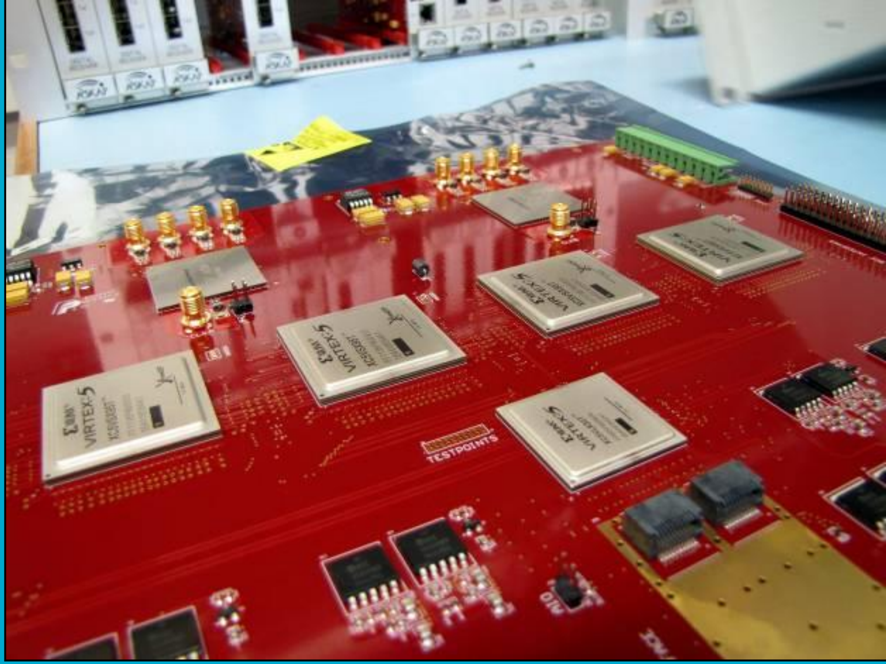

Technological Innovation in the search for high energy particles

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15 Sept 2016

Looking for UHE particles

- Search for high energy particles – neutrinos, CRs – using the radio frequency radiation resulting from interaction with the moon
- Generated radio pulses of order ~ 1 ns
- Entirely different regime to conventional Radio Astronomy
- Required an entirely new suite of signal processing approaches and algorithms
- Heavily time domain, single event focussed
- Provides opportunities for unique information and understanding of phenomena and observing systems

Outline

Some novel technical challenges that we faced

How we solved them in interesting ways.

What we learned

Unforeseen applications to other areas

- Topics

  Handling ionospheric dispersion

  Real time RFI mitigation

  Subtle digital sampling effects

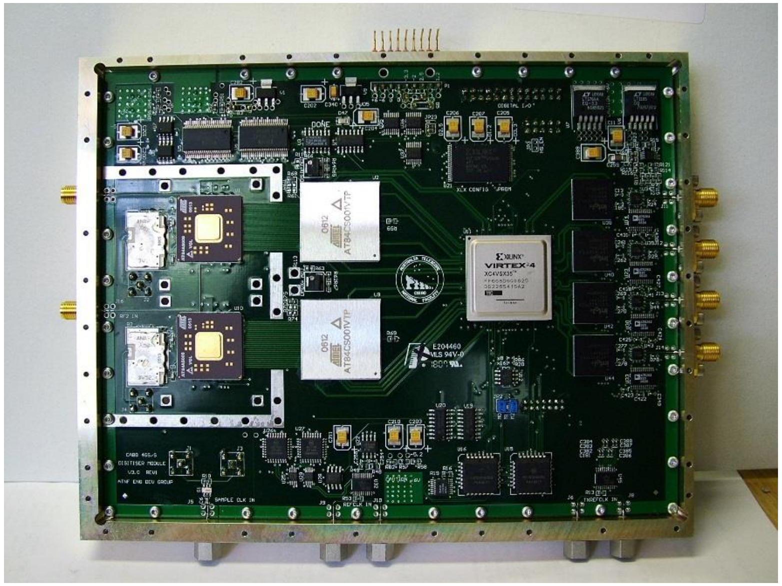
  Pulse calibration

History

- First mooted in CSIRO by Ron in ~ 1994
- Recognised as a novel and exciting and motivating idea
- Initial simple experimental attempt made – 1996
- Required waiting for the necessary technology to eventuate to be feasible with high sensitivity
- Ron had a watchful eye on developments ready to strike
  - Compact Array Broadband (CABB) upgrade provided the opportunity

