V-FASTR: The VLBA fast radio transients experiment

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The University of Western Australia

The VLBA (Very Long Baseline Array)

10 x 25m antennas. 327MHz → 86 GHz.

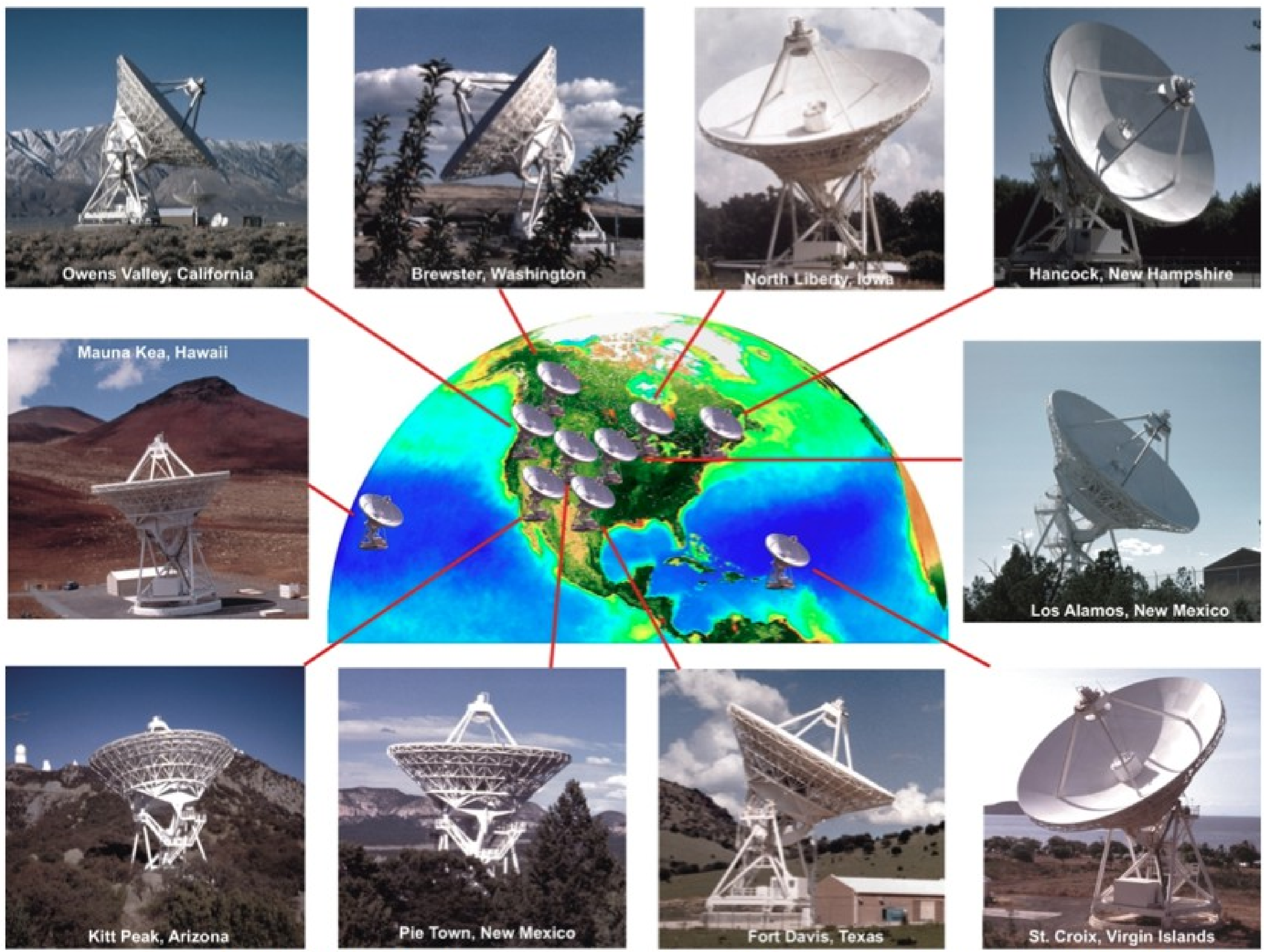


Image courtesy of NRAO/AUI and Earth image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE.

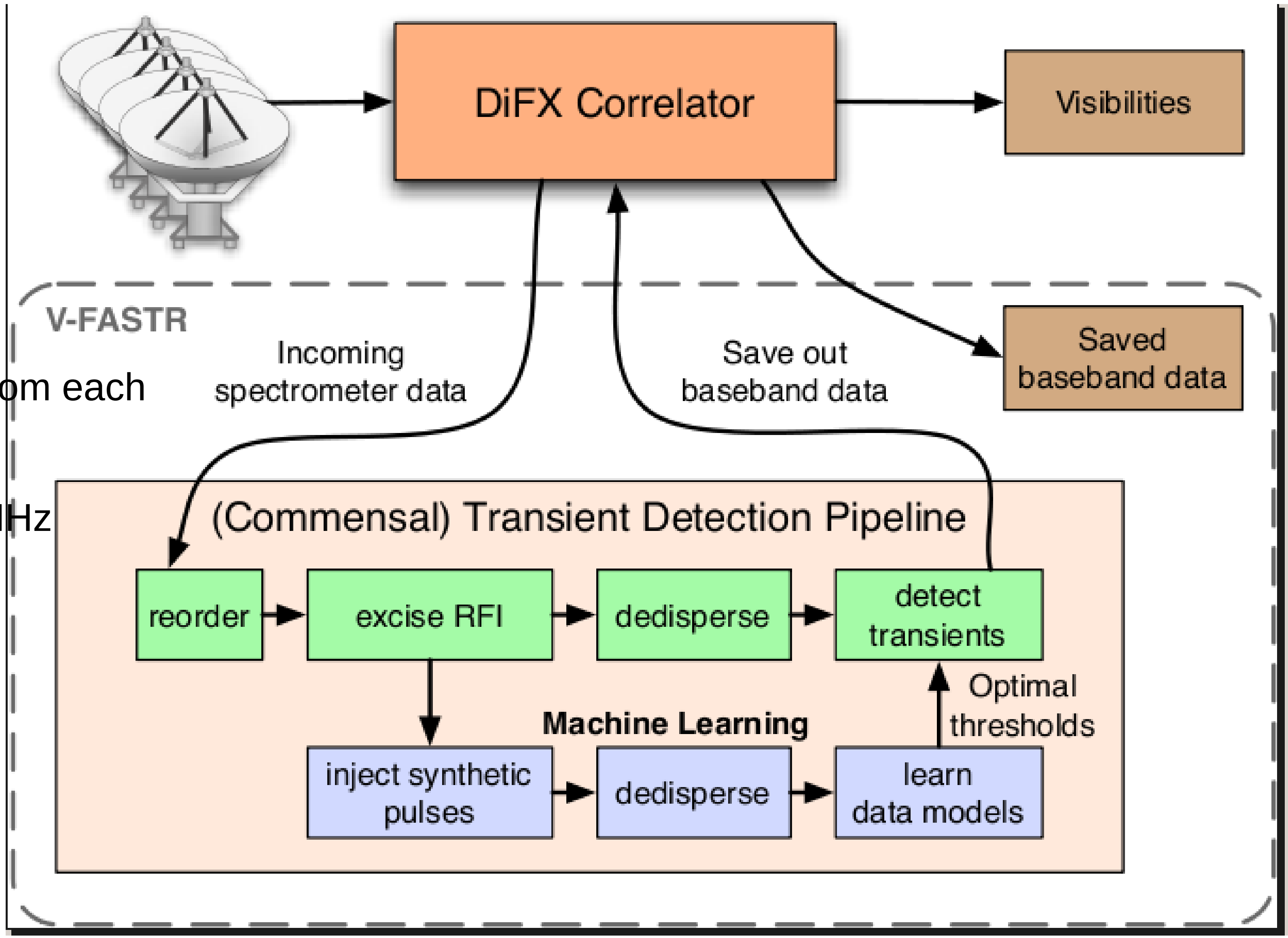
V-FASTR overview

- A **commensal** search for FRBs using the VLBA.
- Lots of benefits!
  - Good sensitivity. Lots of time on sky.
  - Can follow up to potentially milli-arcsec resolution
  - Geographically distributed antennas provide robustness against local RFI and LEO satellites.
  - VLBA uses the DiFX software correlator- can get spectrometer data almost for free.
- Not 100% straightforward
  - Details of how DiFX works and produces data are important
  - Tcal signals, AGC, 2-bit sampling, etc etc etc

V-FASTR pipeline

Disks from each antenna
shipped to Socorro

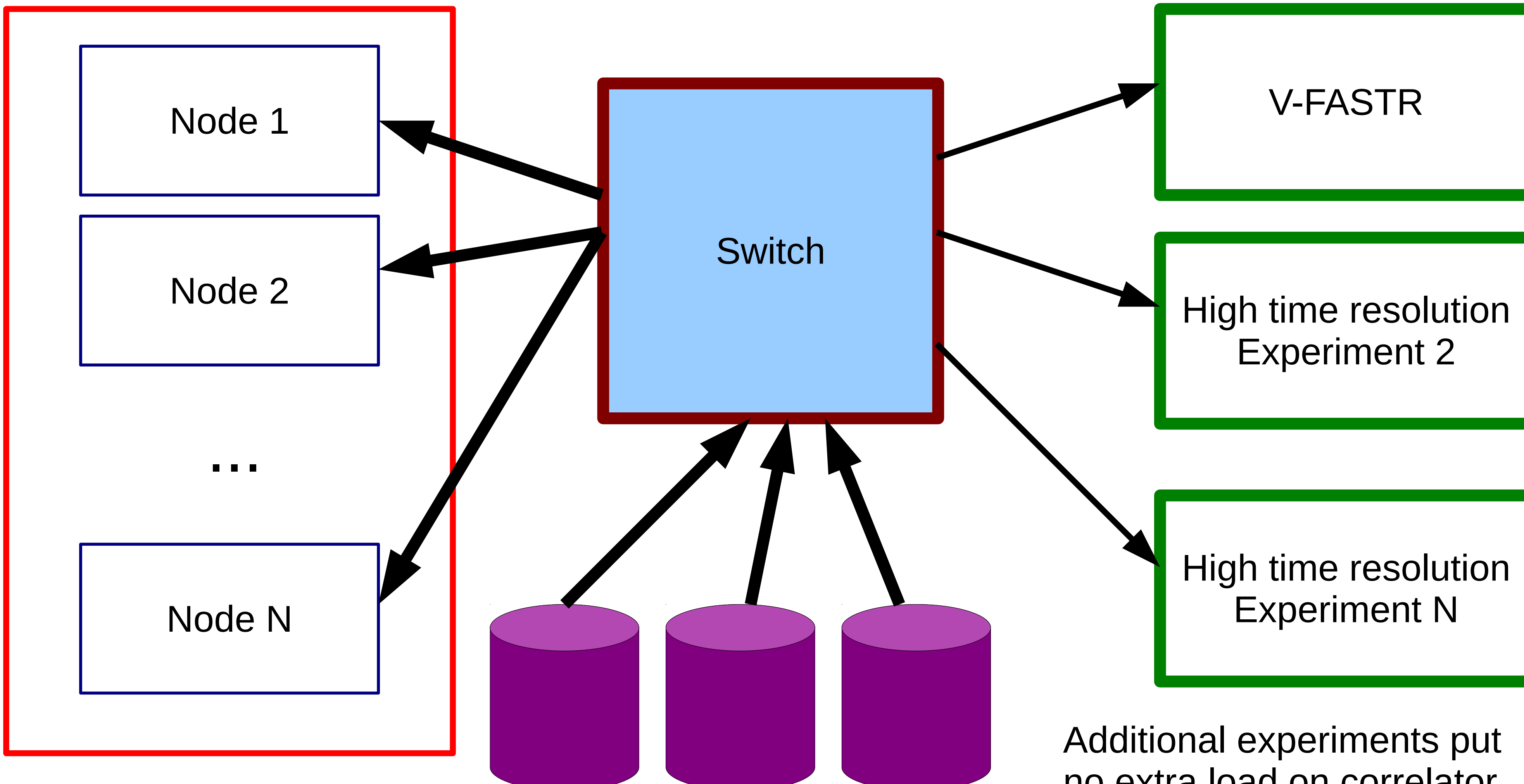
Total power from each
Antenna
•approx 1ms
•approx 0.5 MHz



