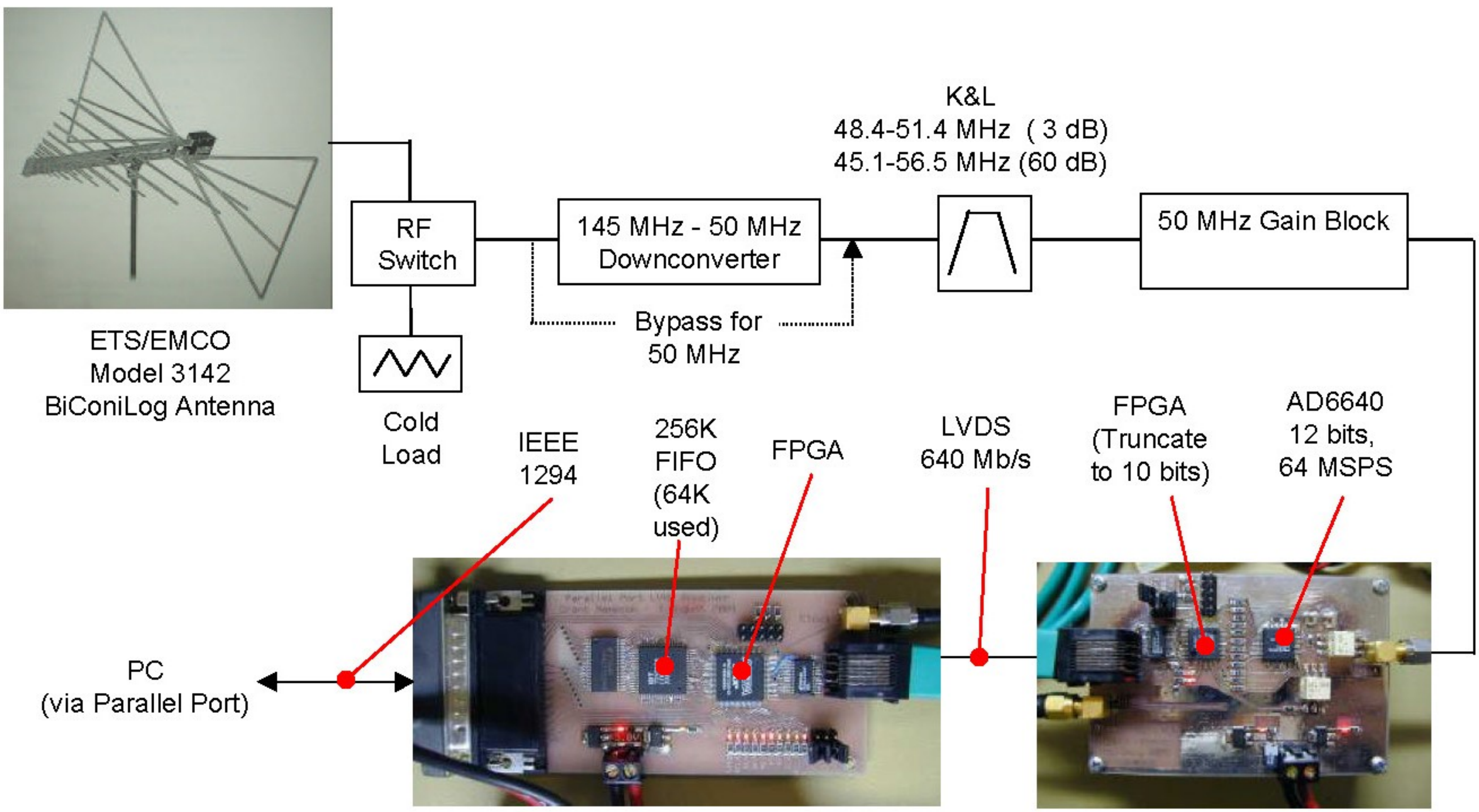


FPS-117 radar received at Arecibo (Linear FM Waveform)

