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für Radioastronomie

Ultra-broadband pulsar observations at the Effelsberg 100m: *impact on the EPTA*

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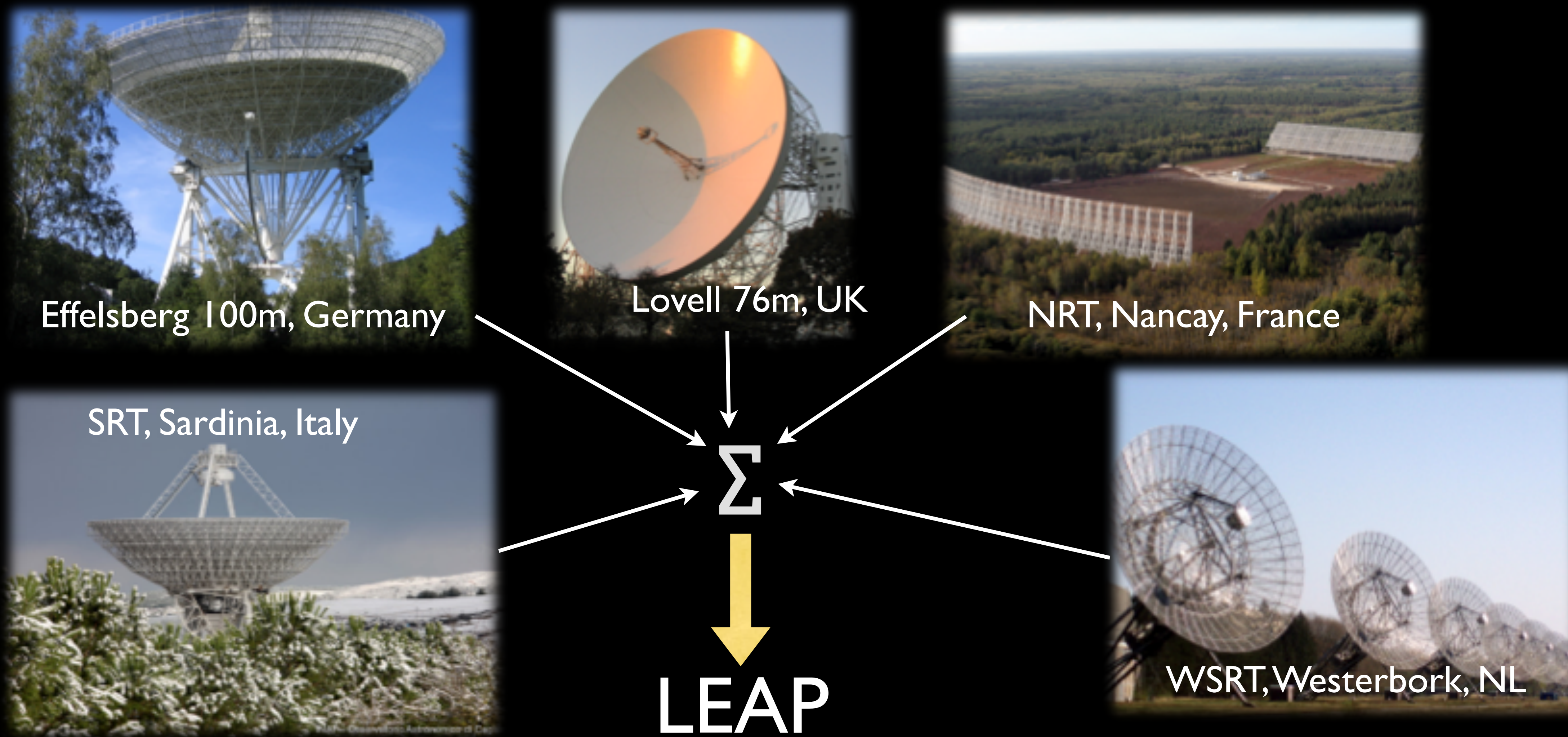
Outline

- EPTA
- Pulsar signals and processing
- UBB system at Effelsberg 100m
- UBB impact on the EPTA

European Pulsar Timing Array (EPTA)

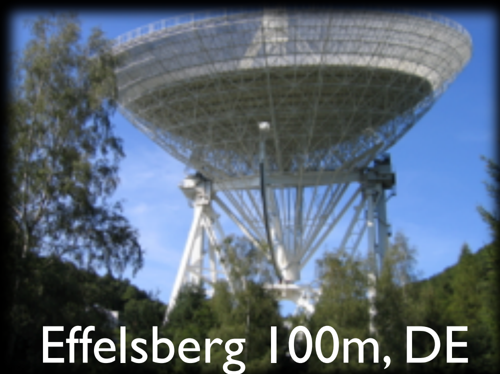


Telescope	Diameter (m)	ϵ	T_{sys}	Alloc. time (h/mo)	Dec. range (deg)
Effelsberg	100	0.54	24	24	> -30
Lovell	76.2	0.55	30	48	> -35
Nançay	94	0.48	35	250	> -39
Sardinia	64	0.6	25	30	> -46
WSRT	96	0.54	29	32	> -30
LEAP	**200**	**0.54**	**30**	**24**	**> -39**

from Ferdman et al. 2010, Class. Quantum Grav. 27, 084014

- Large European Array for Pulsars
- phase coherent summing
- “leap” in collecting area ~200m dish

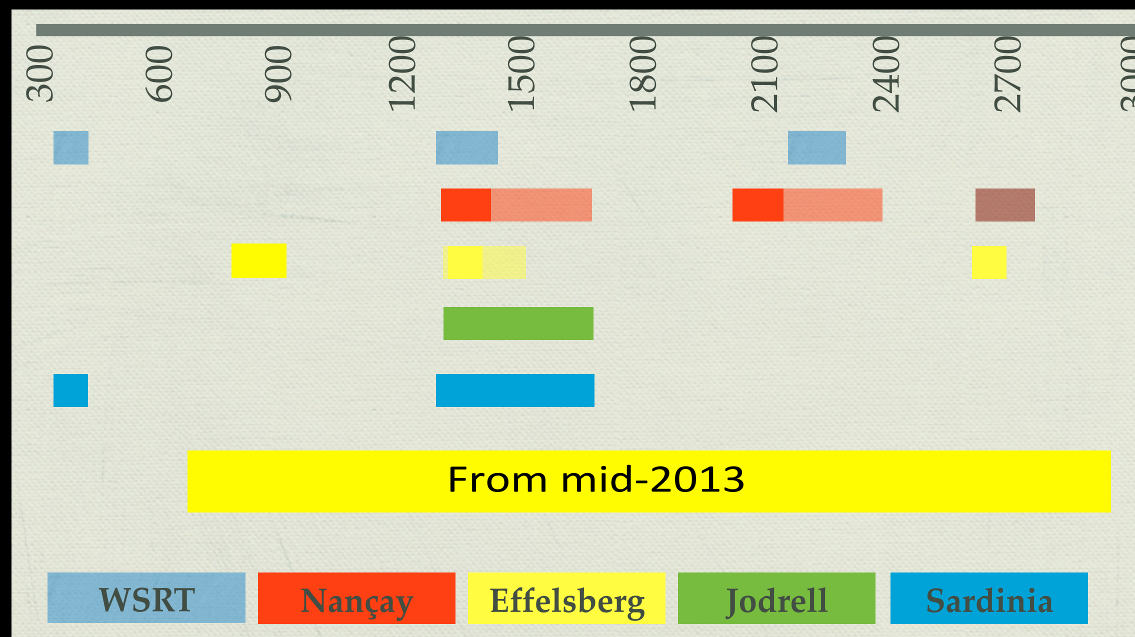
European Pulsar Timing Array (EPTA)


Effelsberg 100m, DE


NRT, Nancay, France


SRT, Sardinia, Italy

- 30-50 sources are monitored
- cadence - 7d(NRT), 10d (Lovell) and 30d
- 30-60 min. per source
- good frequency coverage
- remove interstellar weather



- check on systematic errors
- 25yr baseline on many pulsars
- current best limit on GWB from EPTA data
- Major hardware upgrade is nearly complete


WSRT, NL


Lovell 76m, UK

European Pulsar Timing Array (EPTA)