First experiments

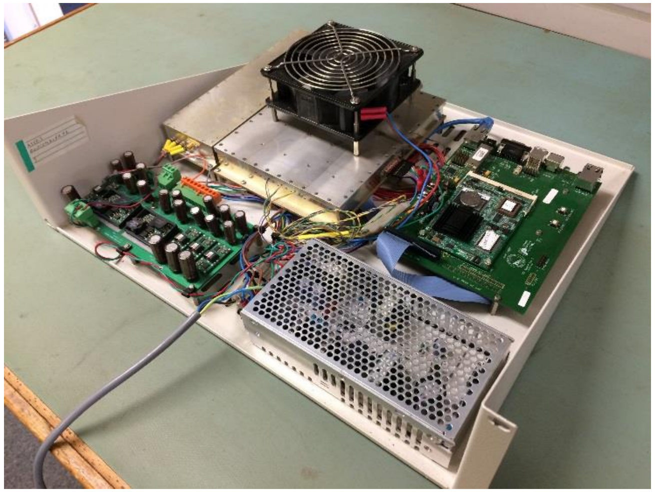
Technology in development for CABB



Prototype hardware – before final CABB

Bolted to side of IF rack

Used monitor point on IF module

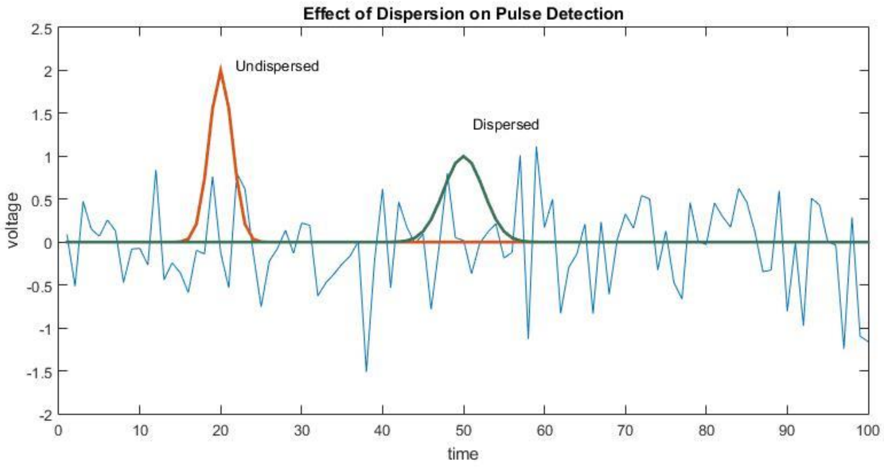


Many novel and innovative techniques

Look at one – correcting for ionosphere

Problem

Ionospheric dispersion broadens pulses to below detection level



Ionospheric Dispersion Compensation

ATCA UHE Neutrino detector. 1.2-1.8 GHz, 2.048 GS/s sampling.

Ionospheric dispersion ~10ns. Small, but critical to recover for ~1 ns pulses.

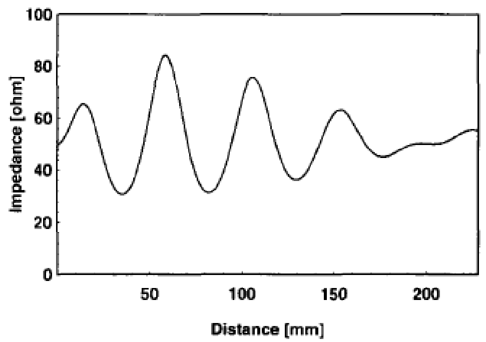
Only modest DSP resources in prototype hardware. How to implement a filter with 1/f^2 nonlinear Tg response over 600 MHz and 2 GS/s. Insufficient processing power to do this digitally

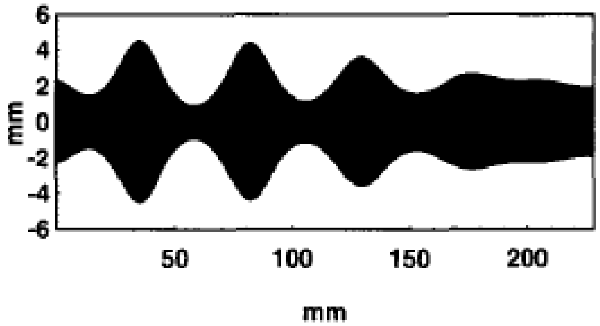
Can an analogue filter be designed to provide this coherent dedispersion (allpass with prescribed non-linear phase)?

Microwave filter designs based on uniform TL elements have frequency response defined by prototype polynomials and are narrow band

Fractional bandwidth is > 40 % at 1.5 GHz

In optical fibres chirped Bragg gratings are used to correct chromatic dispersion so
how about a filter with a continuously varying transmission line width/impedance profile?





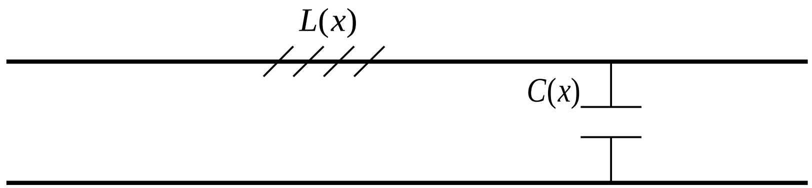
Can this be designed to give an arbitrary complex frequency response? But how to do this?

Look at this as a general scattering problem ->

Propagation on a transmission line

$$I(x) \rightarrow$$

$$V(x) \uparrow$$



Telegrapher's eqns (lossless)

$$\frac{dV(x)}{dt} = -i\omega\, C(x)\, I(x)$$

$$\frac{dI(x)}{dt} = -i\omega\, L(x)\, V(x)$$

Make subst

$$y(\omega, x) = \left(\frac{C(x)}{L(x)}\right)^{1/4} V(\omega, x)$$

$$q(x) = \left(\frac{C(x)}{L(x)}\right)^{-1/4} \frac{d^2}{dx^2}\left(\frac{C(x)}{L(x)}\right)^{1/4} = \sqrt{Z(x)}\,\frac{d^2}{dx^2}\left(\frac{1}{\sqrt{Z(x)}}\right)$$

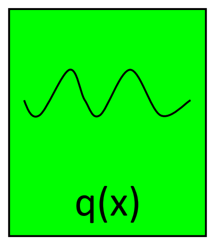
$$\frac{d^2 y(\omega,x)}{dx^2} + \left(\omega^2 - q(x)\right) y(\omega,x) = 0$$

c.f.

$$\frac{d^2 \psi(x)}{dx^2} + \left(E - V(x)\right)\psi(x) = 0$$

$y_i(\omega,x) \rightarrow$

$y_r(\omega,x) \leftarrow$



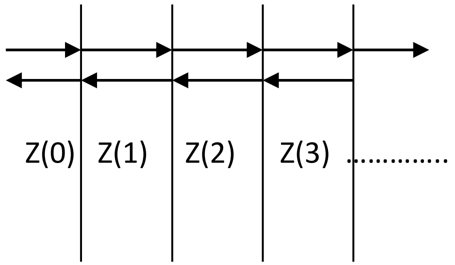
$\rightarrow y_t(\omega,x)$

IS problem solved Гельфанд, Левитан, Марченко 1951.

Given y_i, y_r, y_t can solve for q(x), and thus Z(x).