DiFX = flexible, powerful, scalable

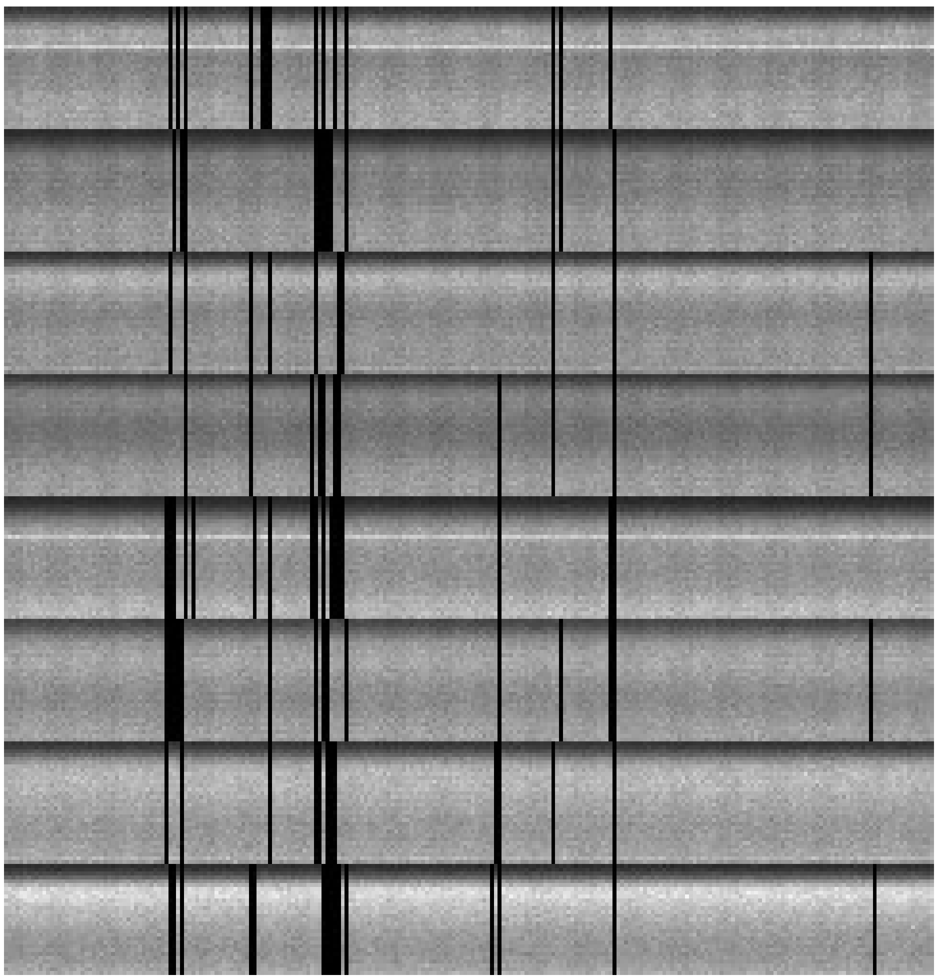
See Deller et al 2007, 2011

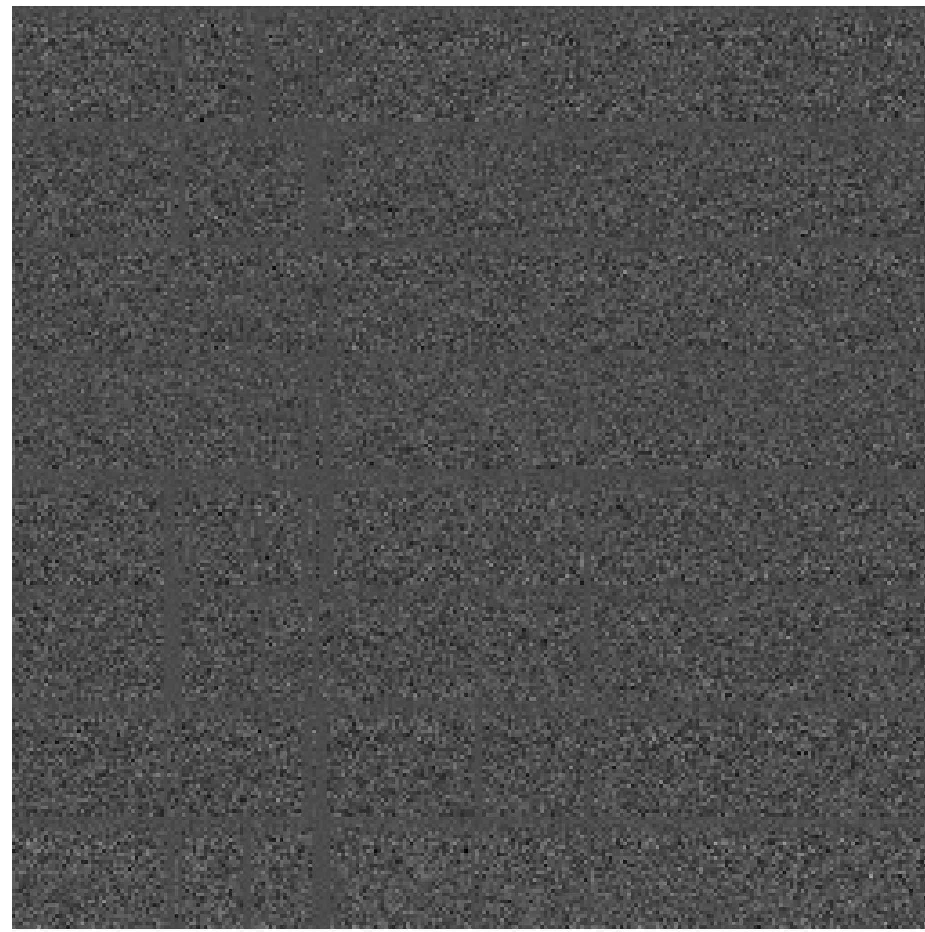
Spectrometer data via UDP multicast.



Additional experiments put no extra load on correlator

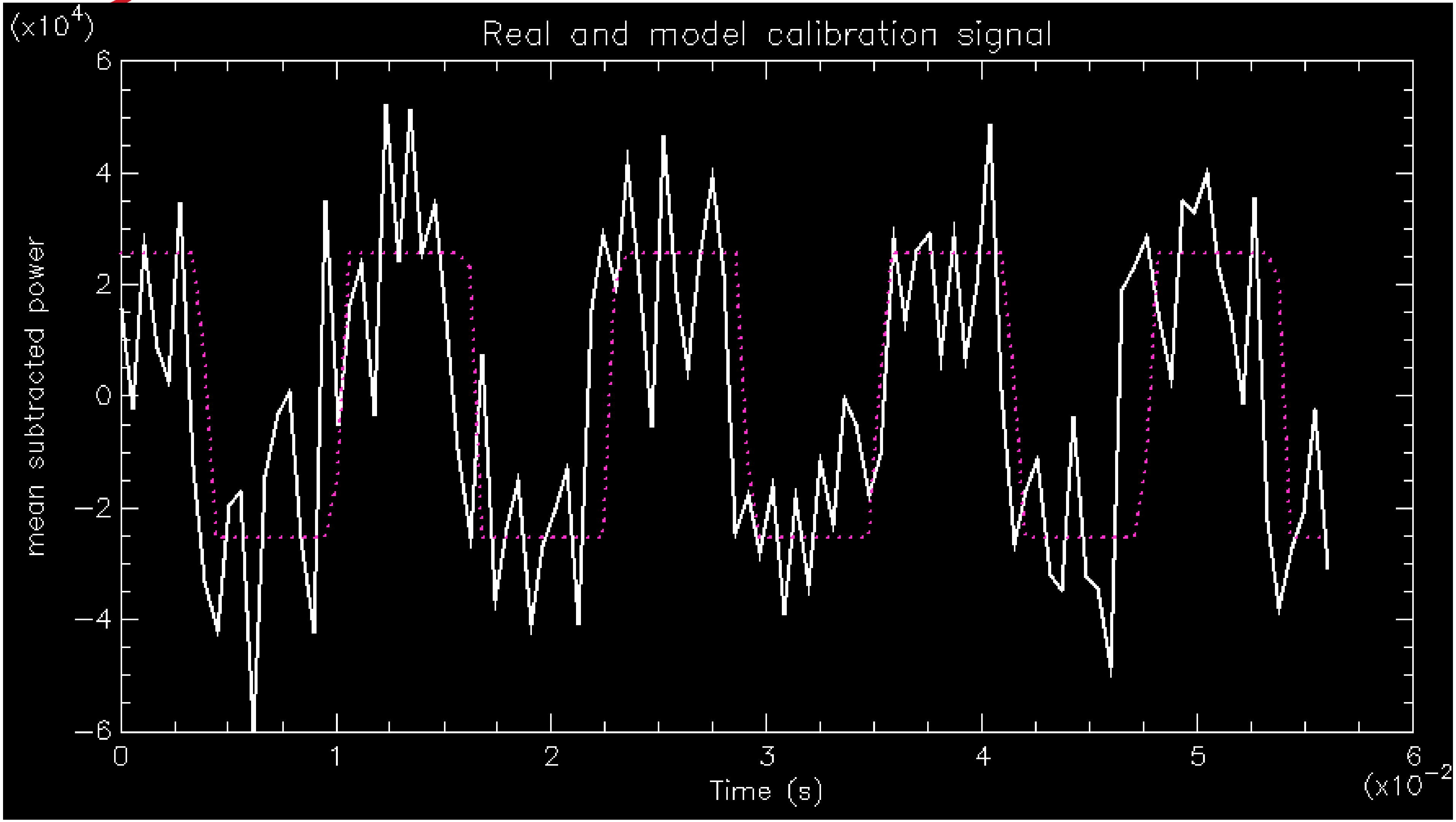
Technical Issues I: Tcal



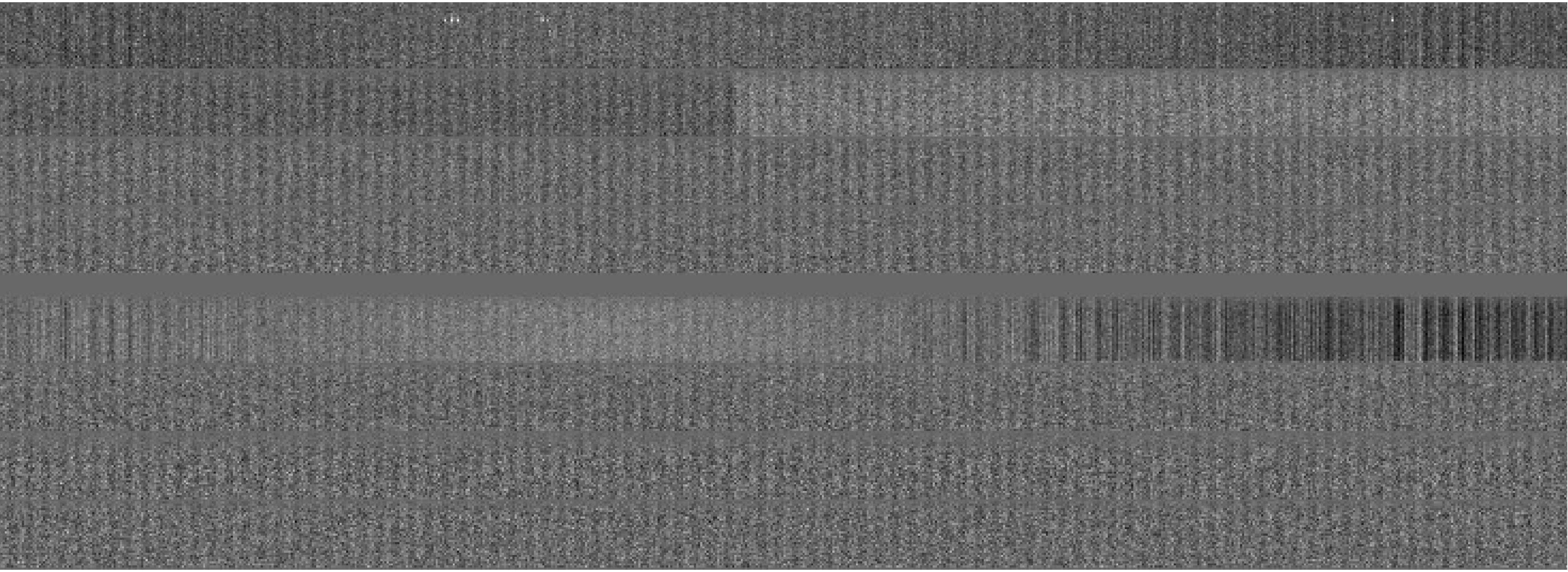


UDP packet loss causes black bands of missing data (this is an unusually bad case)