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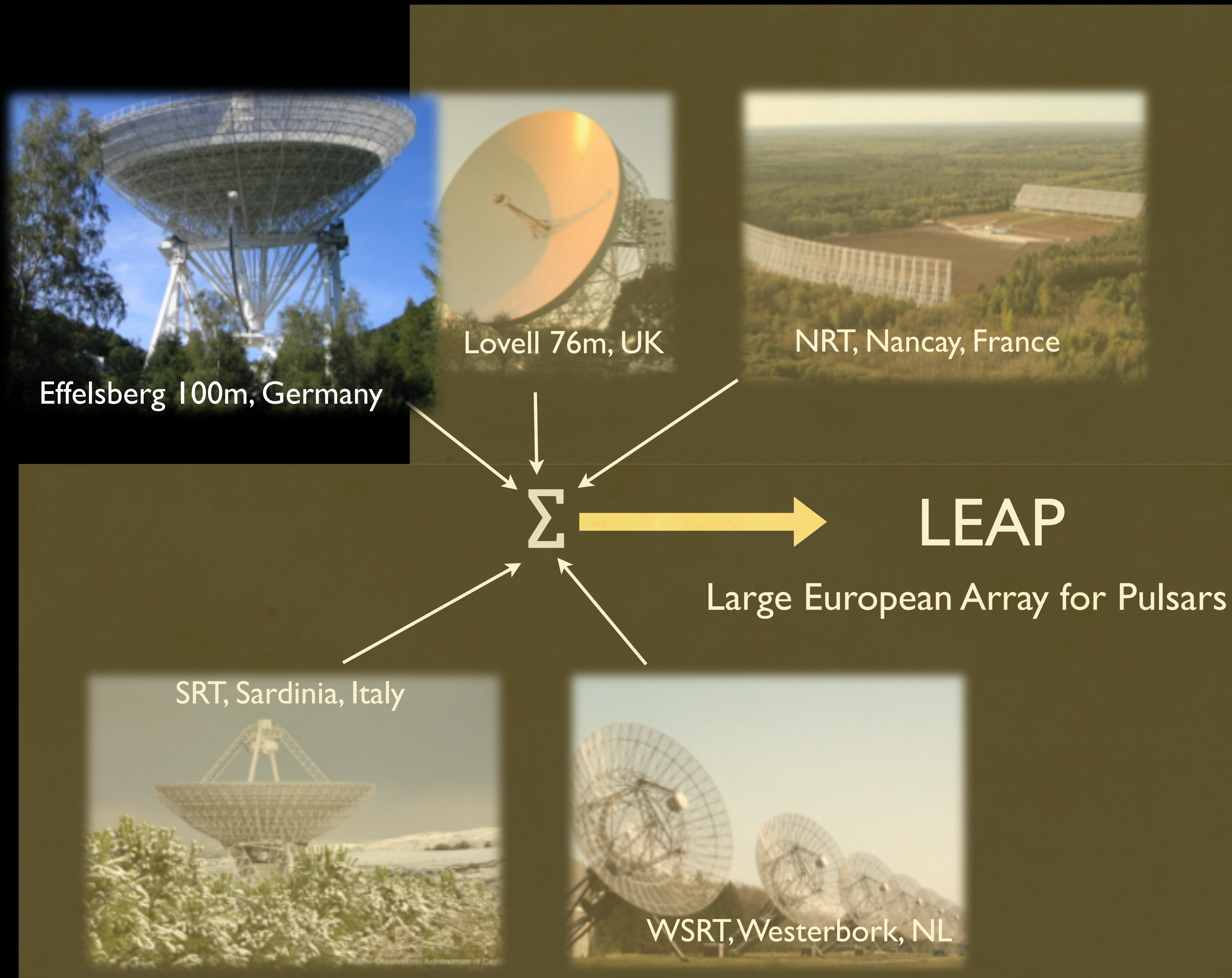

Pulsars signals

- Pulsar signals are
  - a product of radio emission along NS magnetic axis
  - extremely periodic - rivals atomic clocks
  - dispersed and scattered by propagation in ISM
  - wideband signals
  - display steep spectrum $\sim \nu^{-1.8}$
  - scintillates - intensity varies with time/frequency
  - ... and they are <u>weak</u>

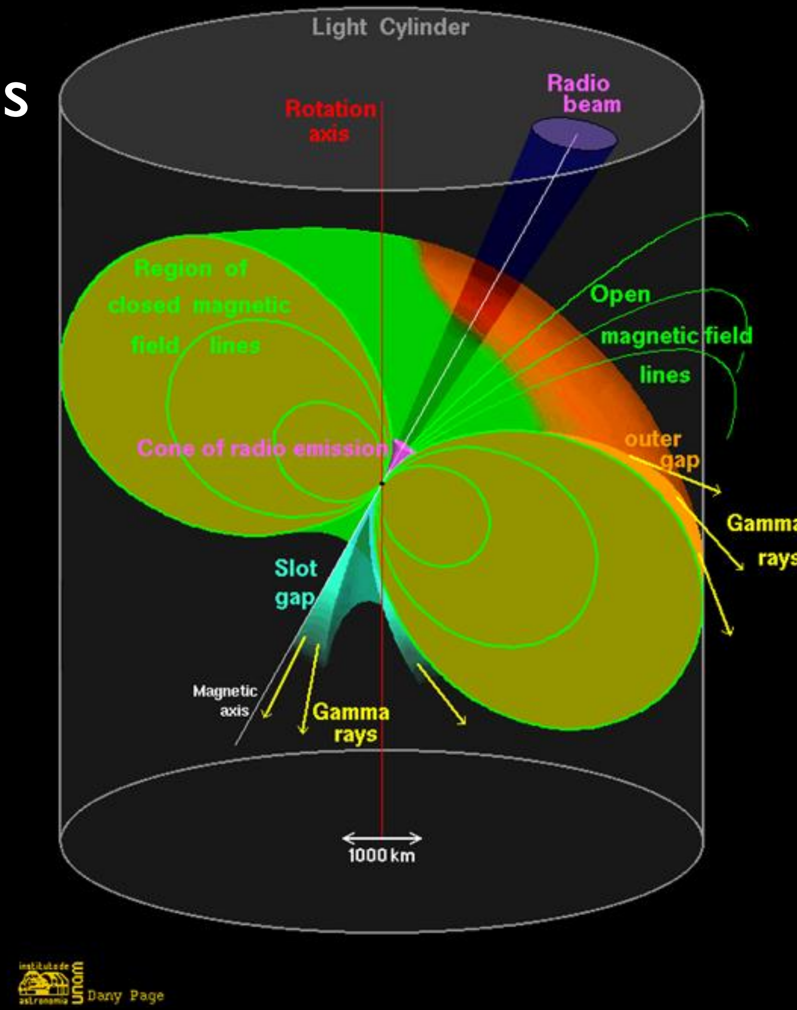

Image credit: Dany Page

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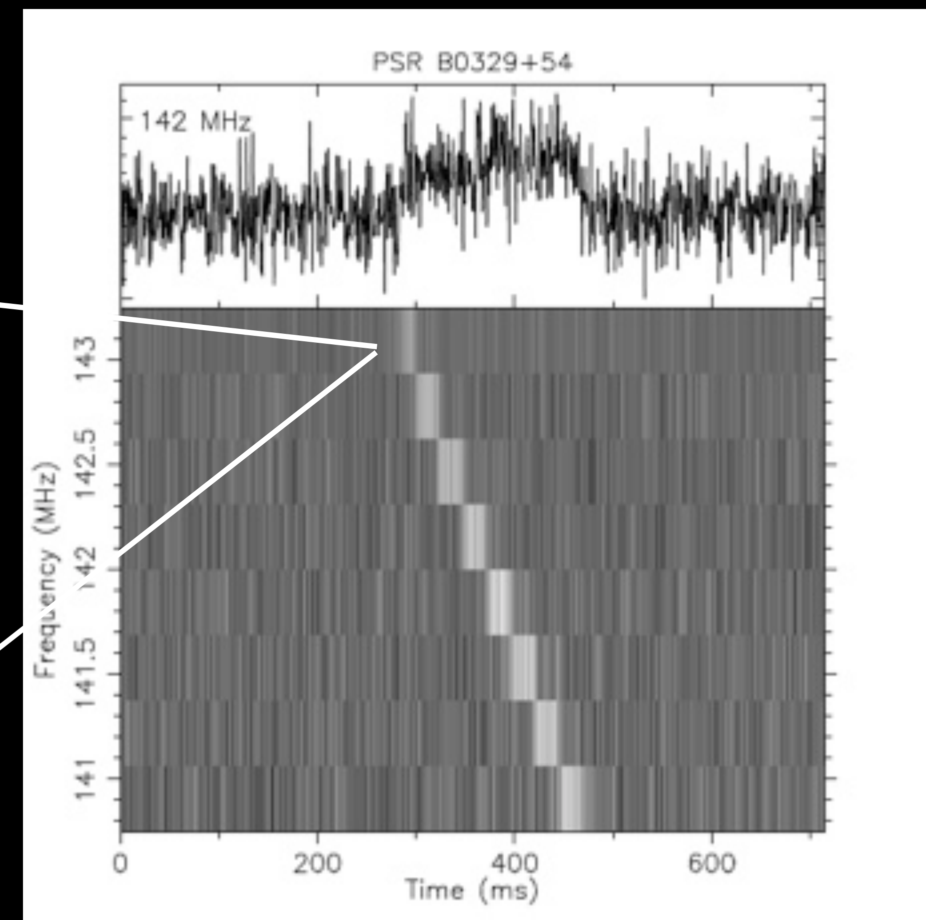
Pulsar signals - dispersion

- Signals are dispersed by the ISM
  - higher frequencies travel faster ....
  - results in freq-dependent arrival time
  - smearing depends on pulsar's location
  - If uncorrected, renders PSR undetectable



$$H(\nu + \nu_0) = \exp\left[\frac{i2\pi D\nu^2}{\nu_0^2(\nu_0 + \nu)}\right]$$

sky frequency

Dispersion measure

Pulsar signals - dedispersion

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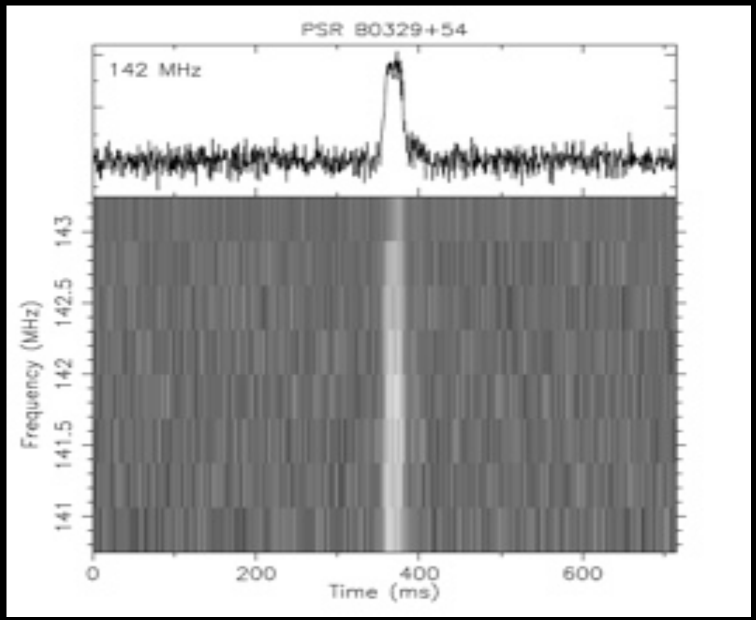
- Incoherent dedispersion
  - detect signal & correct channel delays
  - limits time resolution