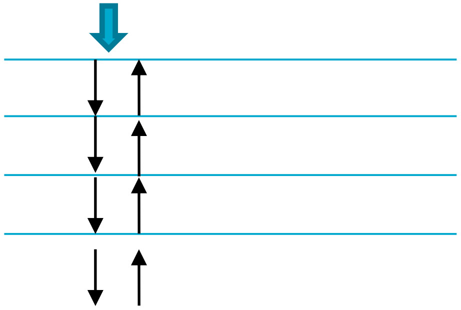
Alternative solution algorithm

- Discretise the impedance changes to steps
- Work backwards given required impulse response



Layer stripping Algorithm

Seismic remote sensing to determine crust density profile



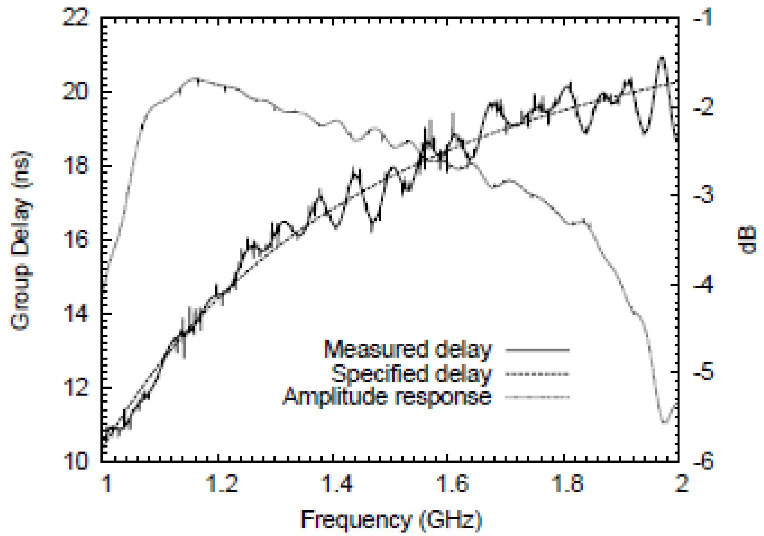
Results in

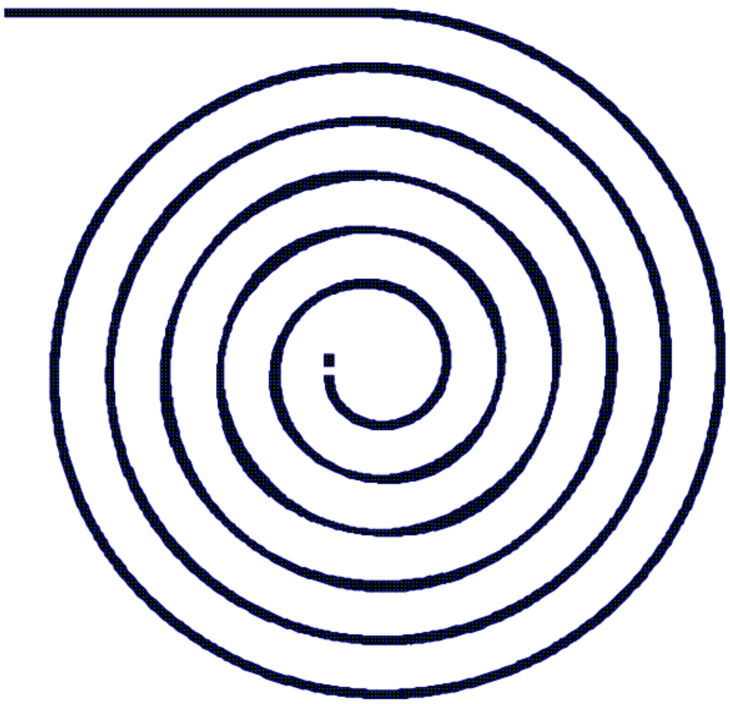
600 MHz BW at 1.5 GHz – 1.2m long

GD error 0.5 sample relative to ionospheric response

1 dB gain slope

Reflection mode filter – circulator at input port





So the solution was

Idea inspired by Optics

Modelled by engineering transmission lines

Recast as canonical problems from Quantum Mechanics and Geophysics

Solved to design a physical microwave structure

To overcome a problem with ionospheric dispersion

Nice example!

Problem High level of background RFI at Parkes

Success of ATCA experiment inspired a dedicated experiment using 4 beams of the Parkes multibeam