Technical Issues I: Tcal

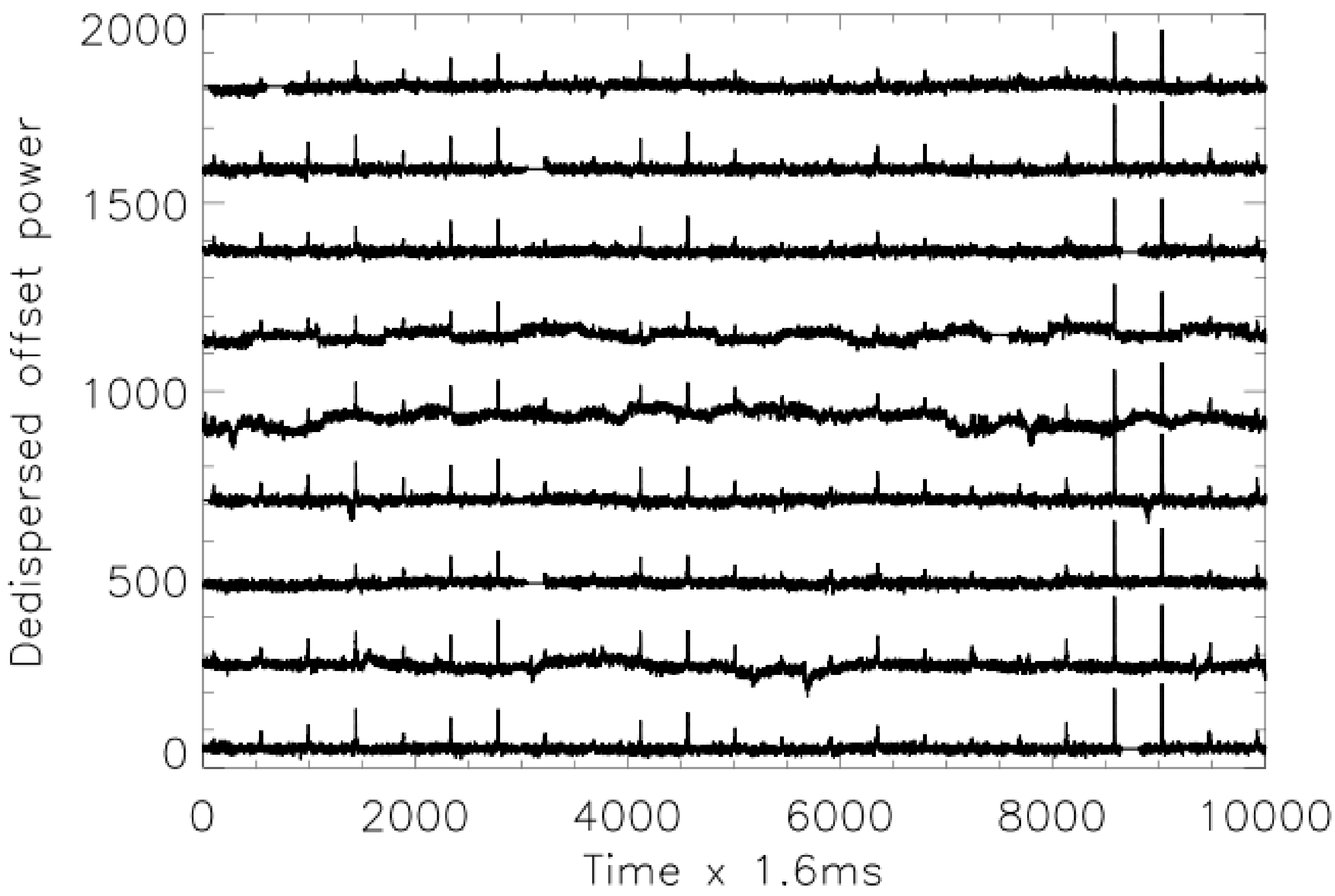


Technical issues II: RFI



Short-term (ms) bursty RFI is easy to detect and deal with. Longer term RFI (both narrow and broadband) that is strong enough affects the gain control and sampler statistics making the total power seen by the correlator change with time. This makes median subtraction difficult.

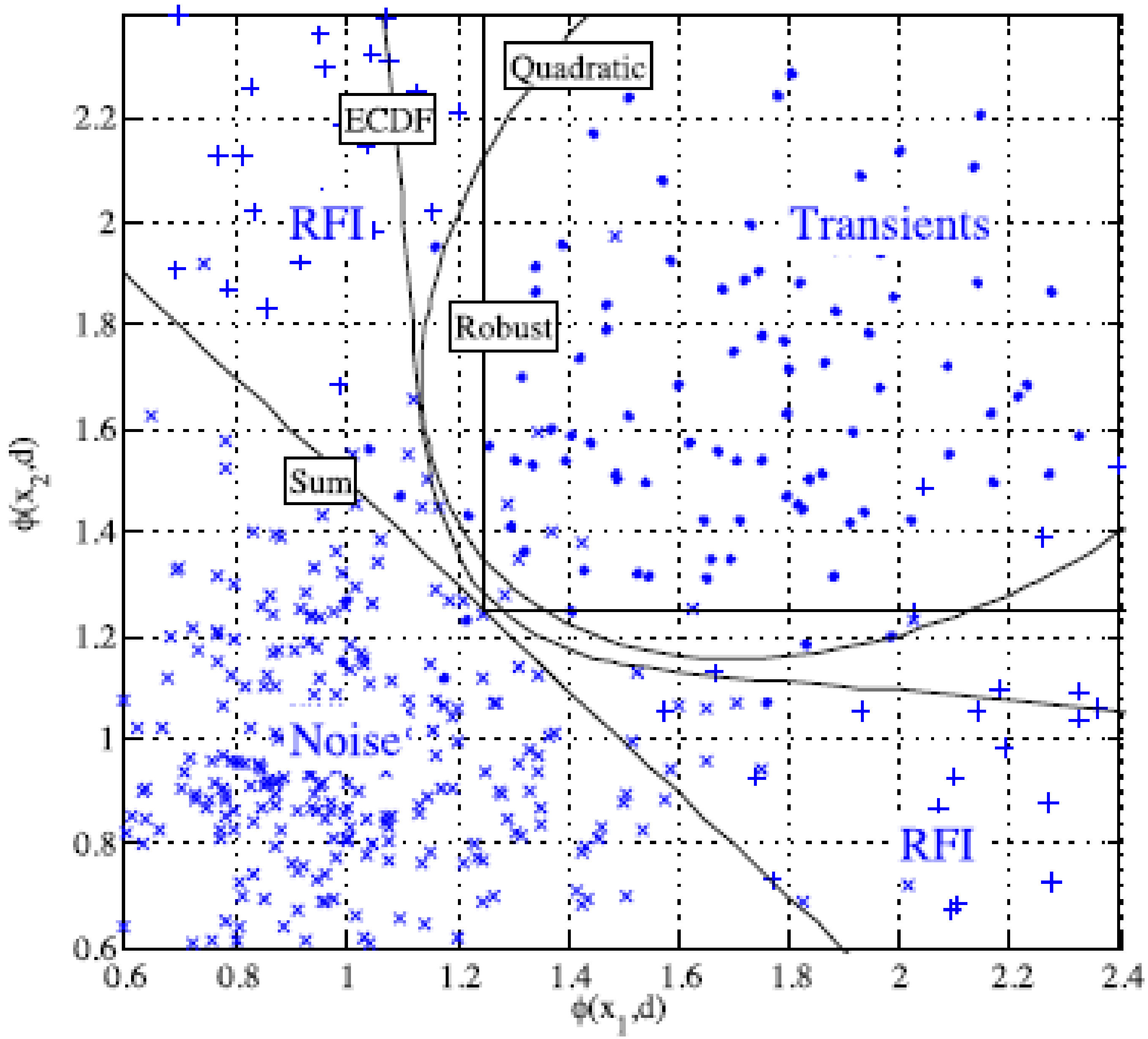
Test data – Pulsar B0329



Blazing a trail towards SKA

- V-FASTR is a “trailblazer”, beating a path towards ASKAP/CRAFT and eventually the SKA.
- Commensal fast transient searches on interferometers is new. How can we improve on the situation compared to single dishes?
- We have 2N datastreams from N antennas. How should we combine them?
- Naïve approach:
  - simply sum them. Get sqrt(N) improvement in SNR.
  - BUT: a strong signal in any one antenna biases the sum, so strong RFI in any antenna will show up in the sum as well.

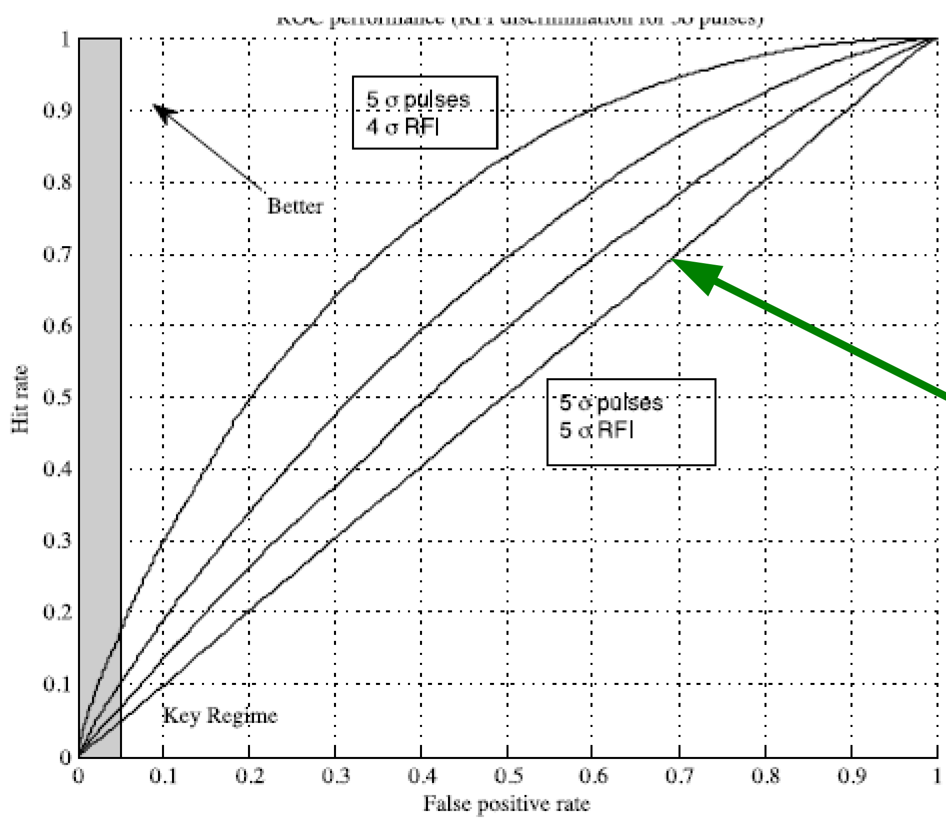
Enter statistical decision theory



Statistical decision theory

- Formalism for evaluating performance of “detection” task.

True positive fraction

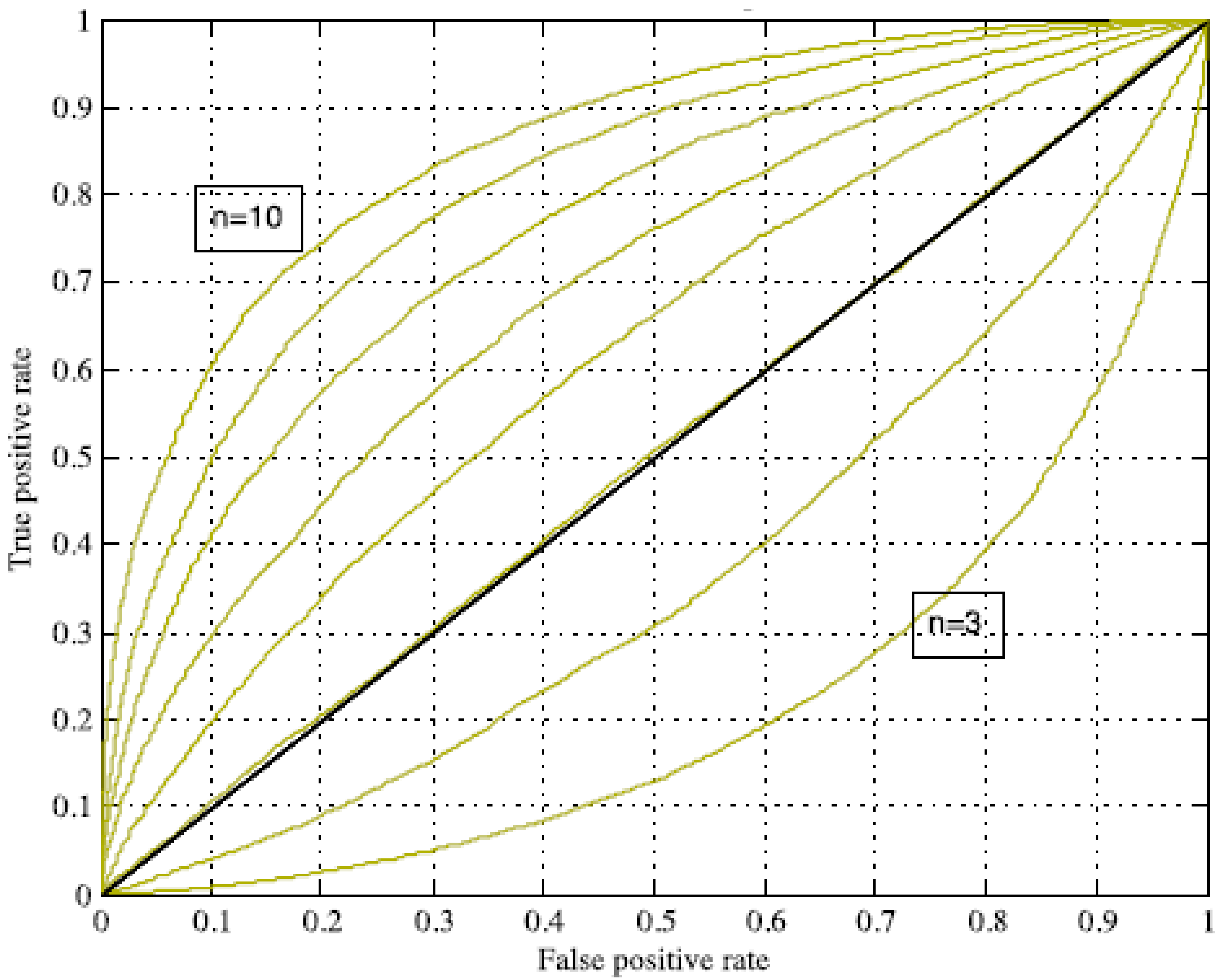


False positive fraction

“ROC” Curve. ROC = receiver operator characteristic.