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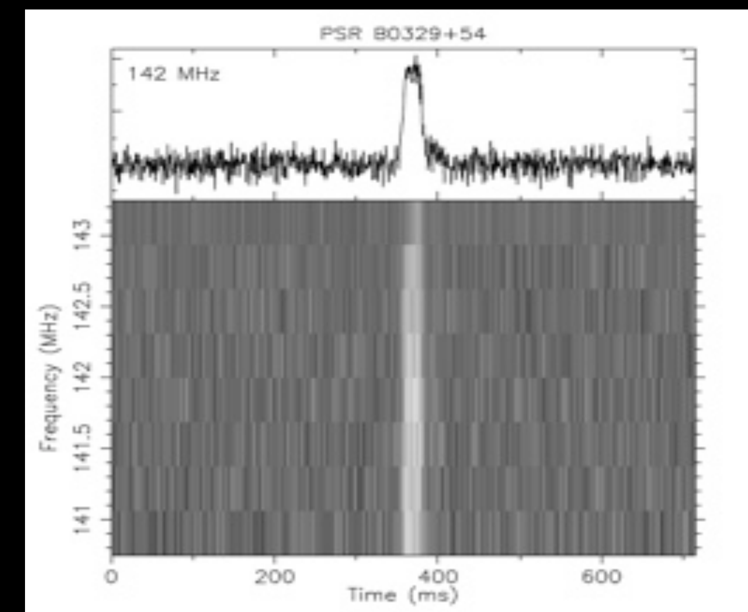
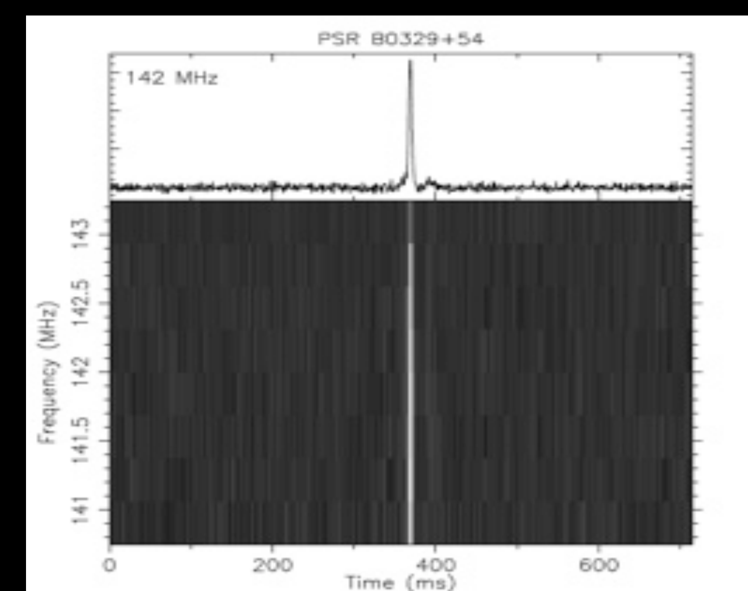
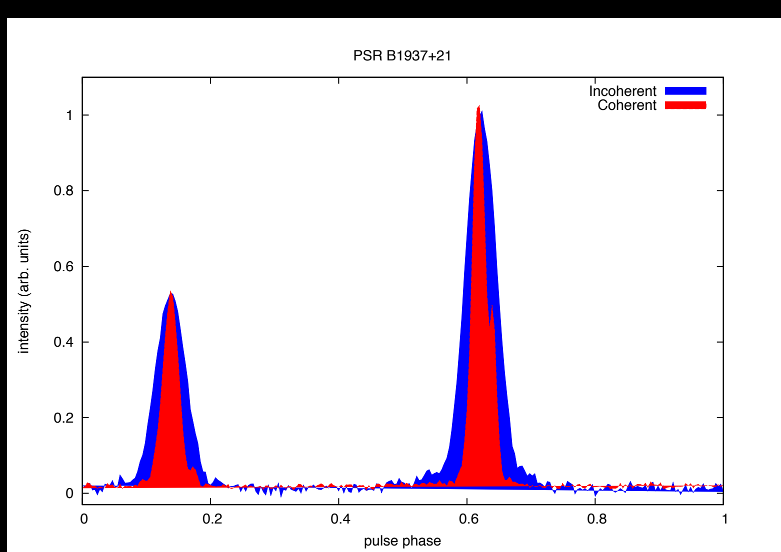
Pulsar signals - dedispersion

- Incoherent dedispersion
  - detect signal & correct channel delays
  - limits time resolution
- Coherent dedispersion
  - reverse ISM’s effect by convolution
  - need raw voltages - large data rate
  - computationally intensive







- ✓ narrower profiles, higher S/N
- ✓ improved timing accuracy

Pulsar signals - weak!

- Eg. strong pulsar ~10 mJy@1400 MHz

$$1\mathrm{Jy} = 10^{-26}\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{Hz}^{-1}$$

- Minimum detectable signal in a telescope

$$S_{\mathrm{min}} = \frac{T_{\mathrm{sys}}/G}{\sqrt{n_{\mathrm{p}}t_{\mathrm{int}}\Delta f}} \quad \text{and} \quad G = \frac{A_{\mathrm{eff}}}{2\cdot k_{\mathrm{B}}}$$

➡ ideally T_{sys} ➤ 2.7K
➡ large BW and telescope surface

- Receiver - feed with good illumination, low side lobes
- Low noise amplifiers

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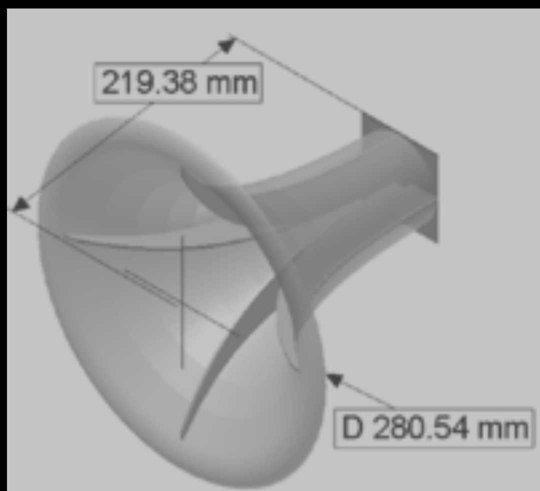
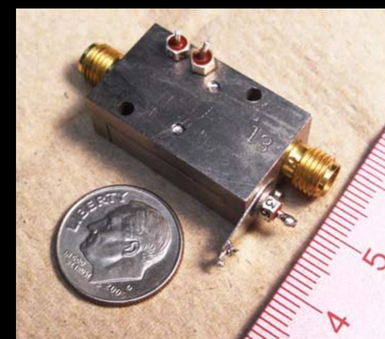
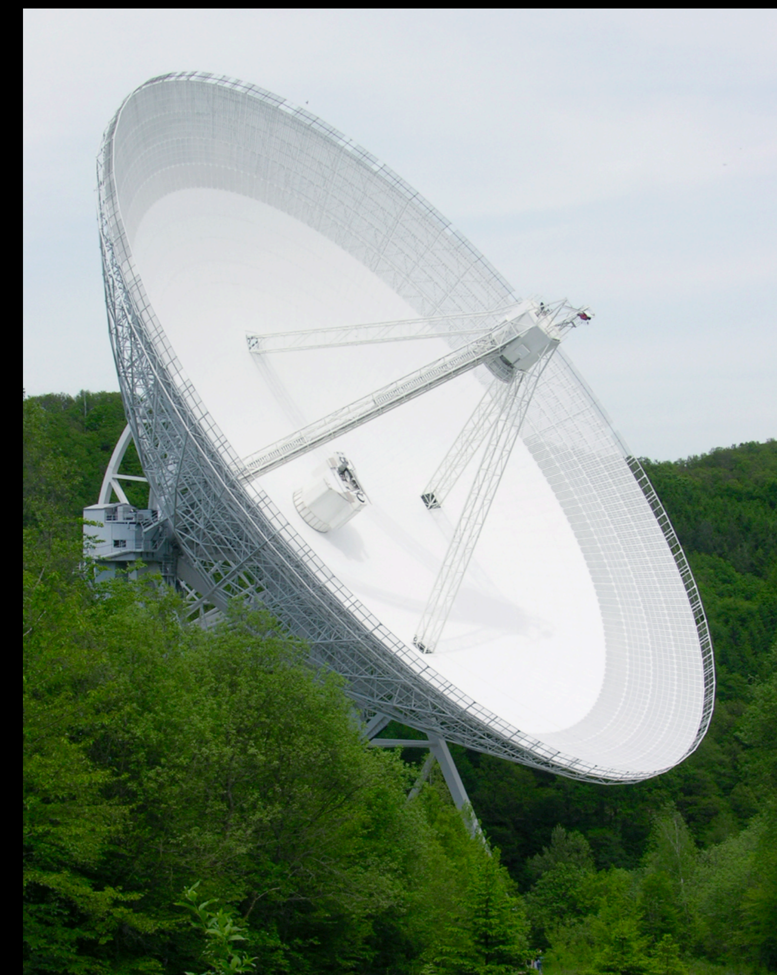
Effelsberg system - overview