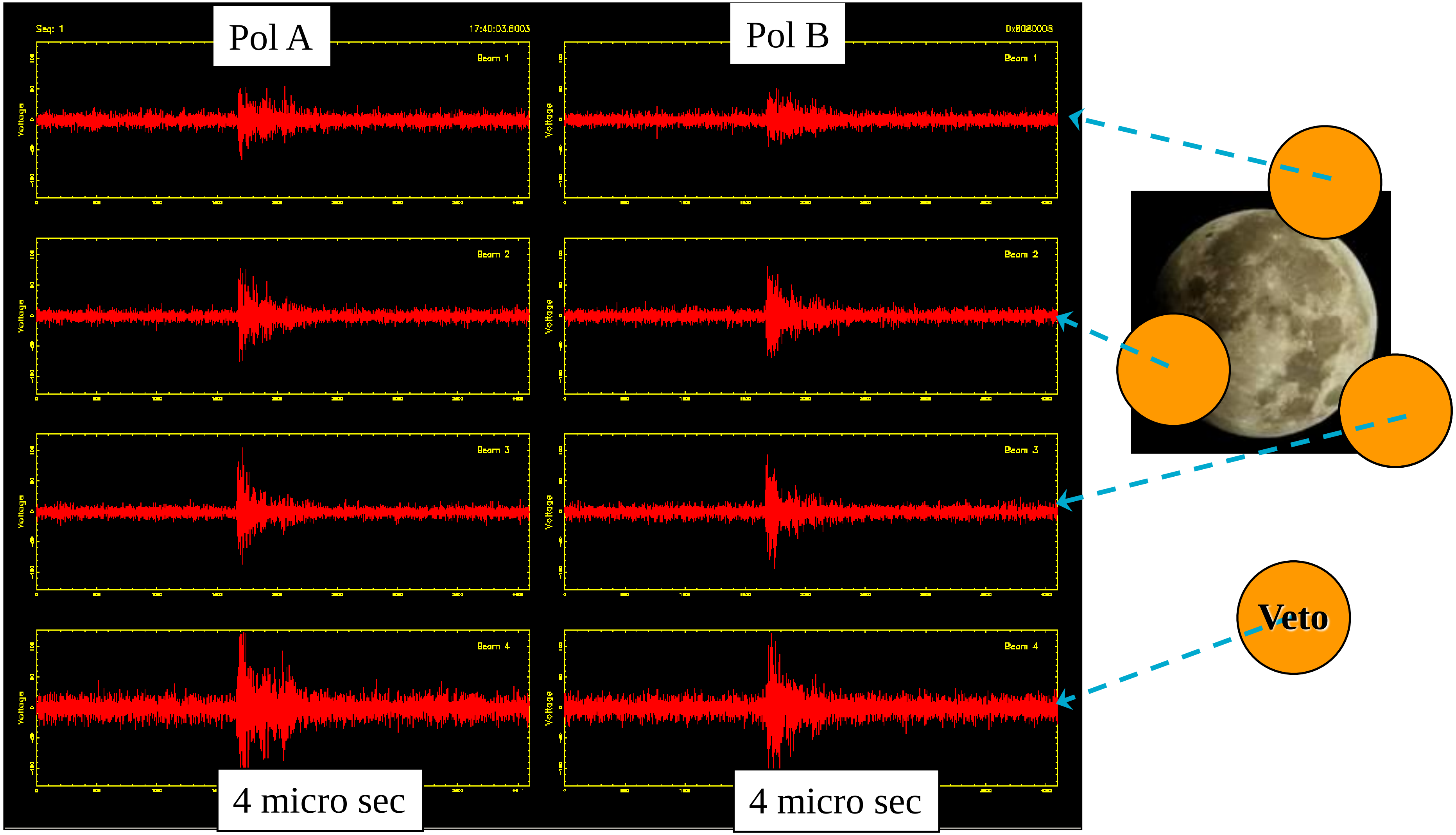
To support this a dedicated backend supporting 4 dual pol inputs was built – BEDLAM

Background RFI though is 10s to 100s of events per second that would saturate the trigger buffers

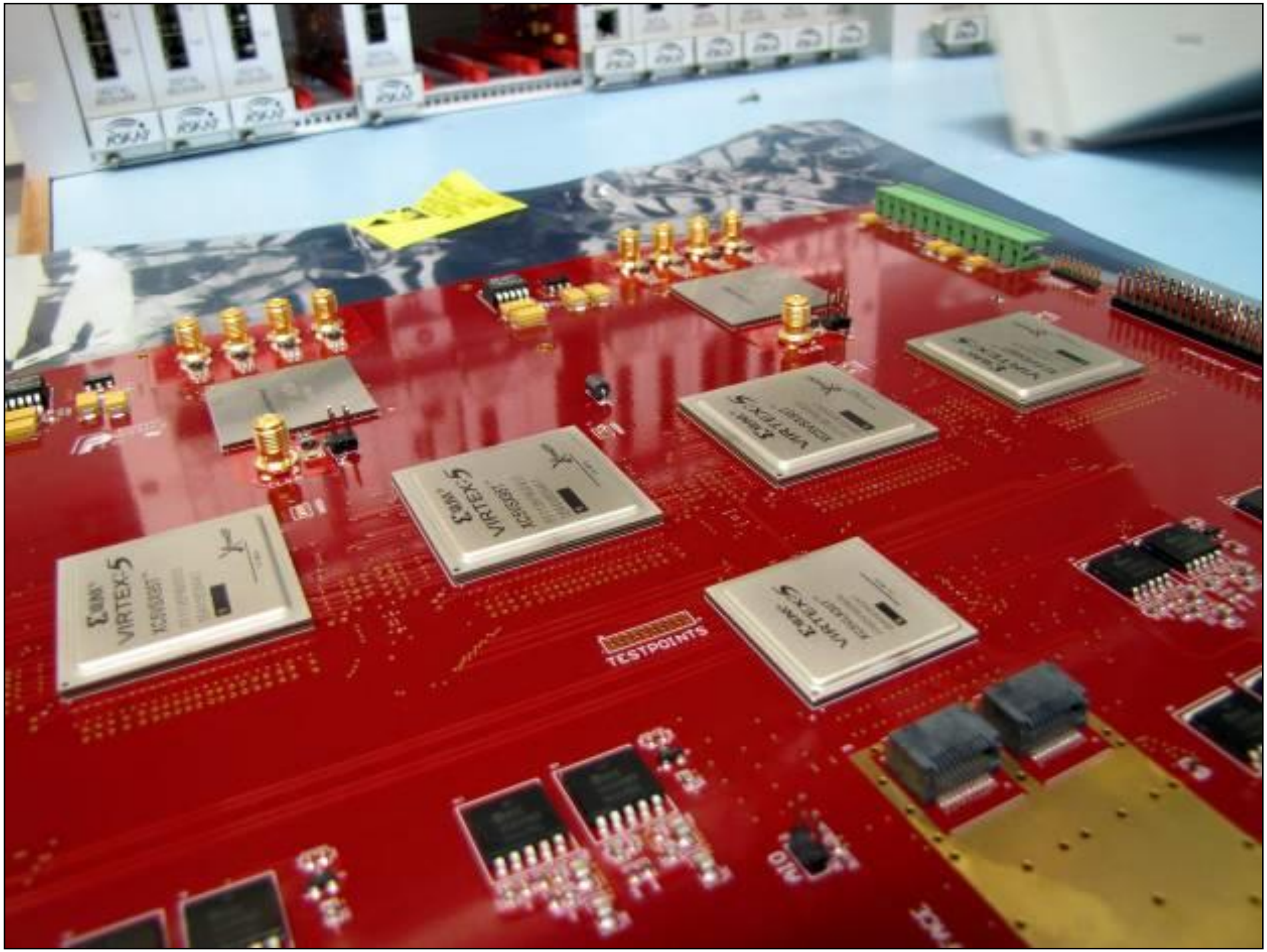
BEDLAM designed for real-time RFI mitigation using known characteristics of a real event