Typical Pulsar Pulse

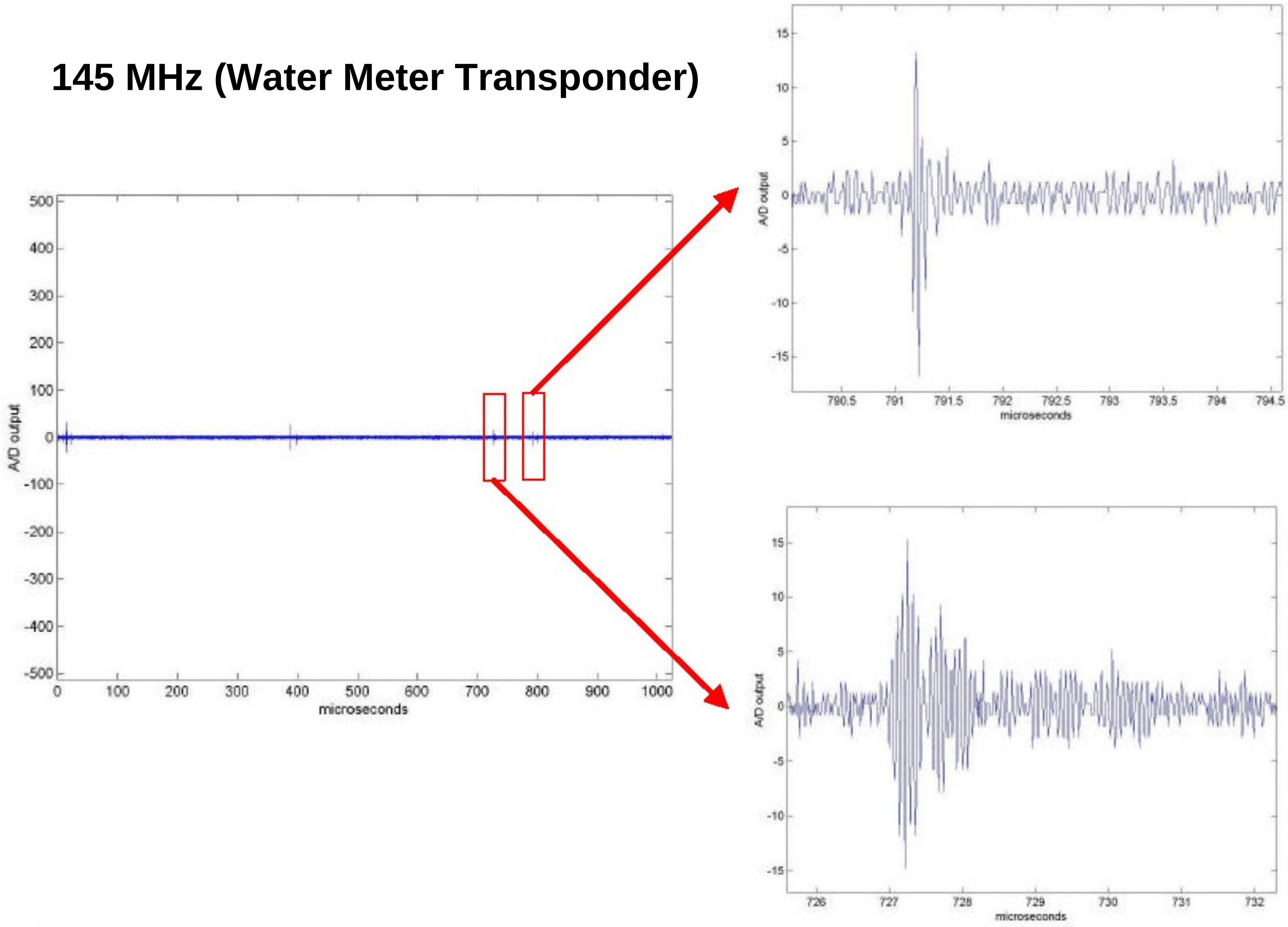
Ellingson & Hampson (2003), *ApJS*, **147**, 167.

145 MHz / 50 MHz RFI Survey System



Other Annoyances…

145 MHz (Water Meter Transponder)



Concluding Remarks

- **Radio transients represent a relatively unexplored area with potentially very high payoff**
- **Existing instruments are very poorly suited to the task, even with new backends**
- **~$US1M would build one heck of a astronomical pulse detector**
- **A big technical challenge is RFI.** ***The fundamental irony of RFI mitigation is this:*** **Making RFI go away is easy: the hard part is detection & estimation**
- **Another challenge will be refining/understanding noise statistics with sufficient accuracy to achieve better sensitivities**

First Announcement (2)

RFI2004

Workshop on Mitigation of Radio Frequency Interference in Radio Astronomy

IUCAF

Dominion Radio Astrophysical Observatory
Penticton, British Columbia, Canada
16-18 July 2004

Held in Conjunction With The 2004 Int'l SKA Workshop
Sponsored Jointly by IUCAF and the Int'l SKA Consortium

http://www.drao-ofr.hia-iha.nrc-cnrc.gc.ca/science/ska/ska2004/ISKA_2004_website/Welcome.htm

Why RFI2004?

For radio astronomers, the radio frequency interference (RFI) environment continues to get worse and has become a critically important issue in the development of the next generation of radio telescopes, including the Square Kilometre Array. The emerging need to deal with interference problems more directly has, in recent years, led to a dramatic surge in activity in the area of active interference mitigation (IM). The recent flurry of published papers in scientific and technical journals signals that IM is becoming a mature activity, with many implications for current observing as well as for new instruments now in the planning and development stages. The last meeting addressing IM as a standalone topic was the IUCAF meeting in Bonn, Germany in 2001. With design effort on a number of new radio instruments (LOFAR, ATA, ALMA, SKA, and numerous national systems and prototypes) ramping up, it is an appropriate time for radio astronomers, engineers, and signal processing theorists to once again meet and share ideas.

Scope of the Workshop

Topics

- An update on the scientific, technical and regulatory issues associated with IM presented by prominent speakers in each area.
- Characterization of RFI: Spectral/temporal properties as perceived by radio telescopes, documented effects on recent observations, site surveys and emerging issues.
- Real-time Signal Processing Techniques:
  - Spatial nulling and beam shaping
  - Wideband array processing
  - Adaptive vs. deterministic techniques
  - Subspace processing / eigenanalysis
  - Post-correlation canceling
  - Focal plane arrays and auxilliary antennas
  - Blanking techniques
  - Parametric estimation and subtraction
  - Frequency vs. time domain processing
  - Detection strategies
  - Observation-specific IM techniques
- Post-observation techniques; editing visibilities
- Field experiences and demonstrations of new