Large BW feed horn
+
Low noise amplifier
+
Large collecting area

Effelsberg system - overview

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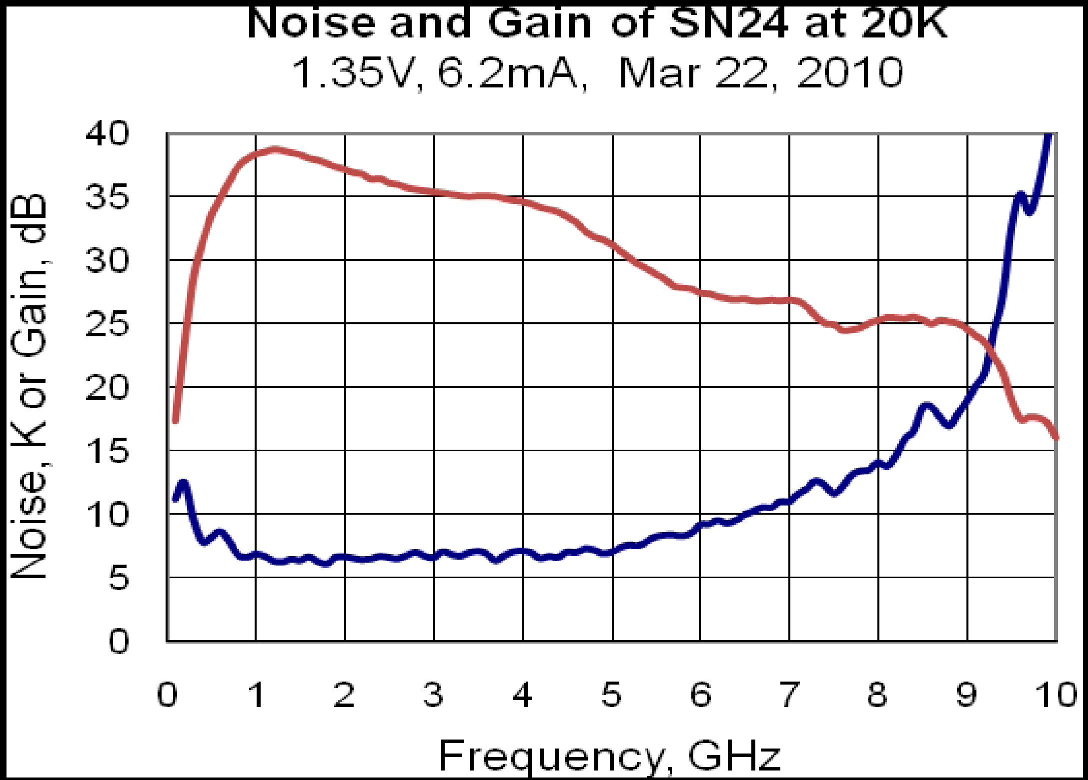
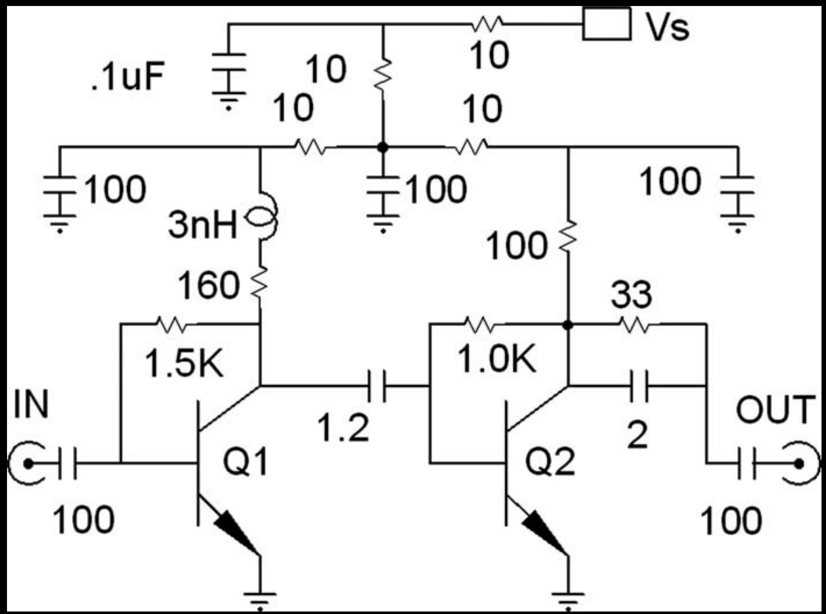
- Low noise amplifier
  - Design by S. Weinreb (CalTech)
  - SiGe, high-perf. bipolar transistors
  - 2-stage design

CITFL4

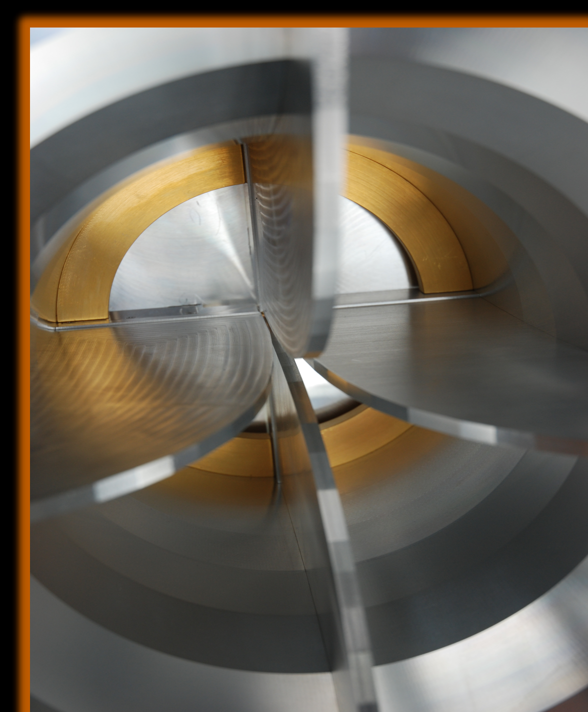
RF Frequency	~0.4 to 4.0 GHz
Gain @20K	36dB ± 3 dB
Noise Temp. @20K	< 8K in 0.5-4GHz
Operating Temp.	4K - 320 K
1dB compression @	-3dBm

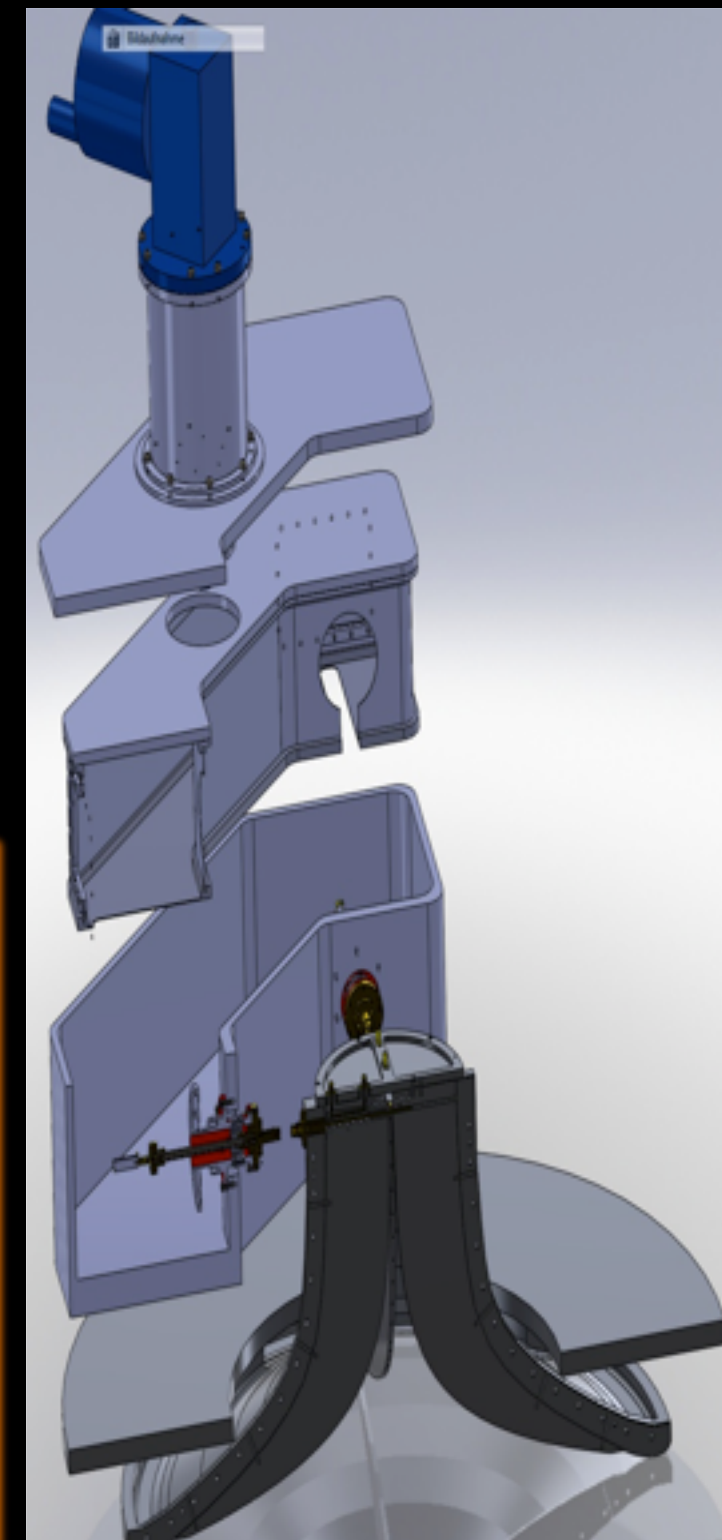




Effelsberg system - overview

- Flared quad-ridged feed horn
  - broad band 5:1
  - based on numerical simulations from S. Weinreb's Team (CalTech)
  - exponential profile for ridges and the wall
  - ~800mm diameter and length
- radiation pattern is asymmetric