- Can only be in one moon beam at a time
- Short duration < 10s of ns
- Not present at all in off moon beam (VETO)

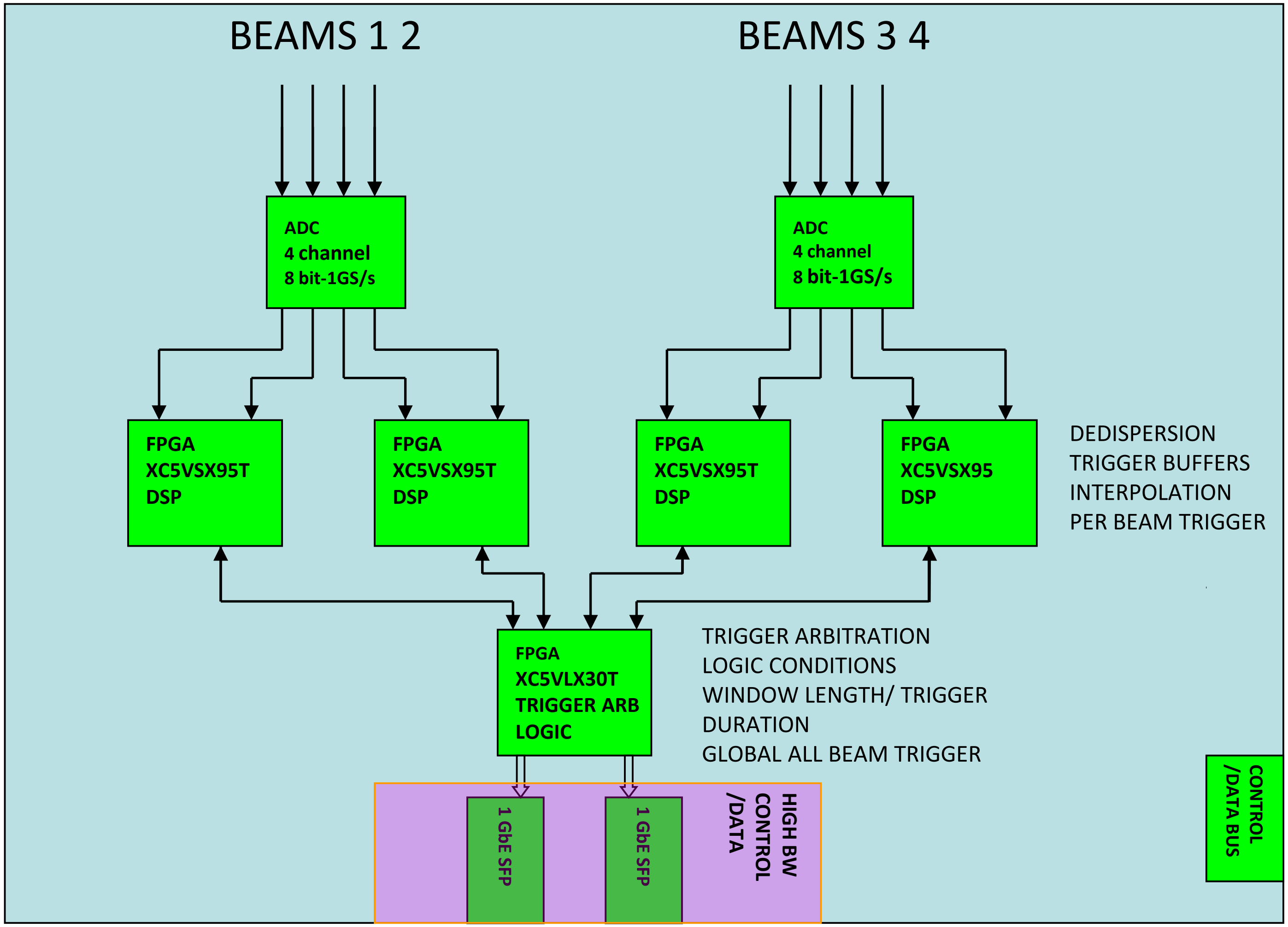
Typical RFI – Fails to satisfy event logic



DSP Board "Bedlam"



DSP Board System Schematic



Real Time RFI Mitigation Results

Raw RFI event rate is few 10s to 100s of events per second

-> This would saturate trigger buffers due to dead-time

-> Experiment would not be possible

With BEDLAM real-time RFI trigger based on event logic

>1000:1 reduction in RFI triggers

From 100/s false triggers to <1 every 10s in worst case

-> Experiment can proceed with almost no impact on efficiency

BEDLAM spinoffs

Versatile platform used in a number of unforeseen applications

RFI monitoring system at Parkes and Boolardy
Provides visibility of transient RFI not usually consider or monitored

Used in BIGHORNS EOR prototype experiment and subsequently MRO site RFI monitor system

Component testing for ASKAP system components

Trigger algorithms adapted to time domain RFI removal for ATCA, ASKAP and new UWB system at Parkes

-> Example of technology developed for science – neutrino searching – to a range of practical engineering problems