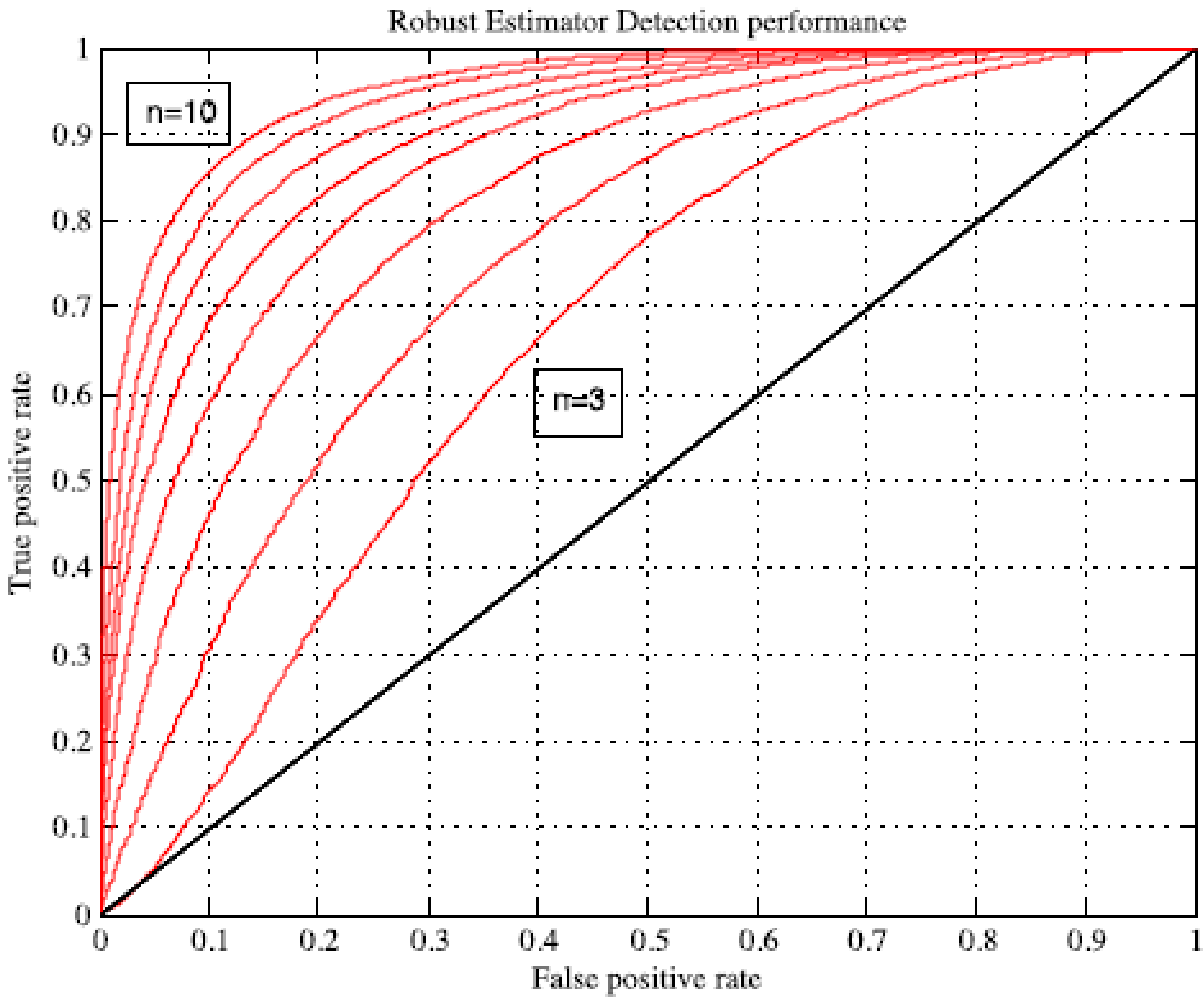
Point along this curve is dictated by detector threshold.
Conversely desired false positive fraction sets detector threshold.

Naive “sum stations” in presence of weak RFI (simulation)

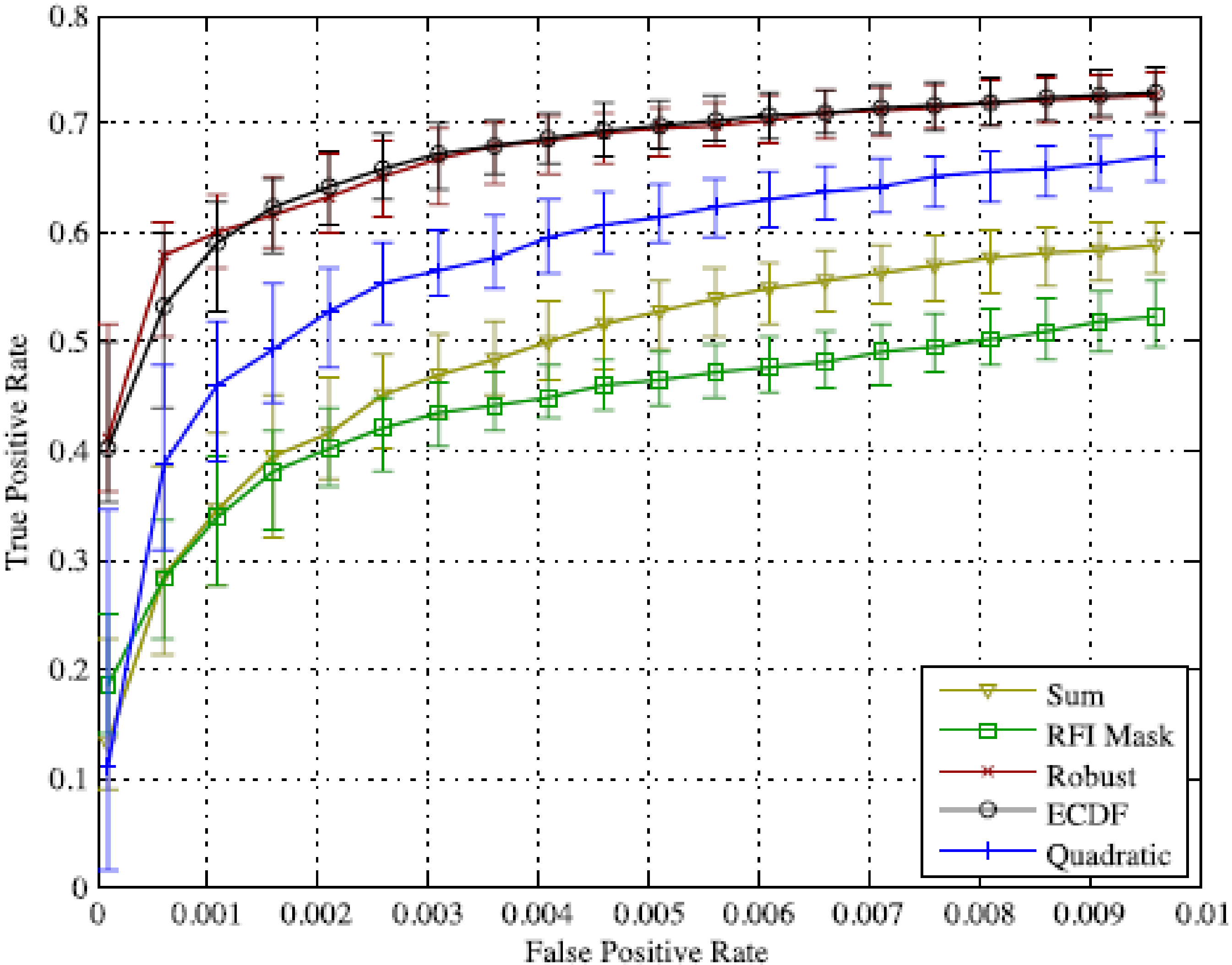


Sum stations via a simple robust estimator with weak RFI (simulation)

e.g. discard highest & lowest values



Comparison of detectors



Thompson et al. 2011.

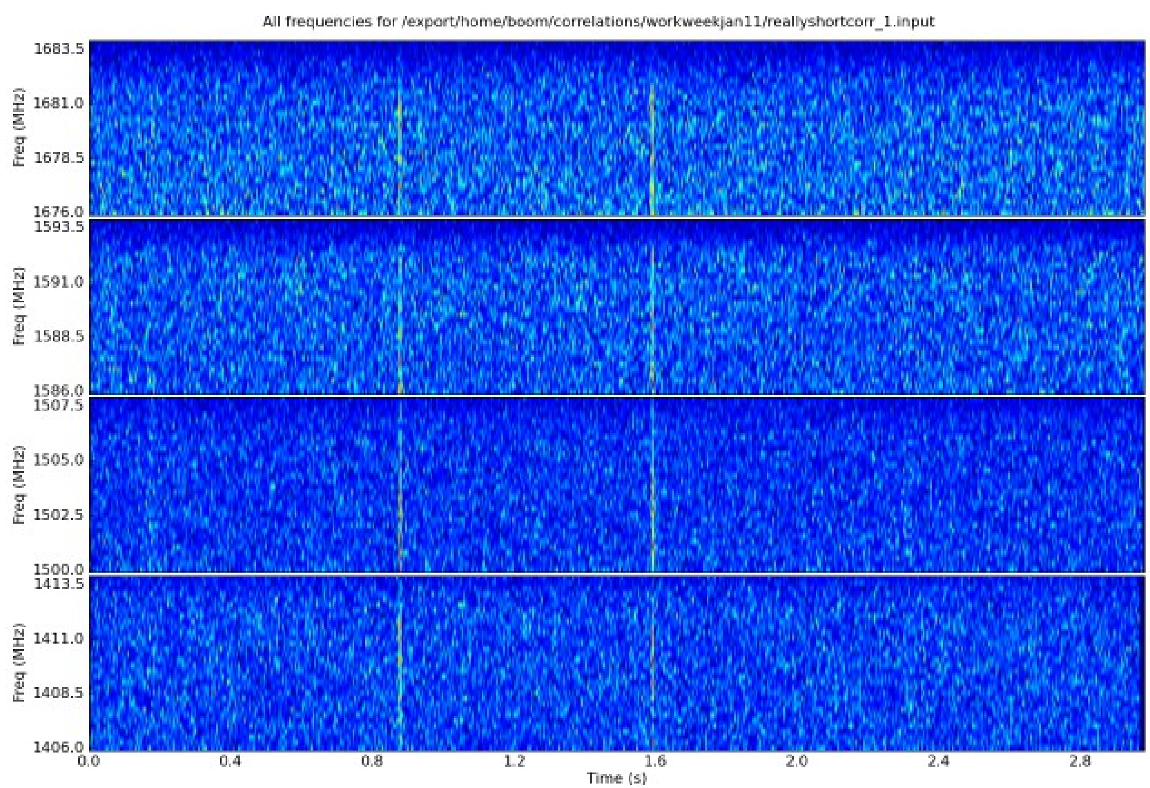
- For B0329 test data, a simple robust estimator was as good as any more sophisticated (machine learning) model.

- Substantially better than a naive summation approach.

Note scale

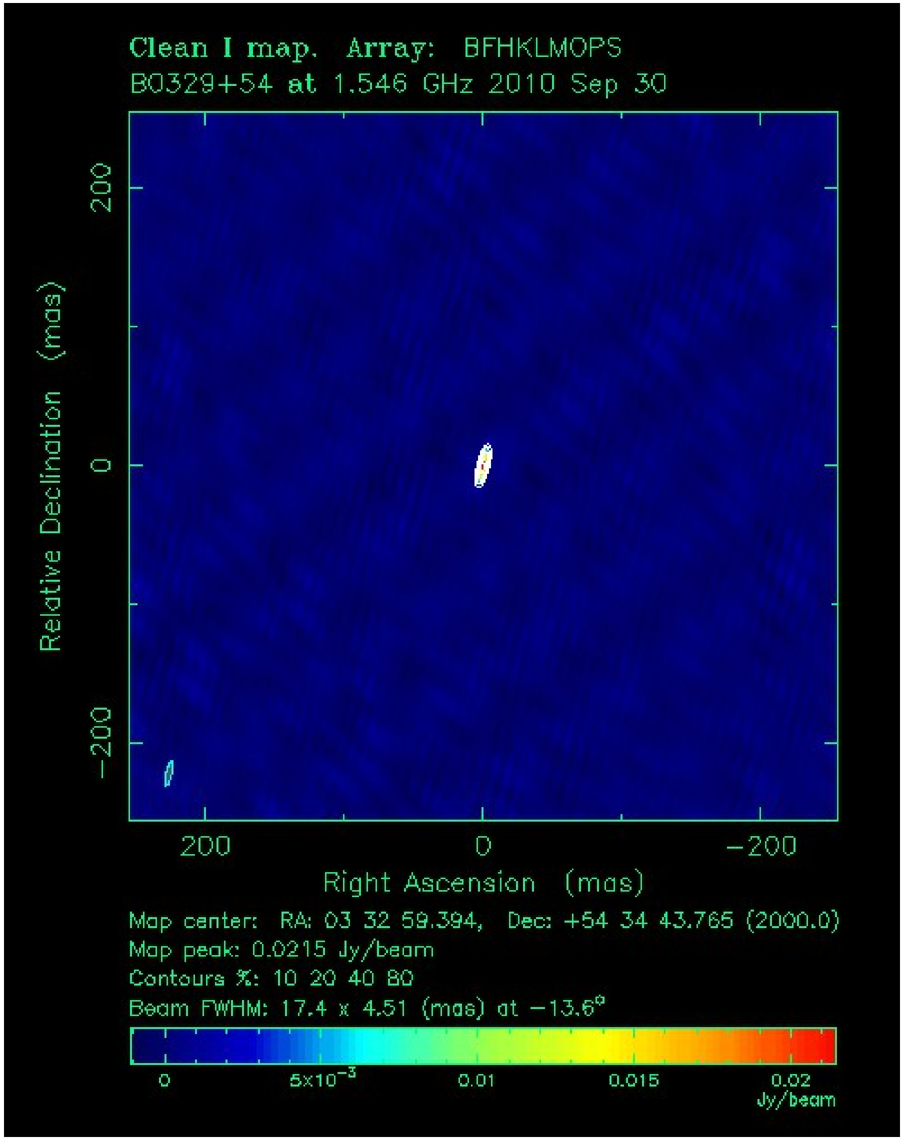
Event follow-up

- Recorrelate baseband data with fine time resolution
  - Output fine time res visibilities in DiFX format
- Dedisperse visibilities (not spectrometer), convert to FITS



Event follow-up

- FRING, selfcal, split, image in AIPS/Difmap. PRESTO!