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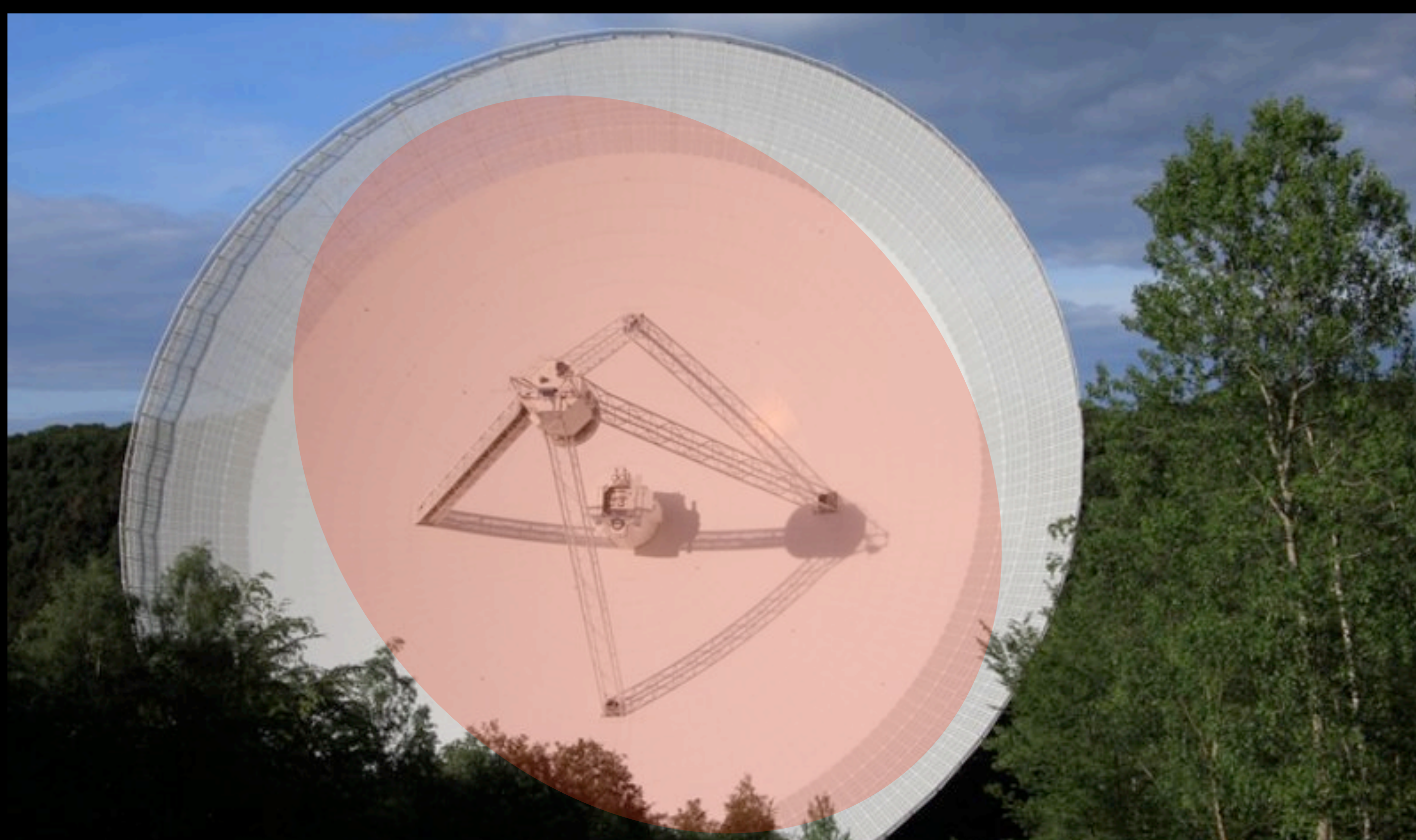
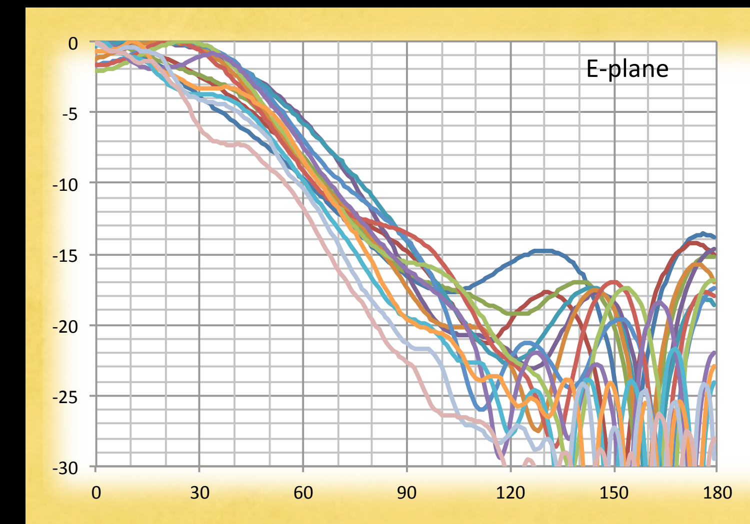
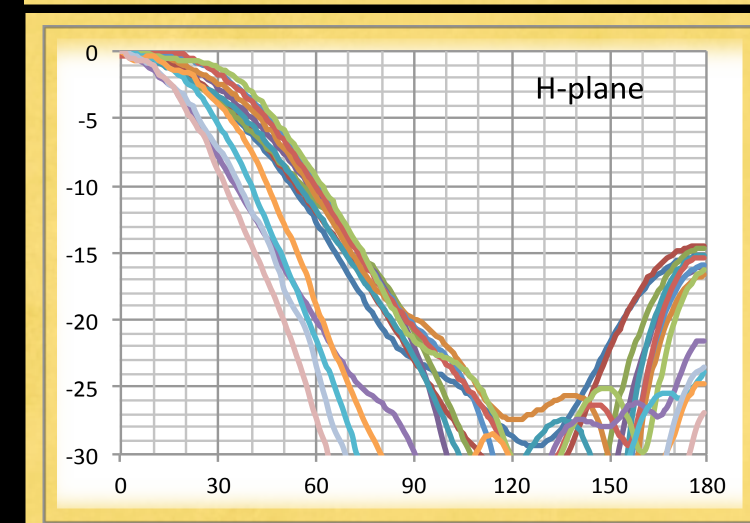
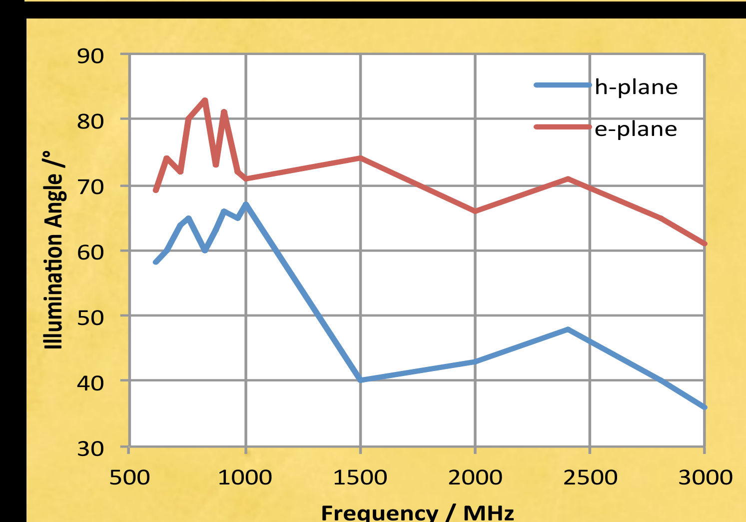
Effelsberg system - overview

- Feed horn near-field measurements
  - E, H-plane beam patterns are non-identical
  - ~ 50% under-illumination at some freqs.
- f/D=0.3 ➟ ± 80° (12 dB edge taper)
- but ... much lower Tsys (<20K)