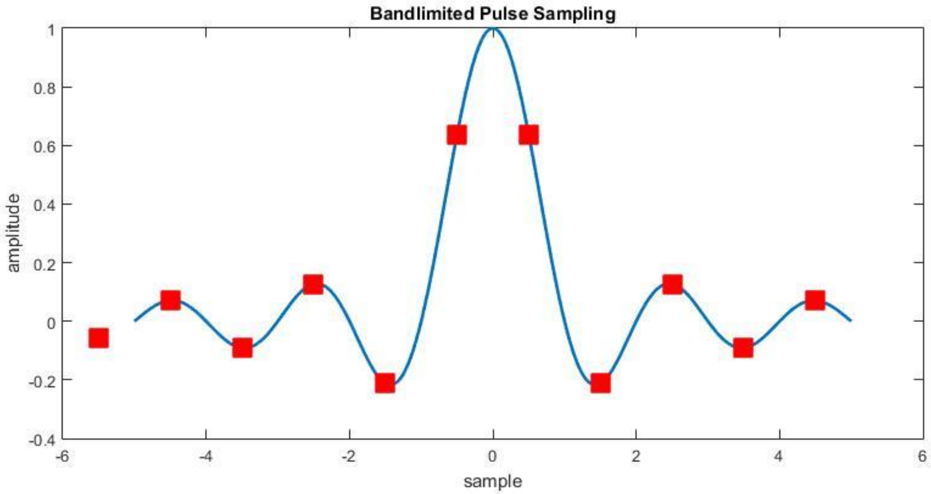
Problem Subtleties of discrete sampling short pulses

Most modern radio astronomy signal processing uses sampled digital data representation

According to Nyquist theorem appropriately sampled data contains all the information to reconstruct the analogue signal

But it is never actually reconstructed in practice. This hides a subtlety when trying to detect a very short pulse, like a neutrino induced event

Consider



Solution Real-time inter-sample interpolation

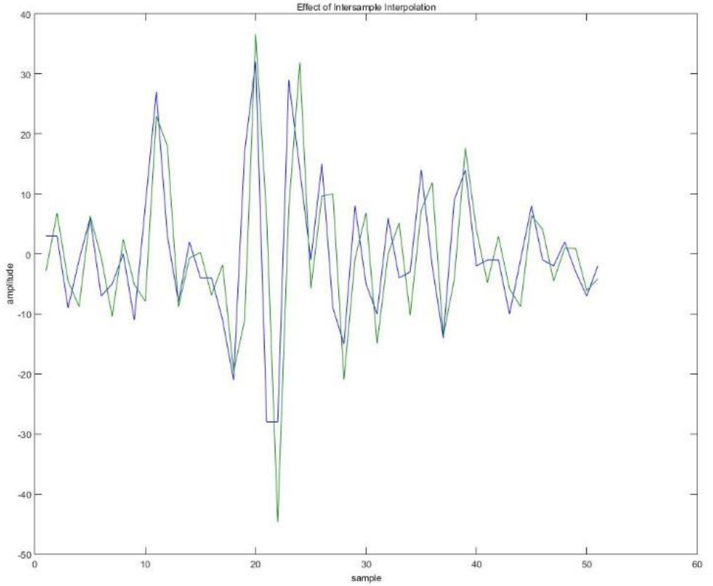
Whittaker-Shannon reconstruction formula

$$x(t) = \sum_{n=-\infty}^{\infty} x(nT).\,sinc(\frac{t-nT}{T})$$

Approximate this by 6 terms to give a x2 interpolation in real time

x(t+0.5) = sinc(-2.5)*x(-2) + sinc(-1.5)*x(-1) + sinc(-0.5)*x(0) +
sinc(0.5)*x(1) + sinc(1.5)*x(2) + sinc(2.5)*x(3)

Only application I have come across where this needs to be considered



CSIRO

Problem   Time alignment of beams to < 1ns

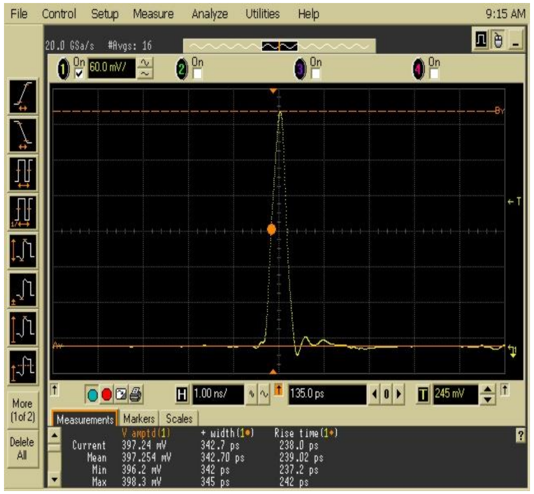
Need to align beam signals propagated over ~150m of cable to ~ 1ns