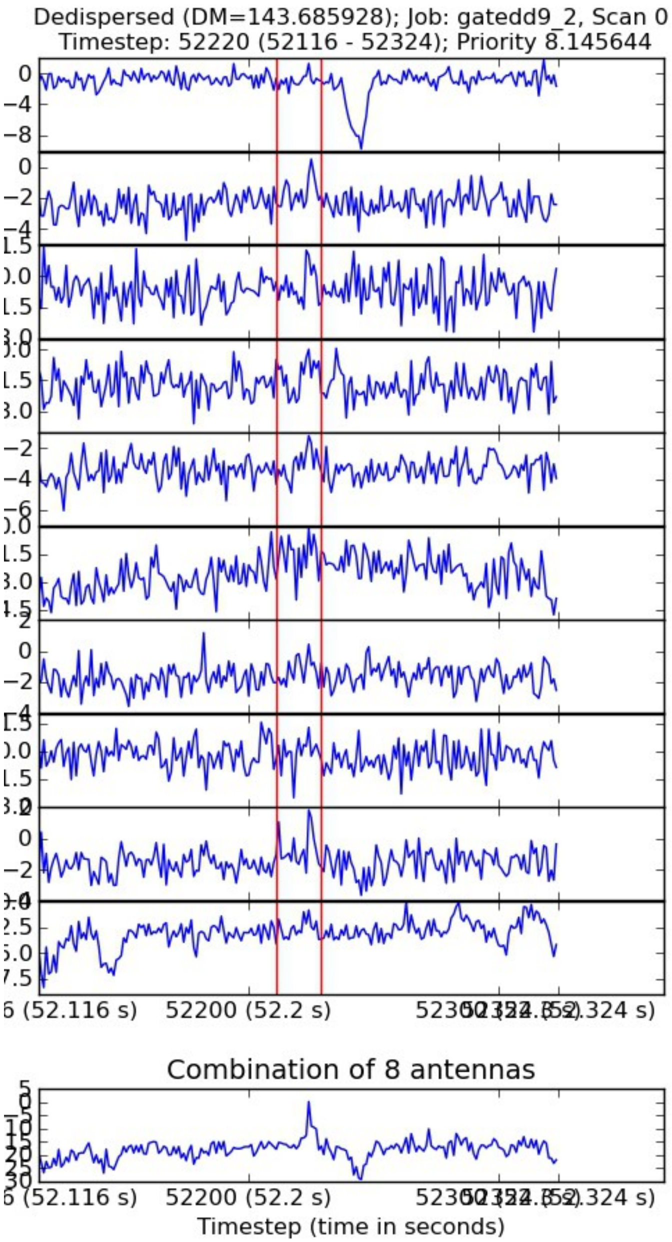


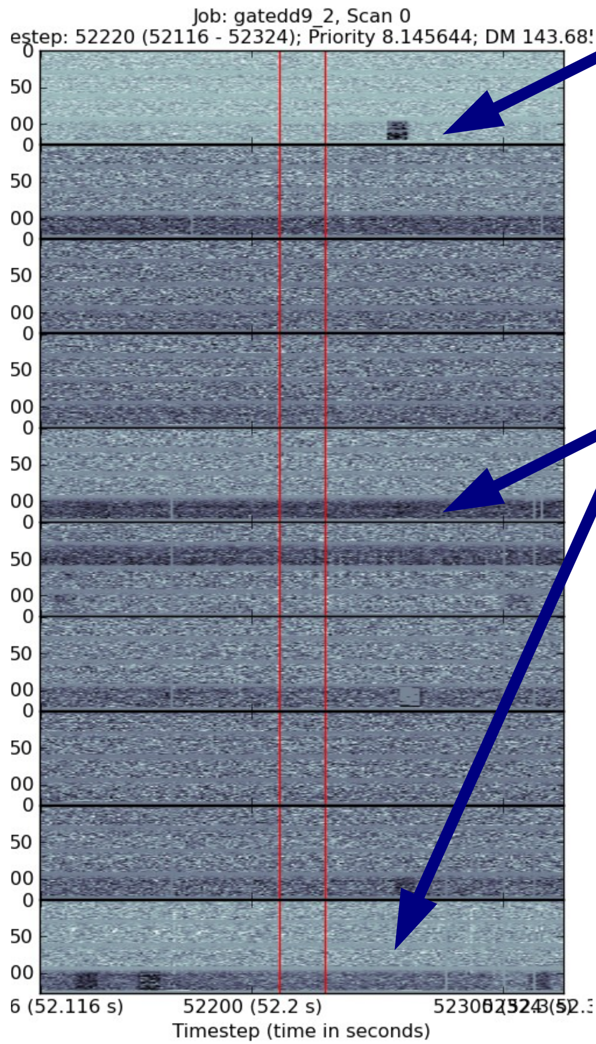
Notes:
-if selfcal, astrometric precision limited to ~1”
- can estimate source location based on delays
- can use phase calibrators if required

Milli-arcsec precision! Take that Parkes...

This is an image of a single pulse from the B0329 test data.

Example SNR ~8 pulse

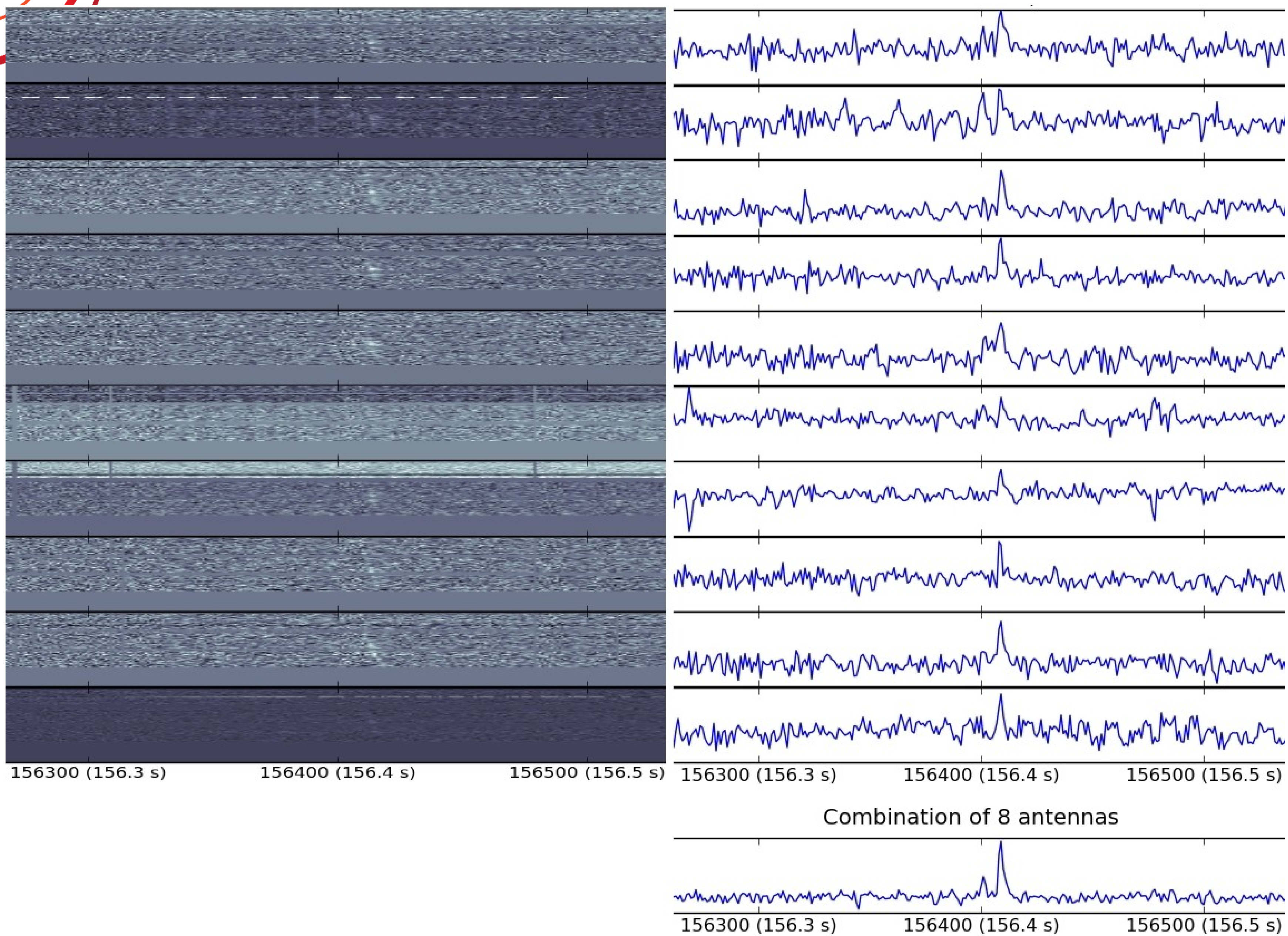




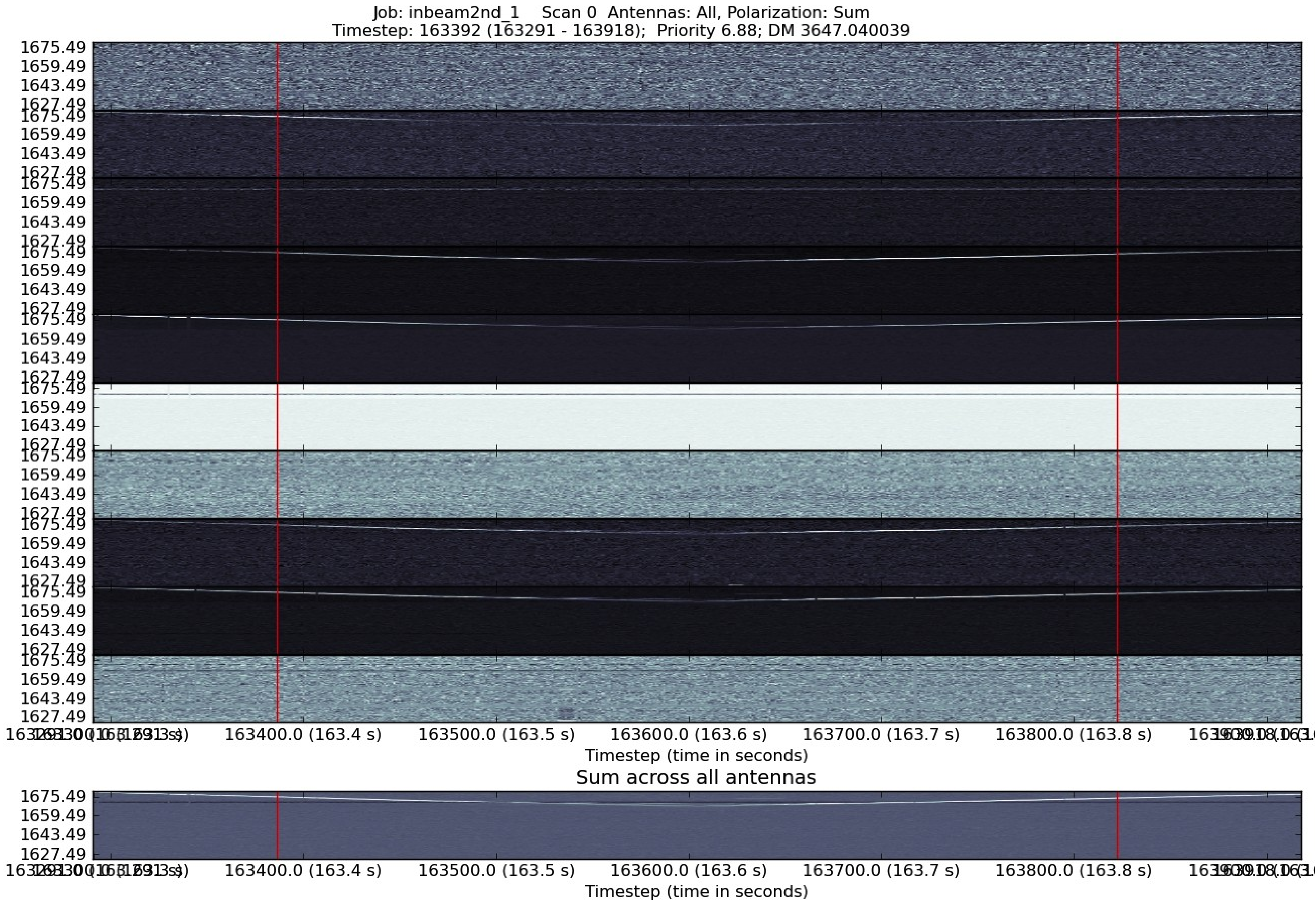
Strong, ~10 ms long transmissions from Iridium satellites. Primarily narrow-band, but 2-bit sampling steals power across band.