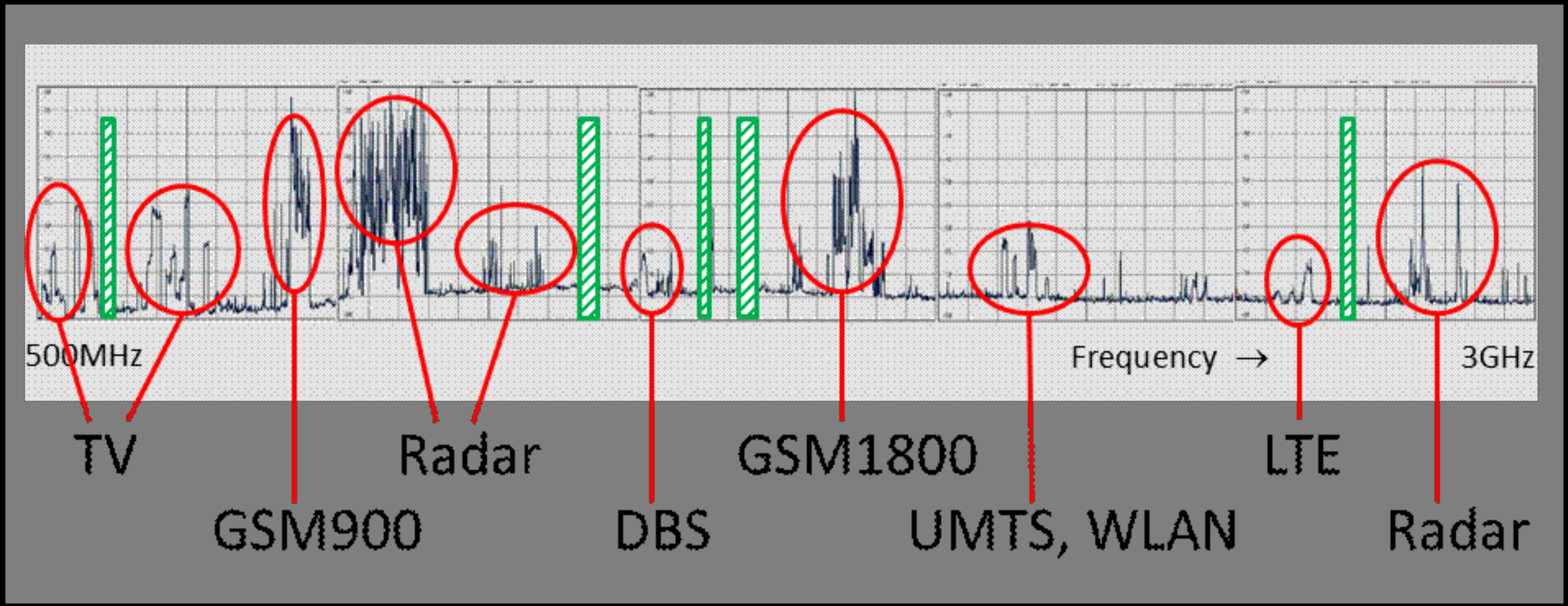






Effelsberg system - overview

- Radio frequency interference ~ 70% useable band!
- Strong RFI @ 380-385, 390-395 MHz (new)
  - pre-LNA 400 MHz high pass filter > 30db suppression
  - ~1K loss in Trx = 17K
  - Other RFI rejected by post-LNA analog filterbank
  - signal processing in backends clean further RFI



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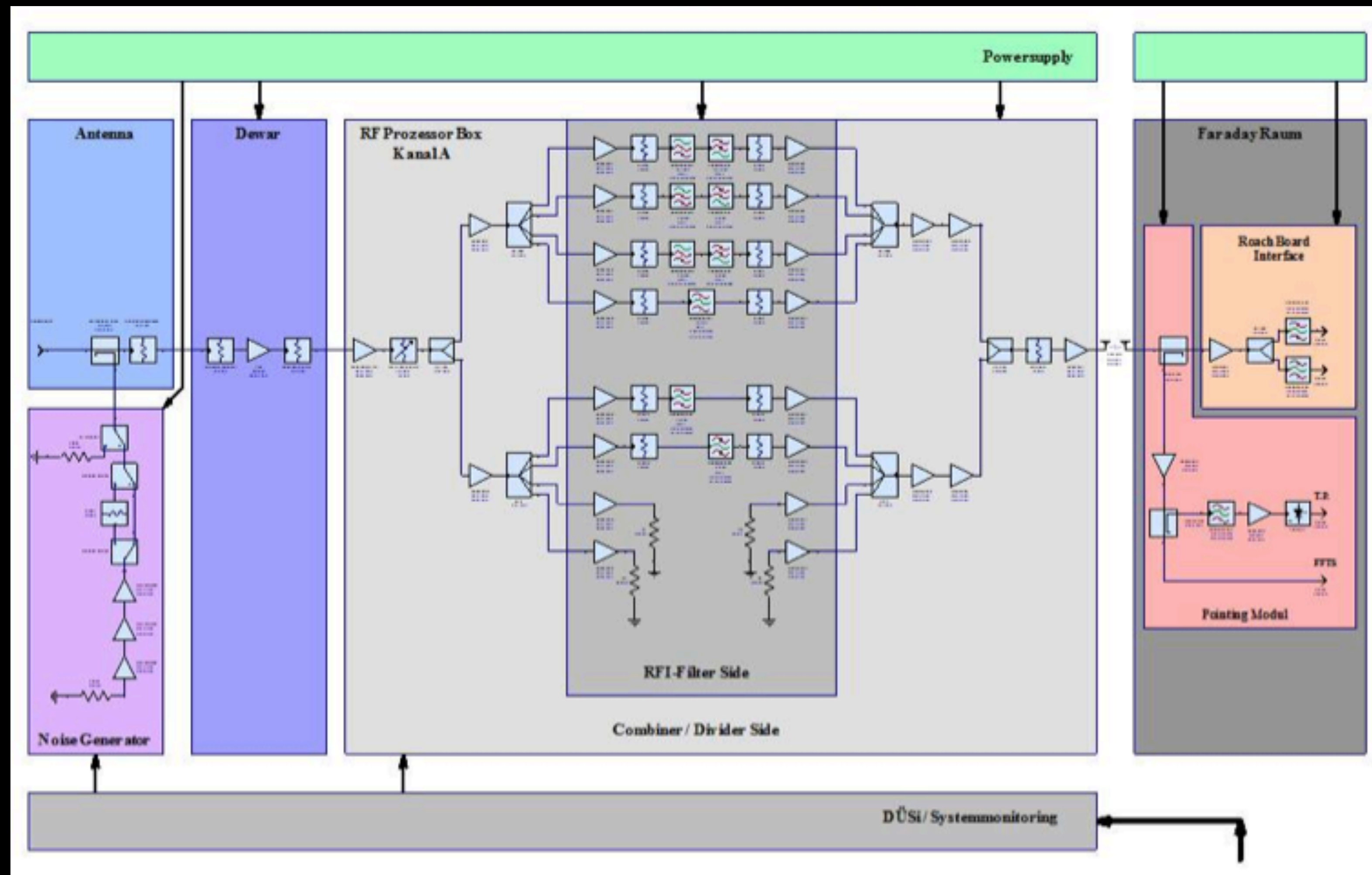
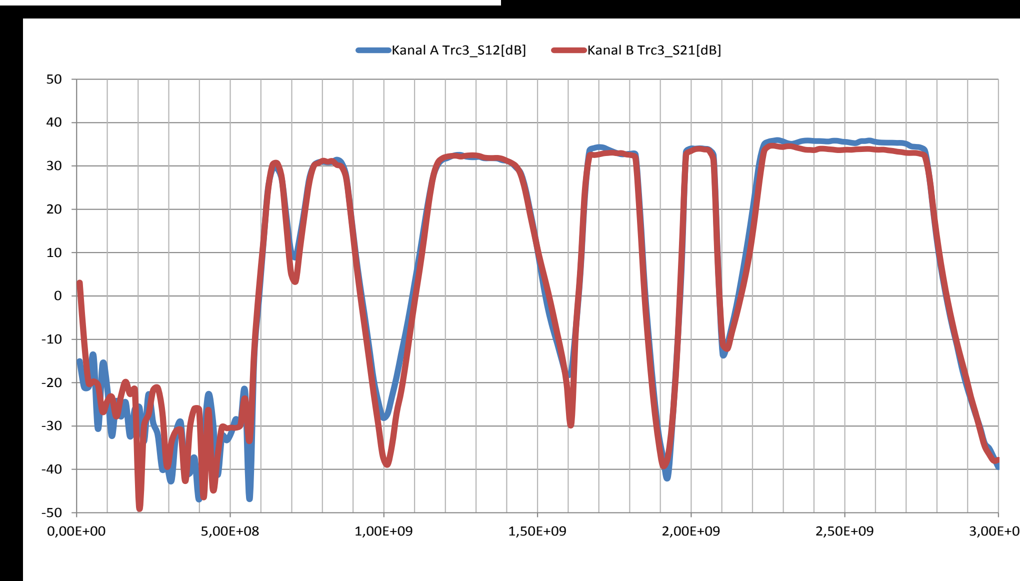
Effelsberg system - overview

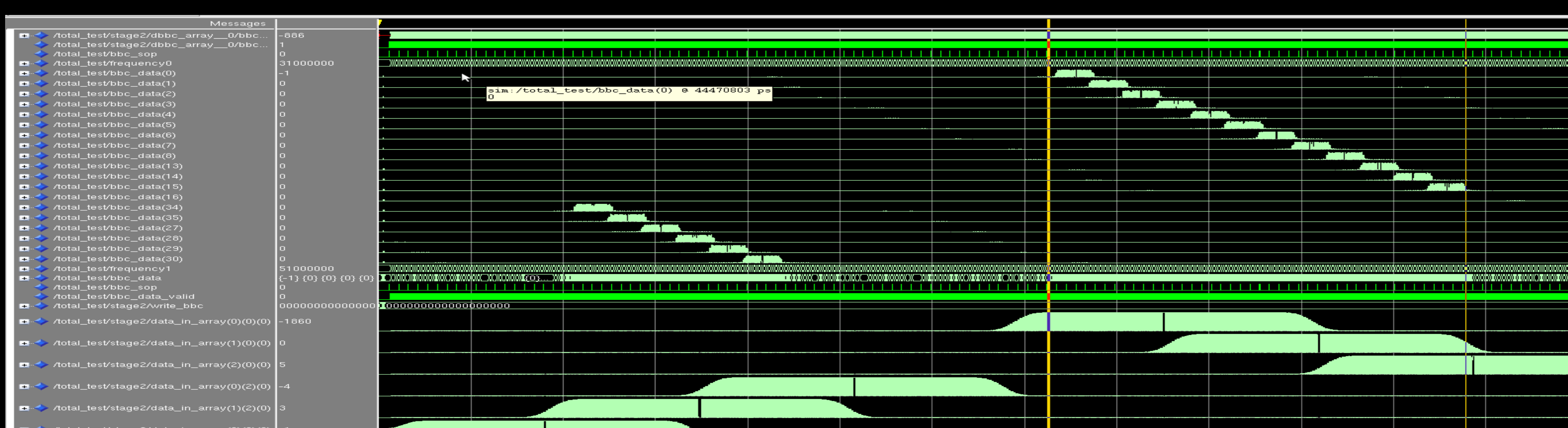




- 15K cryogenic system
- calibration using noise diode
- no down conversion (mixers, LO etc.)
- 7+ filters to remove major RFI
- Signal transported by analog fibers

Signal processing

- Large BW increases sensitivity
- but ... also exacerbates dispersion smearing
    - remove dispersion by coherent dedispersion
- issues ....
    - wide-band ~2.5 GHz ~ 96 Gbits/sec!
    - Coherent dedispersion is formidable ~ multi-gigapoint FFT in ms
- Solution ....
    - use smaller bands, each ~10's MHz wide
    - reduces FFTs to < ~128 Kpts.