-> Allows RFI algorithms to operate correctly

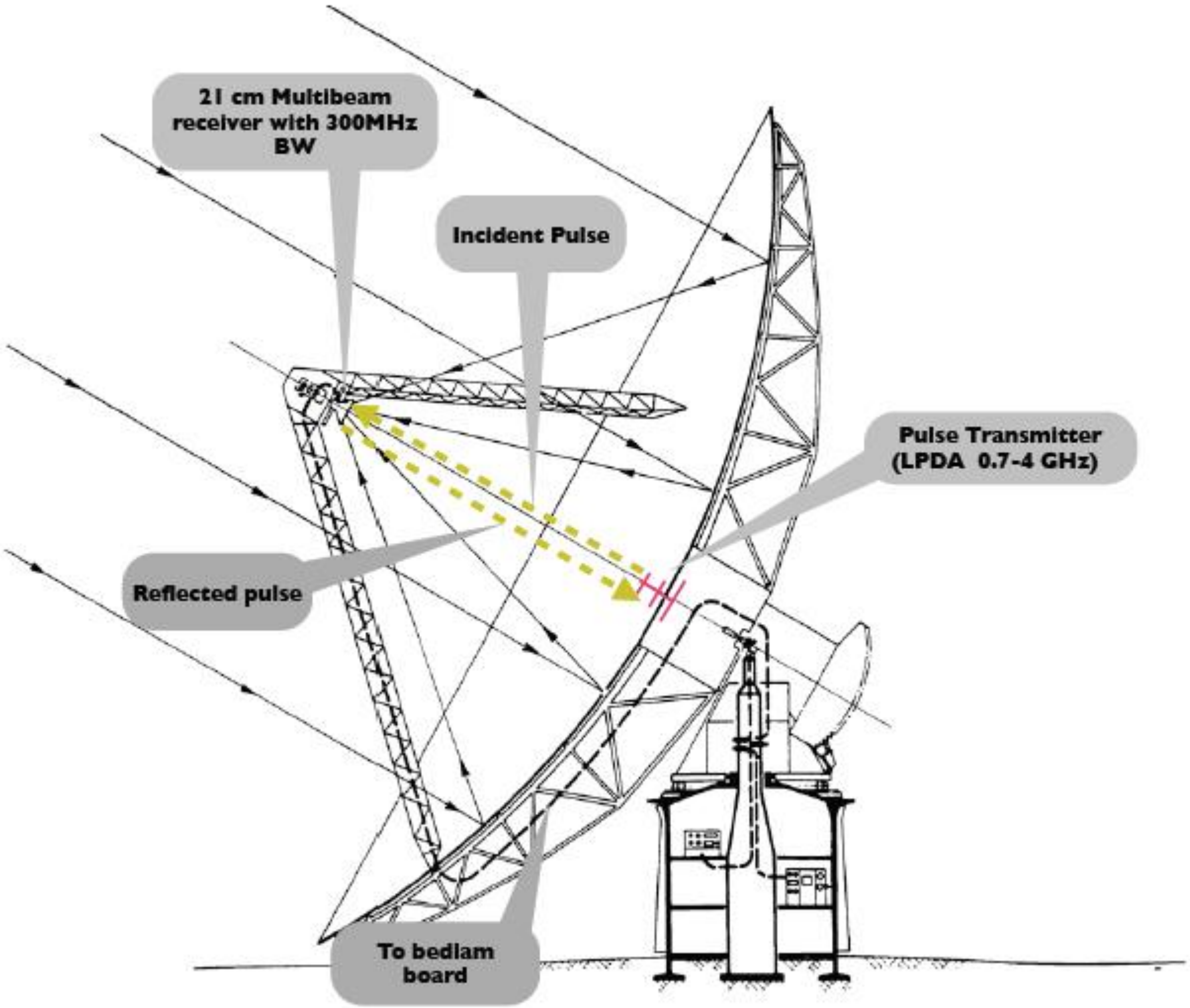
-> Allows unambiguous identification of potential events

Our solution. Propagate a sub-ns pulse from the vertex to all beams simultaneously

Compensate with programmable digital delays in digital backend



Parkes 64m



Schematic courtesy N. Patra / J. Sarkissian

Pulse response

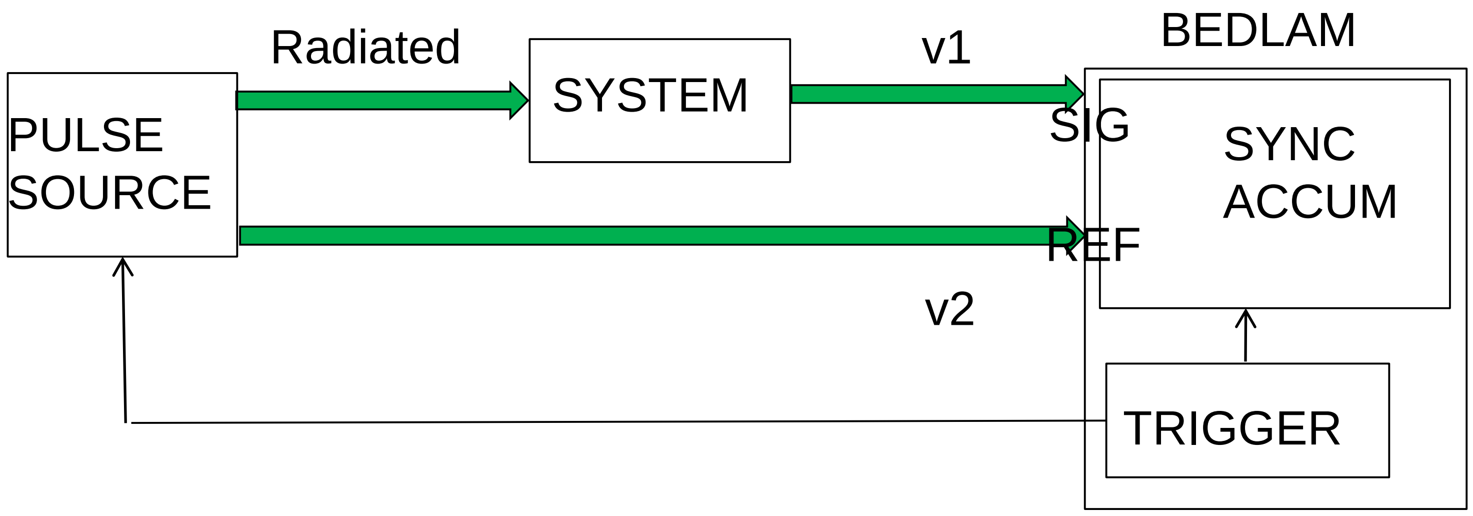
Timing calibration worked fine but then ..