RFI causes errors in average power subtraction

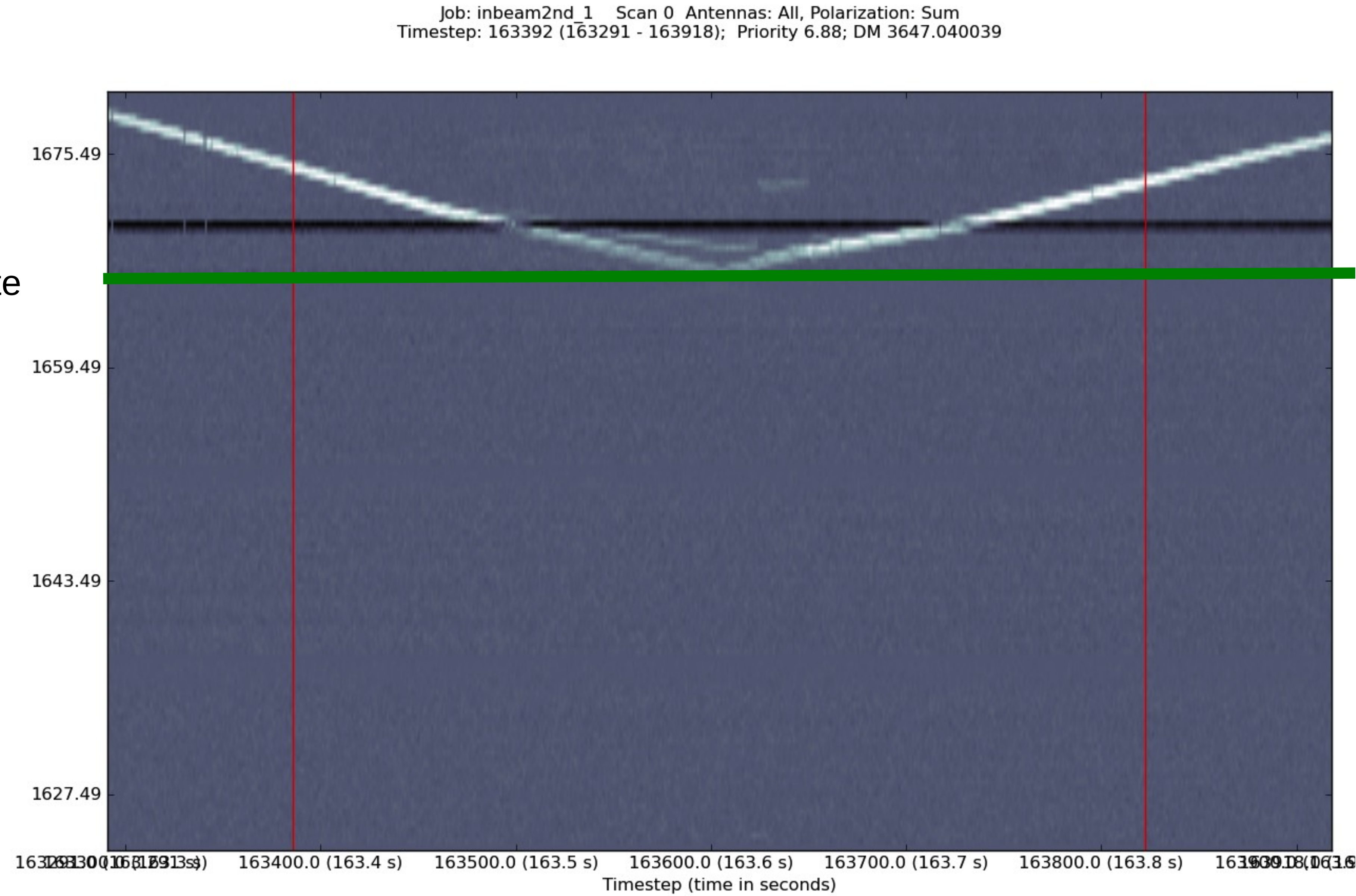
Example SNR 17 pulse



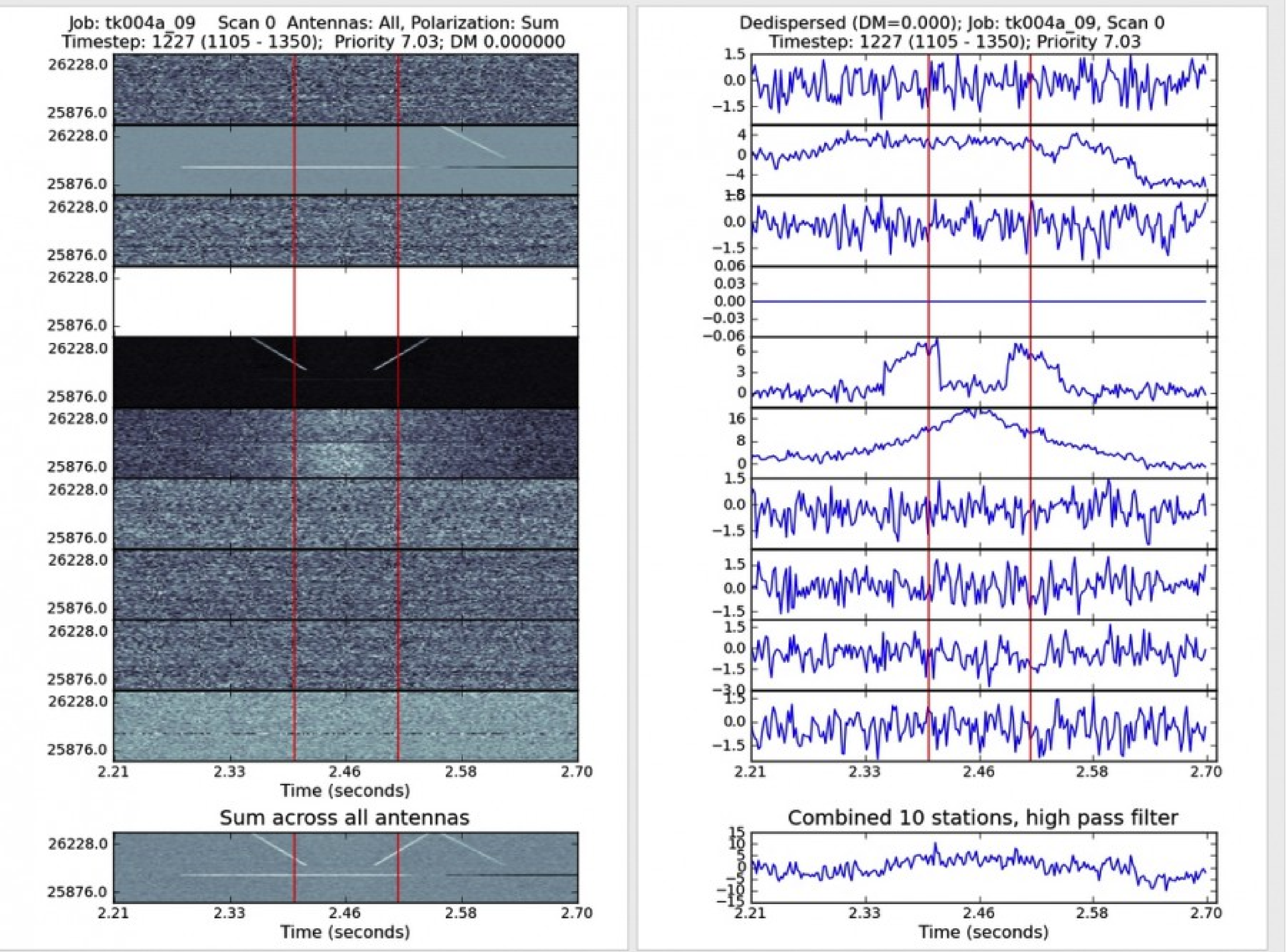
V-FASTR Curiosities



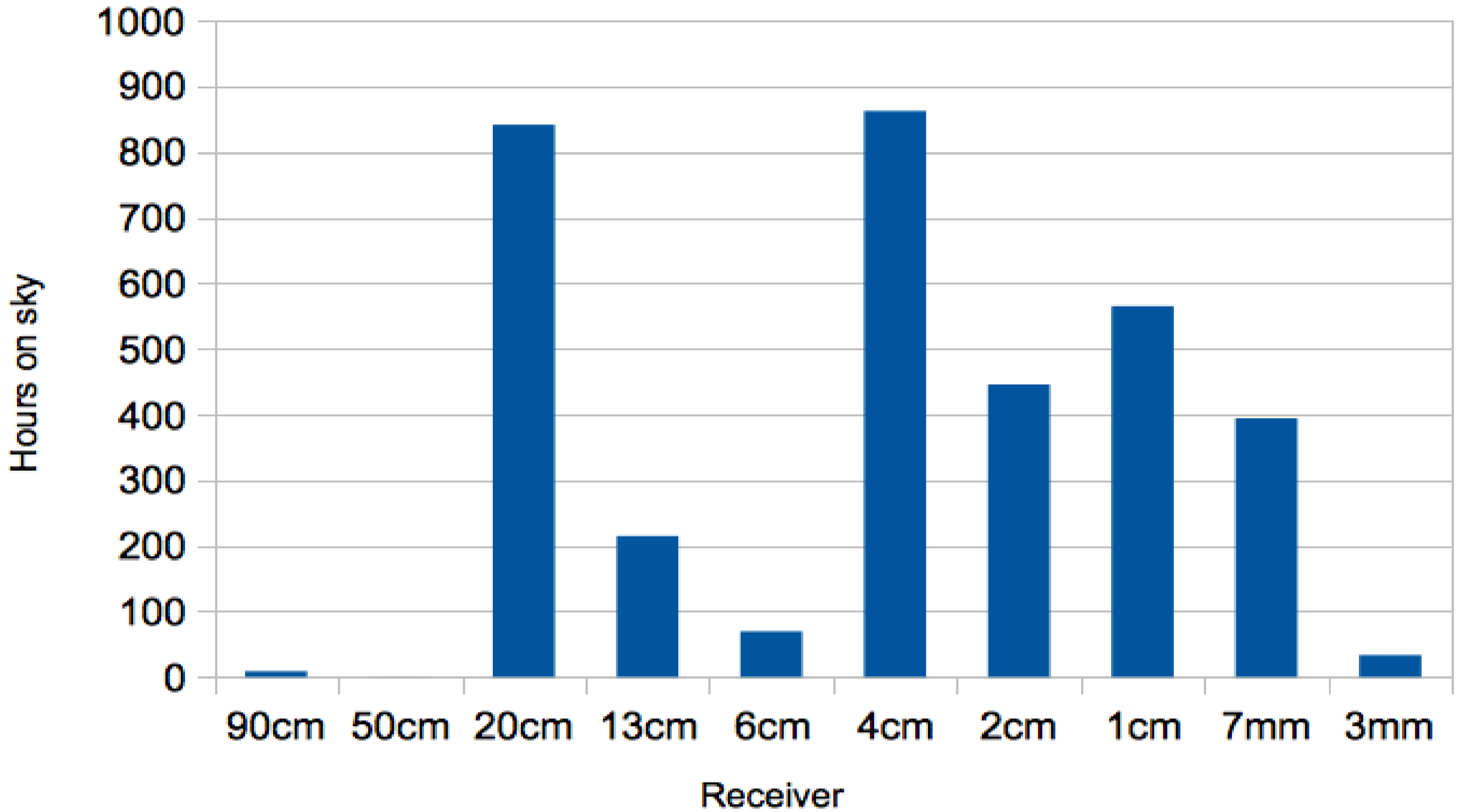
Curiosities: V-chirp



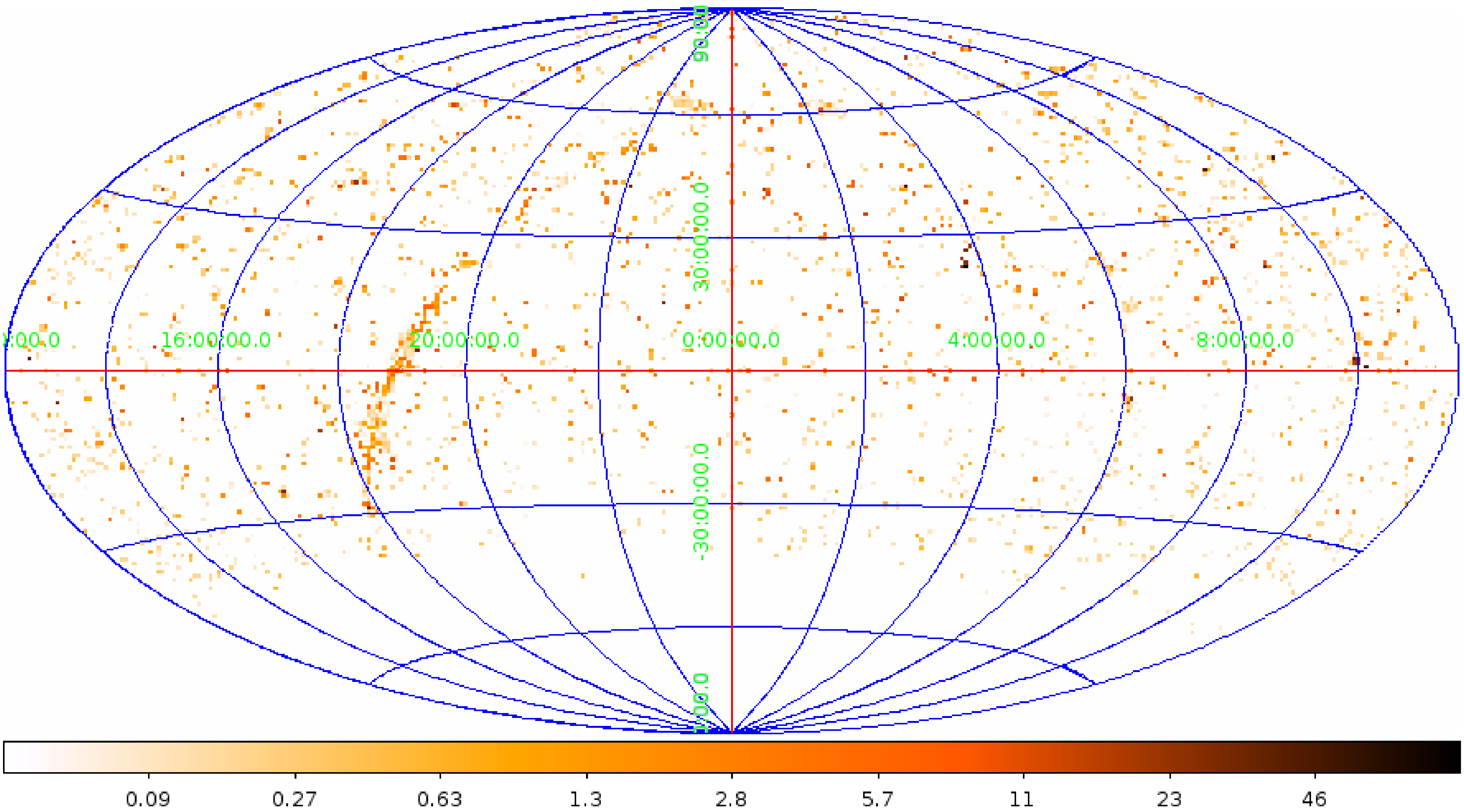
Approximate edge of IF


Job: tk004a_09 Scan 0 Antennas: All, Polarization: Sum
Timestep: 1227 (1105 - 1350); Priority 7.03; DM 0.000000
26228.0
25876.0
2.21
2.33
2.46
2.58
2.70
Time (seconds)
Sum across all antennas
Dedispersed (DM=0.000); Job: tk004a_09, Scan 0
Timestep: 1227 (1105 - 1350); Priority 7.03
Combined 10 stations, high pass filter