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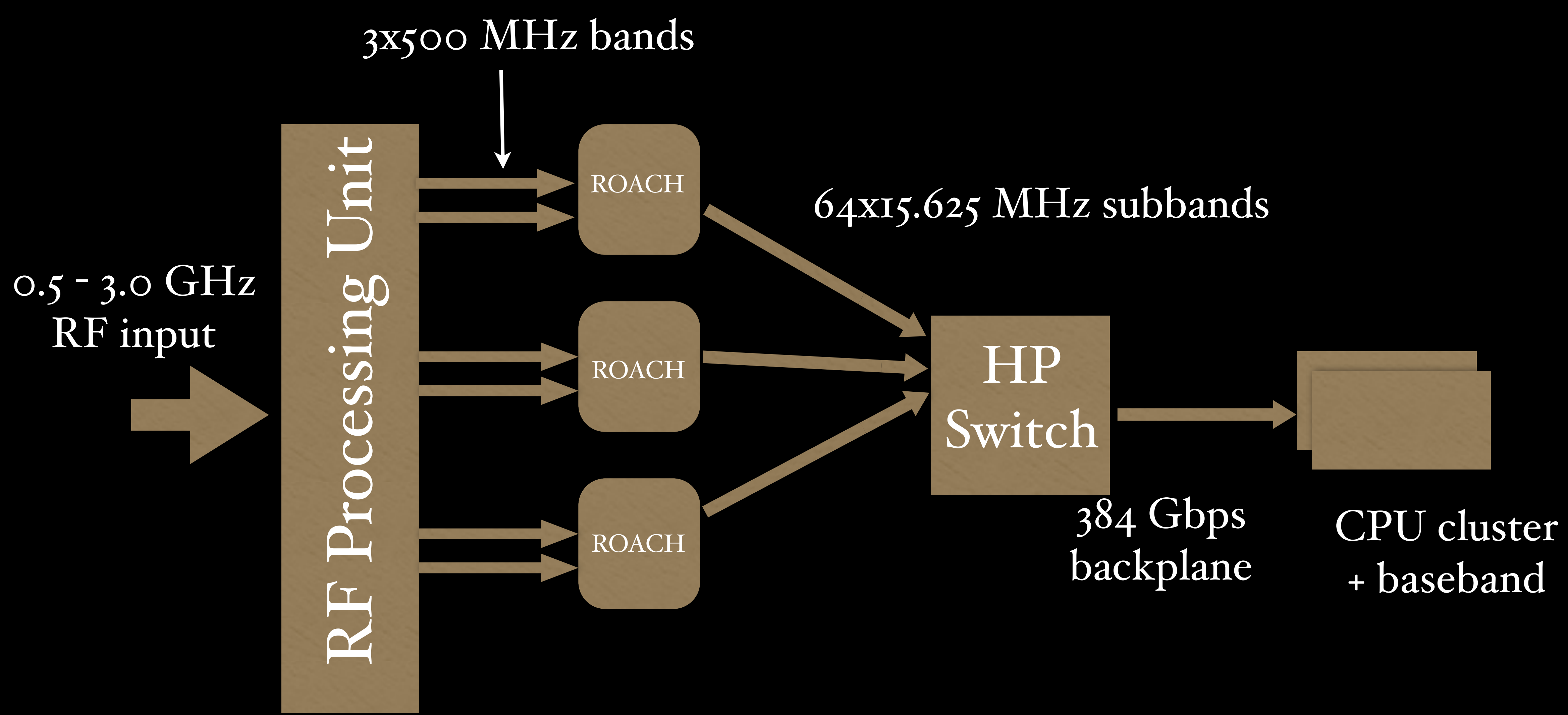
Processing: stop-gap solution



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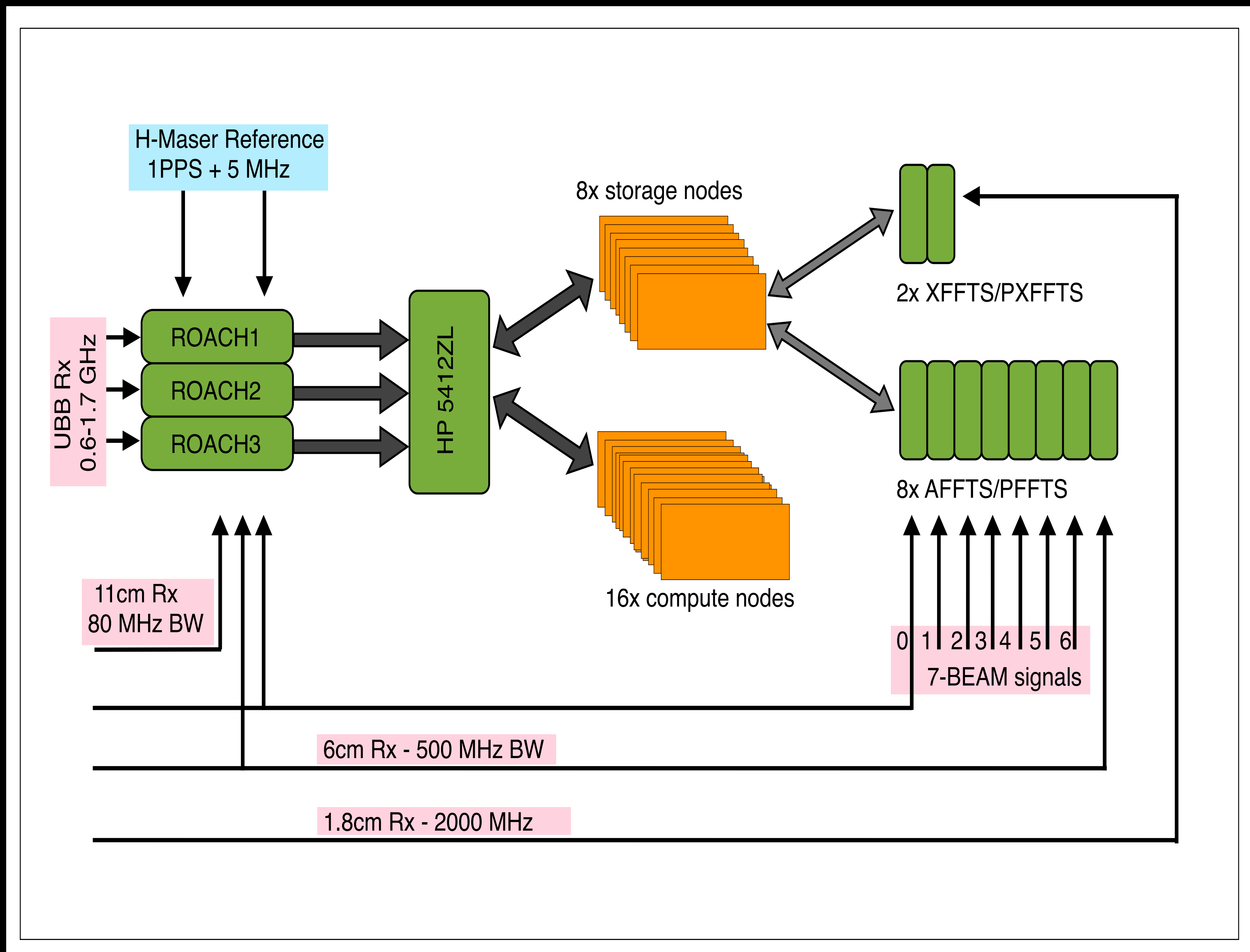
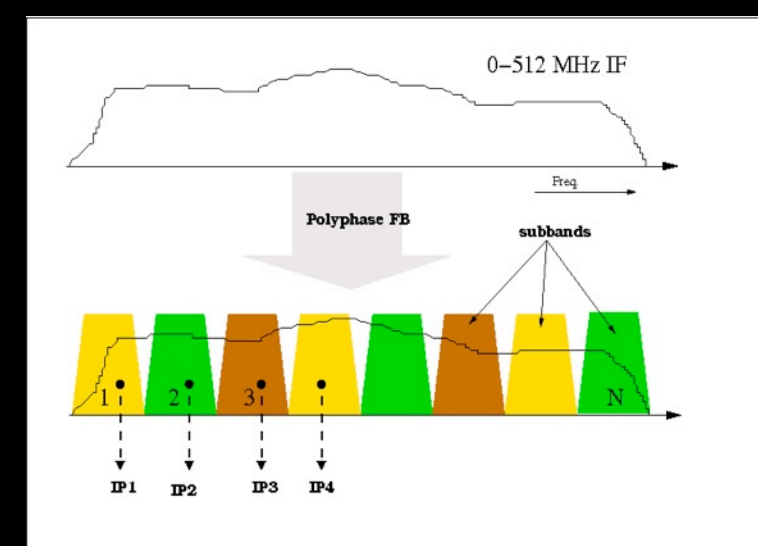
Processing: stop-gap solution