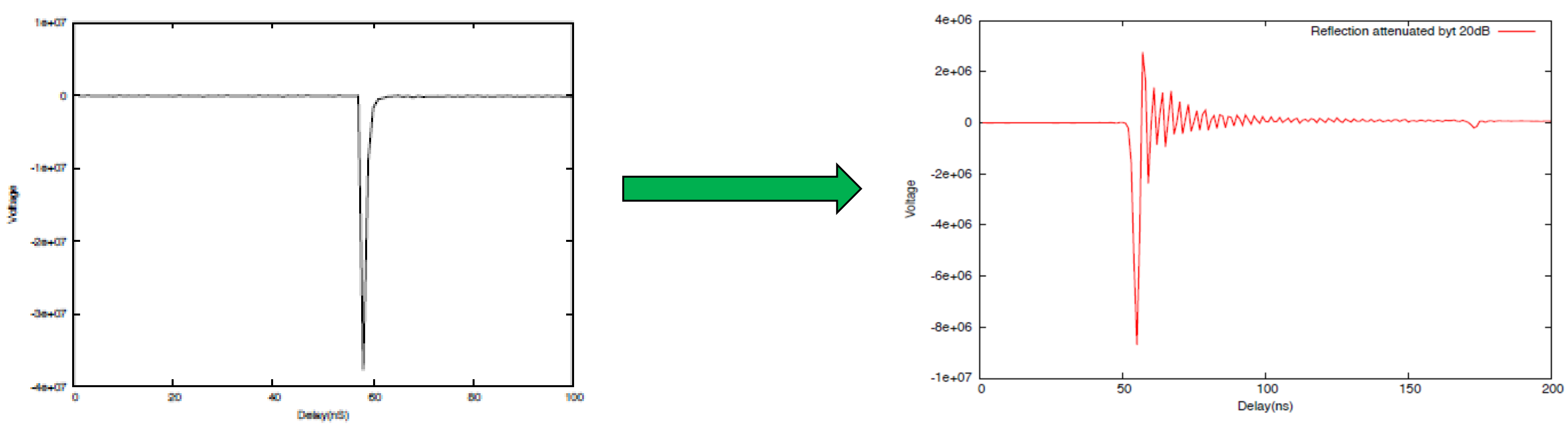
Realised we were actually recording the impulse response of the telescope

-> Could this be used to calibrate the telescope using pulses?

To investigate we developed a synchronous integration backend to average 100,000s of pulses for high dynamic range

Pulse calibration





Pulse calibration

Short pulse directly measures impulse response
=> (Complex) System transfer function

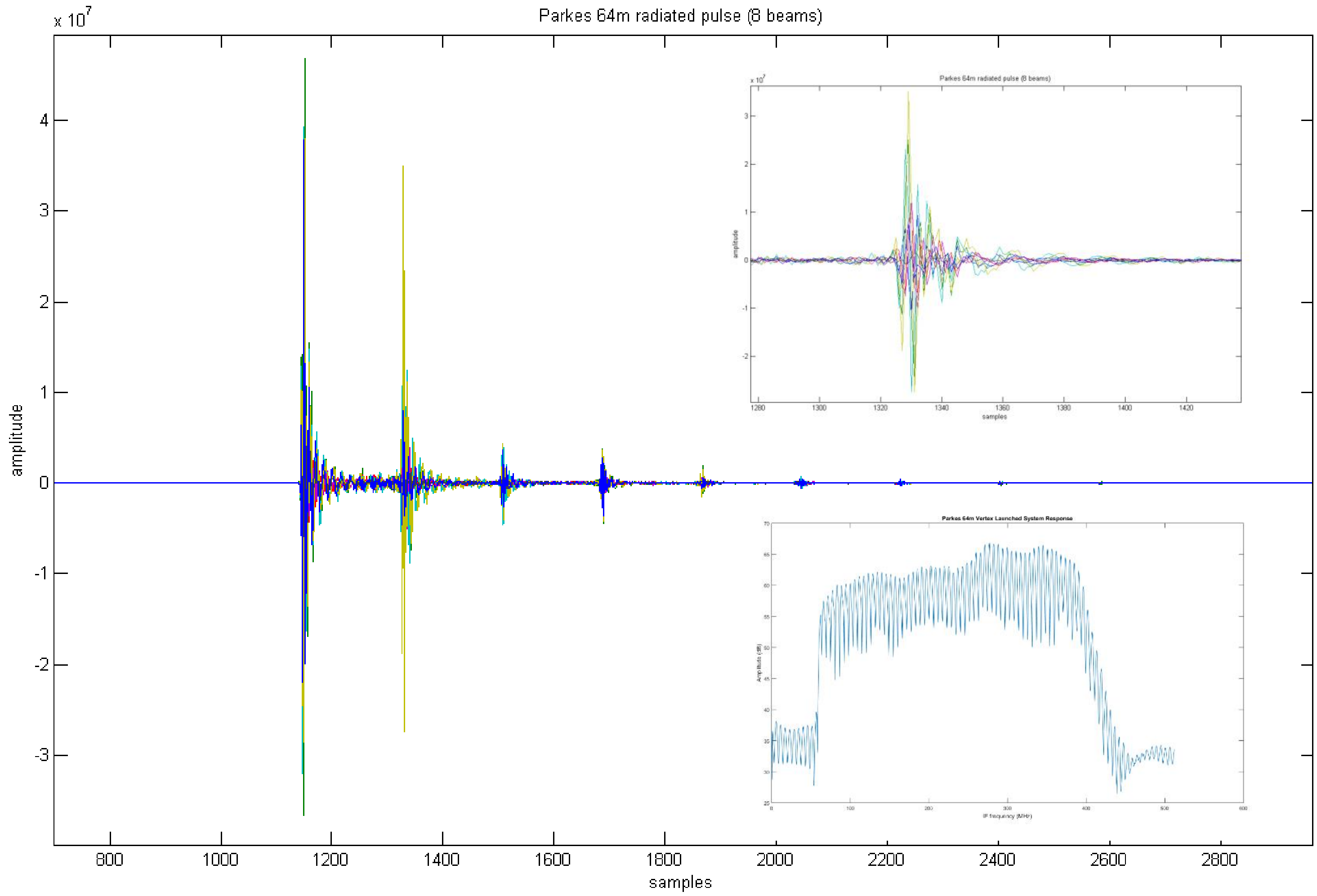
Direct view of time-domain discontinuities, delays etc
=> Often easier to understand

Synchronous accumulation and confinement of energy to small time window allow high DR

Pulses can be low amplitude (below noise) so not push receiver into nonlinearity

Continuous background calibration

Pulse calibration



Summary

Technology originally developed for an esoteric application

-> Problems solved in innovative ways

-> Many applications beyond the use originally envisaged

Open minded cross-disciplinary knowledge and linkages essential to innovation

Always be looking for opportunities beyond the immediate

Thanks for the adventure Ron

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