Time on sky to 2013 Nov 8

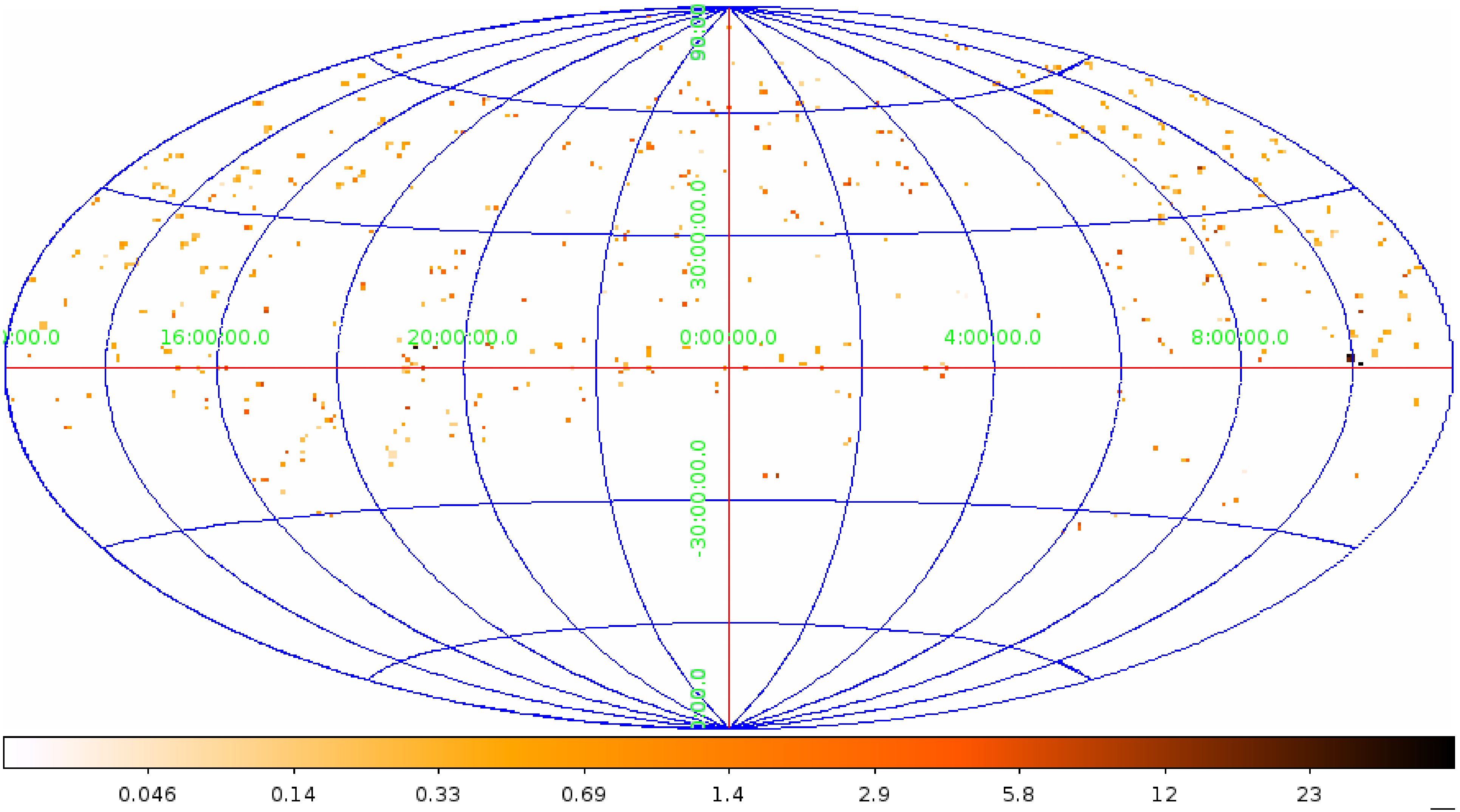


Sky coverage to 2013 Nov 8



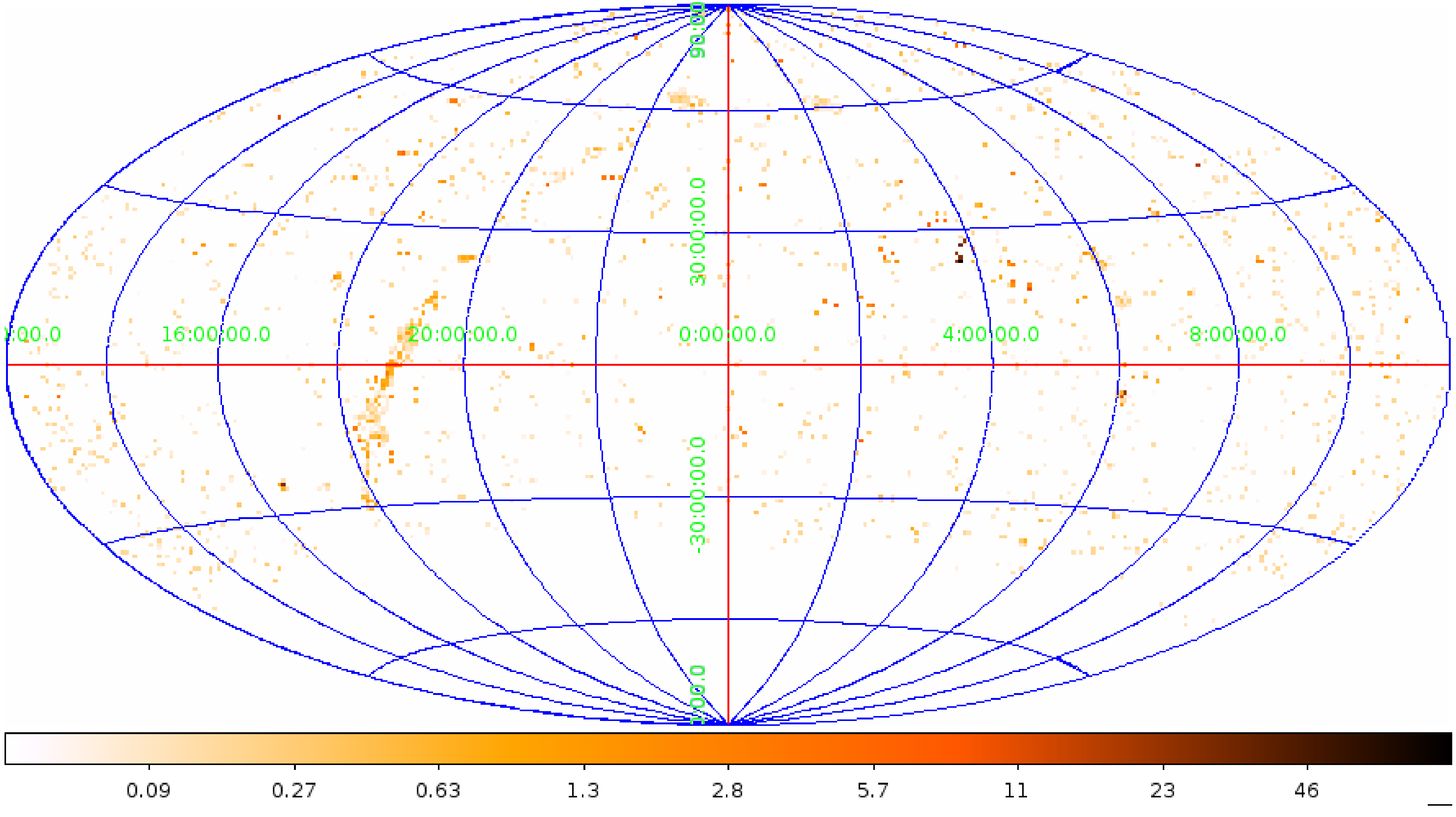
Log Hours – **All receivers** combined

Sky coverage to 2013 Nov 8



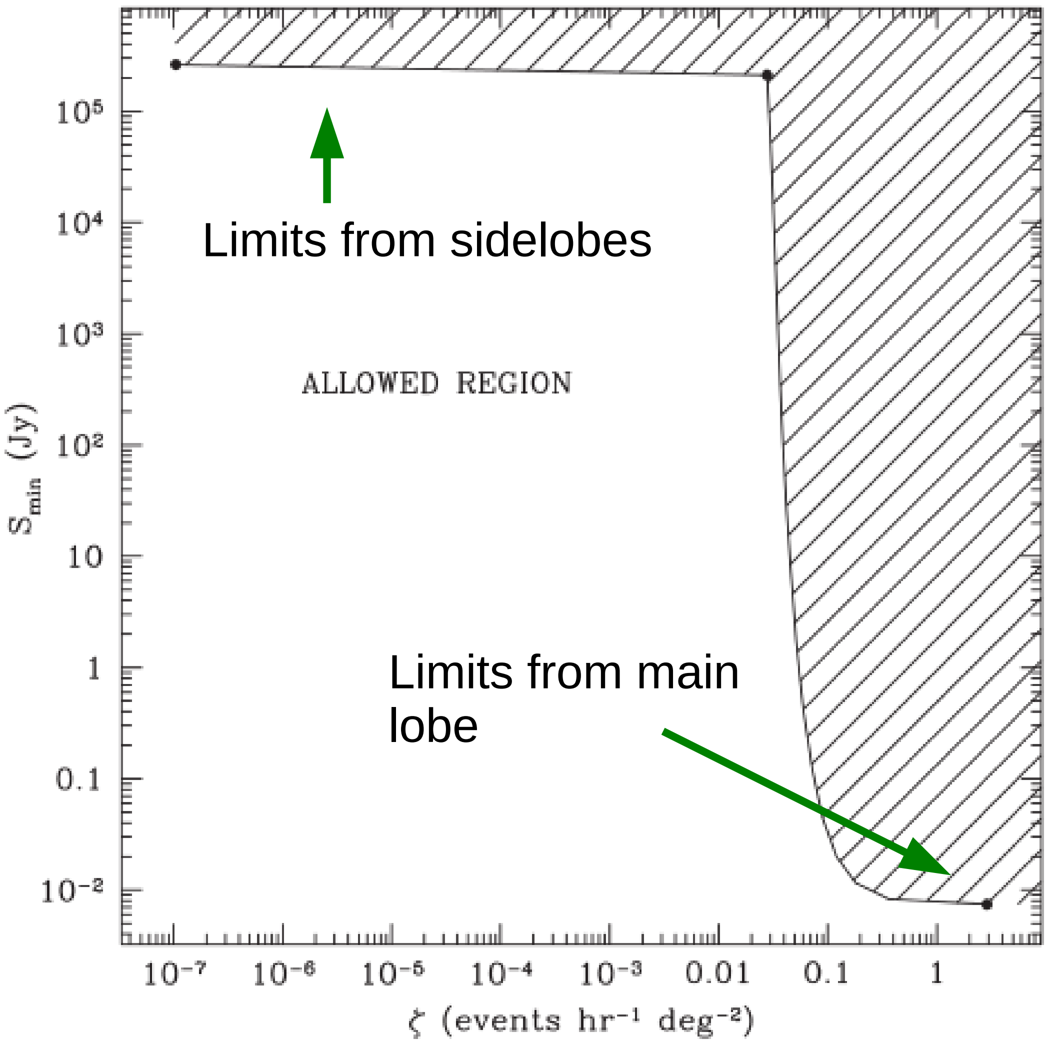
Log Hours – 20cm receiver

Sky coverage to 2013 Nov 8



Log Hours – 4cm receiver

Event rate limits

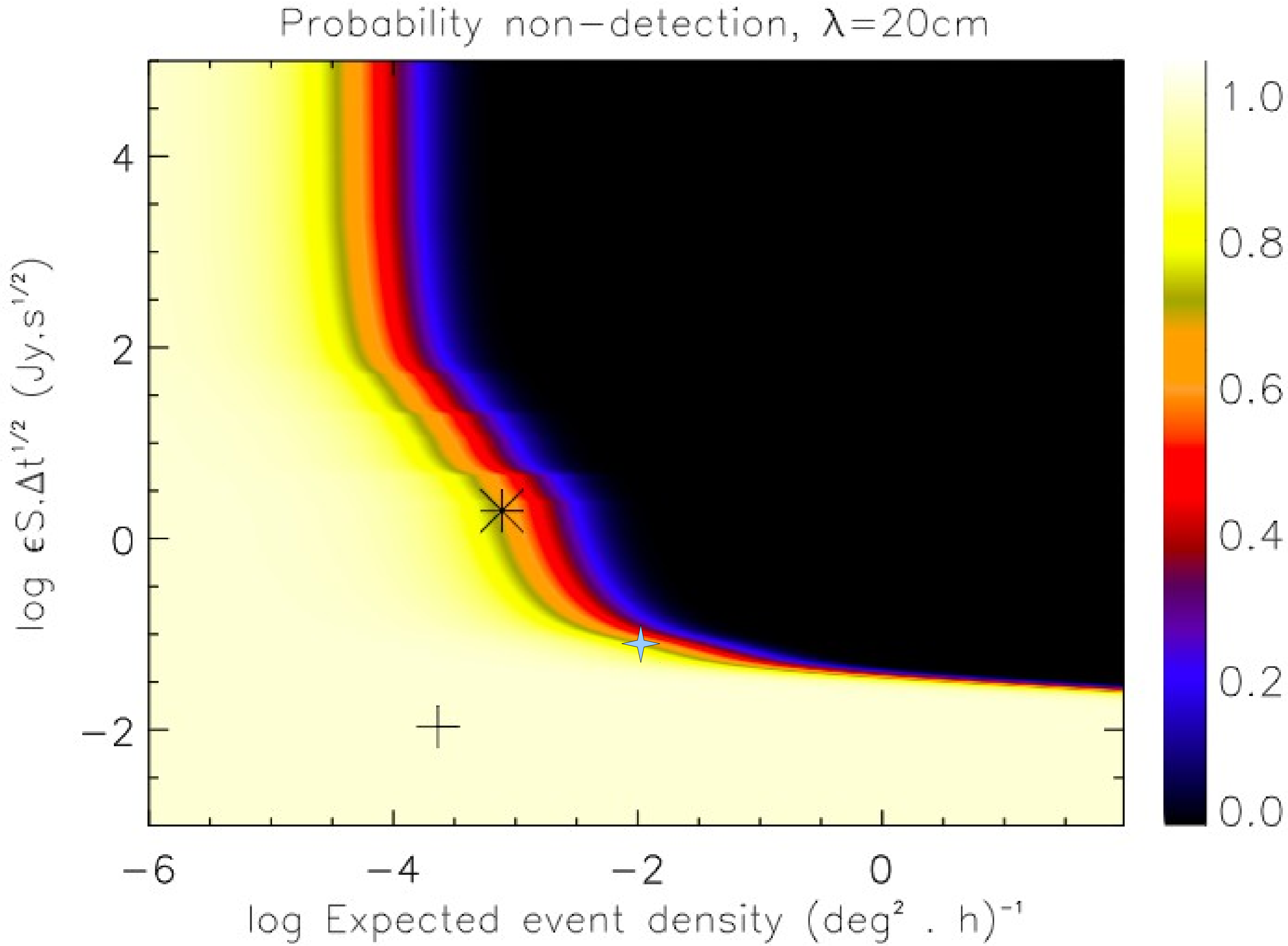


From Deneva et al. 2009

- Deneva et al. 2009 published limits from 461 hours of survey time from PALFA (using Arecibo multibeam @ 20cm)
- Arecibo 5-sigma sensitivity in one beam @ 20cm, 10ms: 0.011 Jy

New FRB! Not a limit any more!

V-FASTR event rate limits

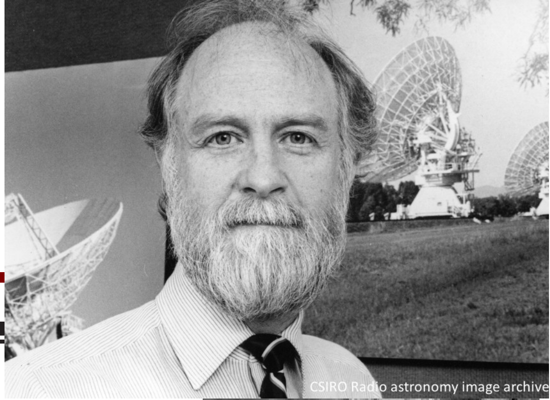


From: Trott et al., 2013. ApJ 767 4T

Summary

- V-FASTR re-uses an interferometer, the VLBA, in commensal mode to search for dispersed radio pulses.
  - Made possible by flexibility of DiFX software correlator
- Robust estimation techniques and machine learning can do an excellent job of maximising detector performance
- Experiment is placing increasingly tight limits on event rates, bordering on a challenge for Thornton et al rate.

Meanwhile back in the 70s...



A better way of searching for black-hole explosions?

BLACK holes of $\lesssim 10^{15}$ g evaporate in $\sim 10^{10}$ yr, and eventually annihiliate into a burst of energetic photons and particles[1]. To test this theoretical prediction would be extraordinarily significant for quantum and gravitational physics. There could be $\sim 10^{23}$ 'miniholes' within our Galaxy[2–4]; on the other hand, there may not be any at all. But even if they exist in profusion, how best could we detect black-hole explosions? Attention has been focused on the problem of directly detecting the γ rays, but the prospects seem bleak[3]. The possibility that the particles ejected in the explosion may generate conspicuous effects has hitherto been overlooked. I argue here that collective interaction of electrons and positrons with an ambient interstellar magnetic field can (on some specific assumptions) generate radio bursts powerful enough to be detected from anywhere in our Galaxy, or even beyond. This opens up a more promising perspective on the search.

Rees 1977. Nature

Limits on cosmic radio bursts with microsecond time scales

IT has been suggested[1] that black holes of mass $\leq 10^{15}$ g evaporate in $\sim 10^{10}$ yr, ultimately annihilating into a burst of energetic photons and particles. This explosion would produce γ-rays directly, and a radio pulse with a characteristic frequency of ~ 3 GHz and an energy of $\sim 10^{32}$ erg may also be generated[2]. It has been shown[2–4] that such a radio burst would be far more easily detected than the corresponding γ-ray burst. Estimates of the energy in the radio burst are uncertain by many orders of magnitude, and it is, of course, not known whether any primordial black holes exist at all; however, the implications of a detection would be enormous for quantum and gravitational physics.

These limits could be improved by using larger telescopes for longer times and simultaneous observations with more than one antenna. Interference rejection in particular would be greatly facilitated by using two or more widely spaced antennas. Large improvements could be achieved either by using a fast multichannel dedispersing backend or possibly by observing at higher frequencies.

O'Sullivan, Ekers, Shaver. Nature, 1978

Scooped 40 years ago?

Fig. 1. Location of the observing stations. C, Cambridge (151, 81 MHz); D, Dublin (151, 70 MHz); G, Glasgow (151, 81, 47 MHz); H, Harwell (151 MHz); J, Jodrell Bank (151, 45 MHz).

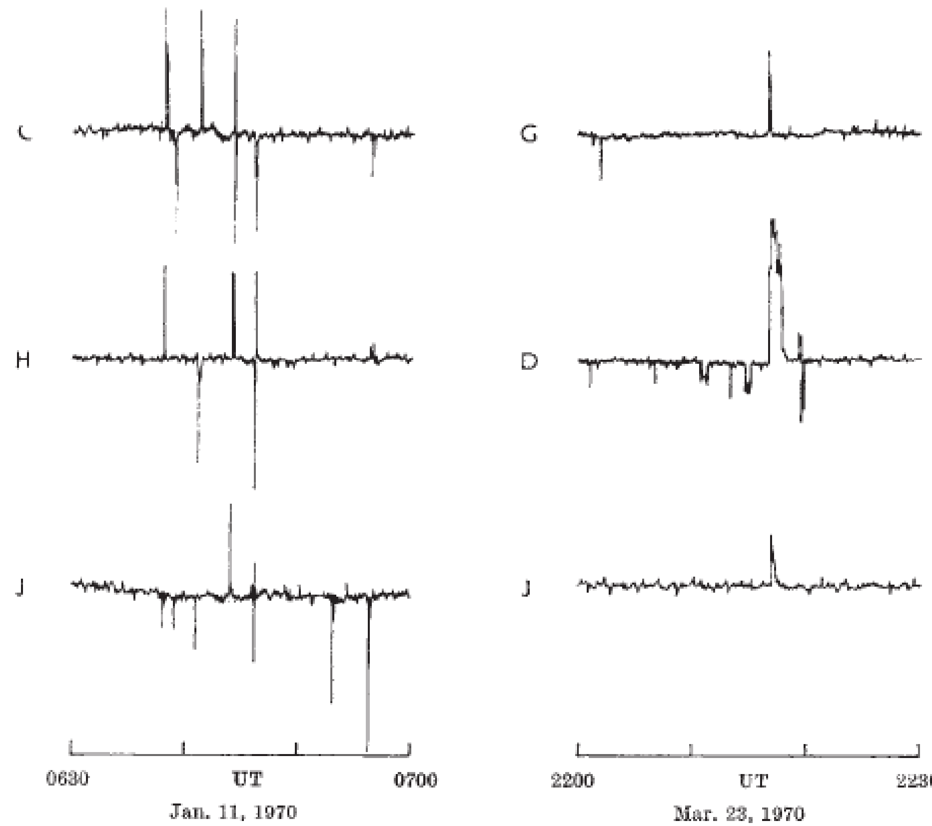


Fig. 2. Tracings of interferometer records for the three stations involved in two of the "triple-coincidence" events.

Network of 2-dipole antennas recording total Power at 150MHz with ~second timescales.

Estimated SEFD 500,000 Jy.

Charman et al 1970. Nature 228

Questions?

- V-FASTR:
  - System description
    - Wayth et al. 2011. ApJ, 735, 97W
    - Thompson et al. 2011: ApJ, 735, 98T
  - First 6 month results
    - Wayth et al., 2012. ApJ 753L 36W
  - Combining events/limits from different telescopes/freqs plus updated results
    - Trott et al., 2013. ApJ 767 4T
- DiFX:
  - Deller et al. 2007 PASP, 119, 318D
  - Deller at al. 2011 PASP, 123, 275D

Blind Pulsar detections

pulsar name	max snr	dm	on-pulse flux density (Jy)
J0332+5434	>50	26	14.0
J1136+1551	20	5	1.0
J0826+2637	19	20	0.5
J1935+1616	12	158	1.0
J0157+6212	10	30	0.14
J01919+0021	9	90	0.05
J0147+5922	9	40	0.13
J1645-0317	10?	34.7	?
B0950+08?? unverified	>8	2.7 (est)	?
J2113+2754	29	25	0.06
J1607-0032	9.79	11	0.11
J1257-1027	~25	det 17.19 actual 29	?