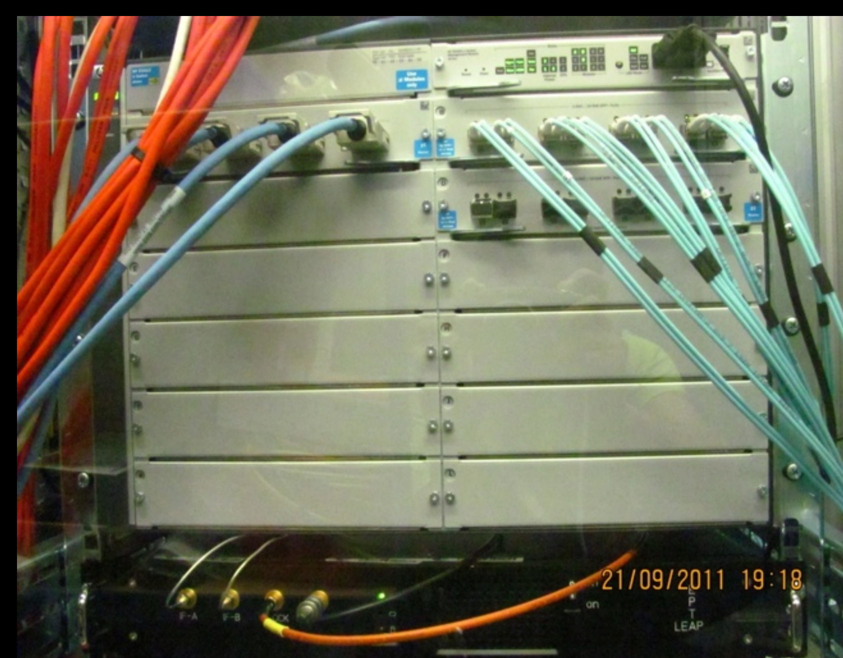
- ✓ ROACH-based PFB
- ✓ flexible instrument
- ✓ Any IF from 0.6 to 20GHz
- ✓ 24 high performance nodes
- ✓ 608 CPU cores
- ✓ 308 TB total storage



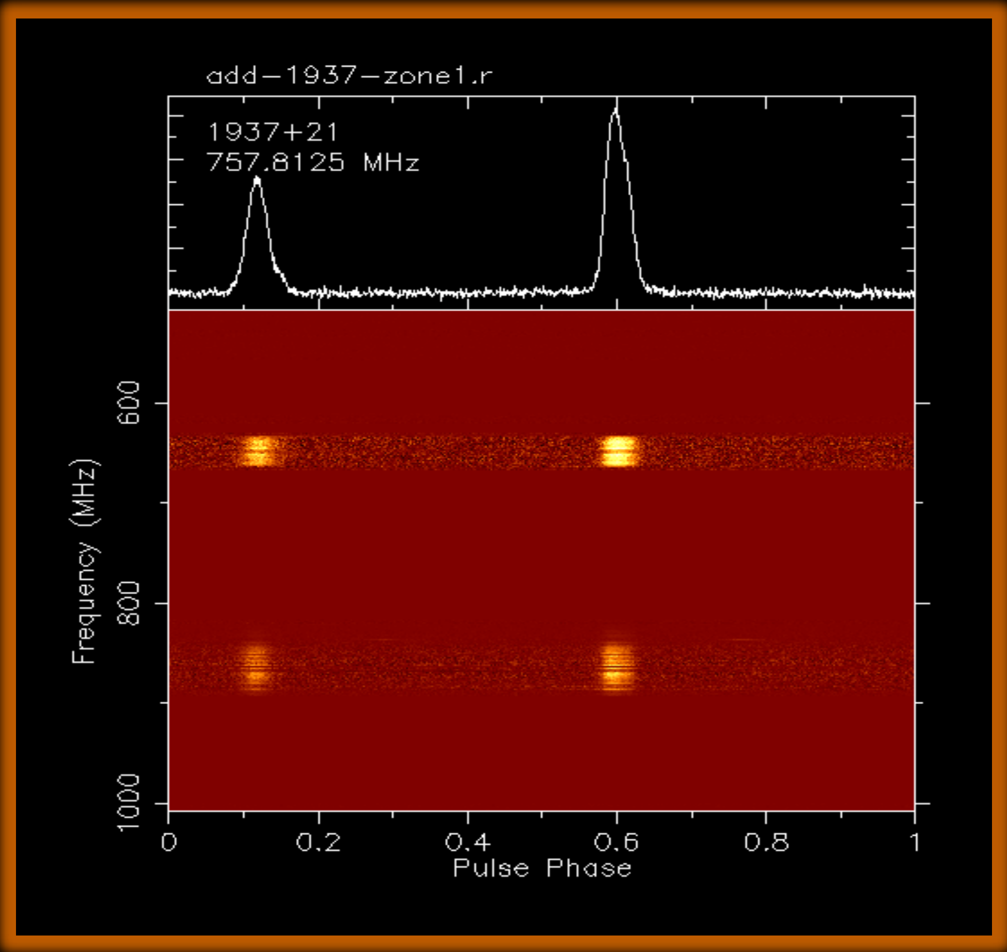
Processing: stop-gap solution

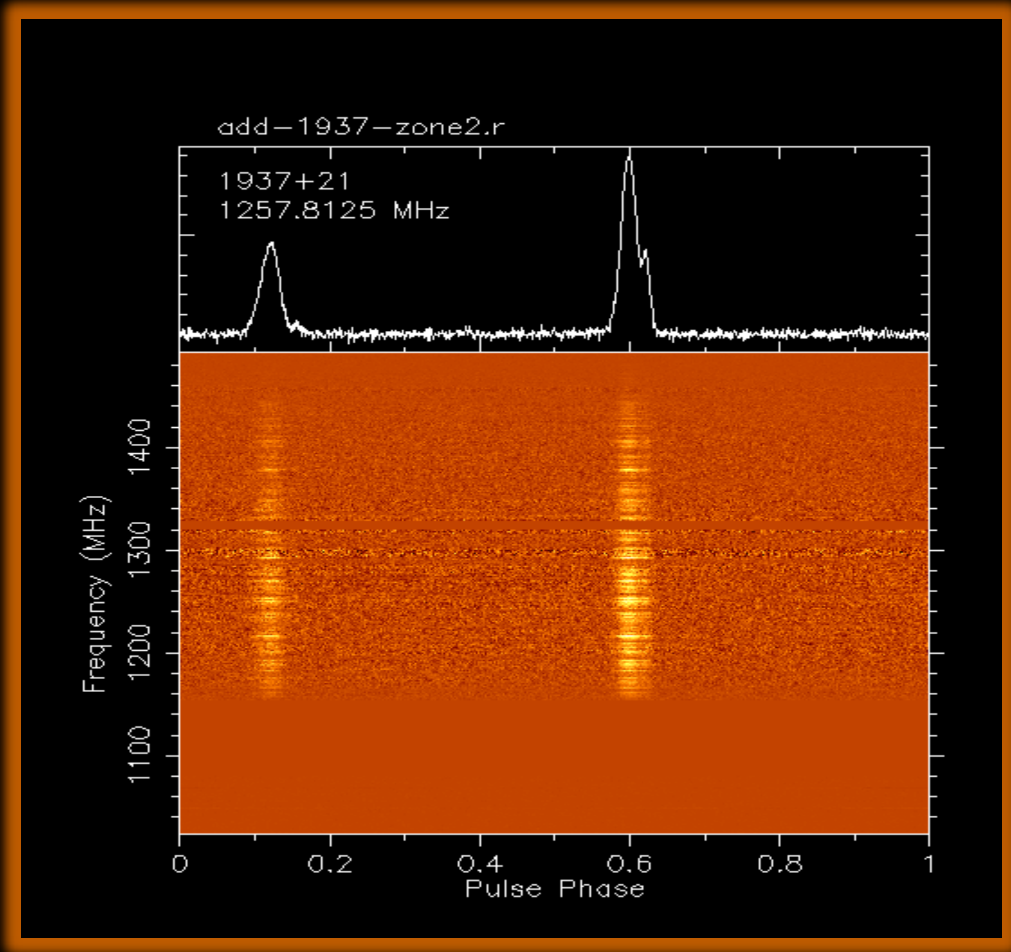
- ROACH board
  - Xilinx Virtex-5 FPGA + CASPER DSP library
  - 1 GSPS, dual 8-bit Atmel ADC
  - 16/32 channel polyphase filter bank
  - 4x10GbE

ROACH: Reconfigurable Open Architecture Computing Hardware
CASPER: Centre for Astronomy Signal Processing and Electronics Research



Some results ...





- First results - June/July 2012
  Could have been better ....
- RFI was a major issue - mild saturation of LNA
- under-illumination of the dish
- phase-centre issues with wide-band feed

UBB's Impact on EPTA

- Current state of EPTA
  - Over 40 pulsars are being timed at the different European observatories.
  - Aim is to achieve sub-100ns timing accuracy for several pulsars

- UBB's impact
  - high-quality TOAs for the EPTA
  - sensitive, better handle on DM
  - Tame scintillation : at the least catch more scintiles
  - improved timing precision - errors on residuals go down

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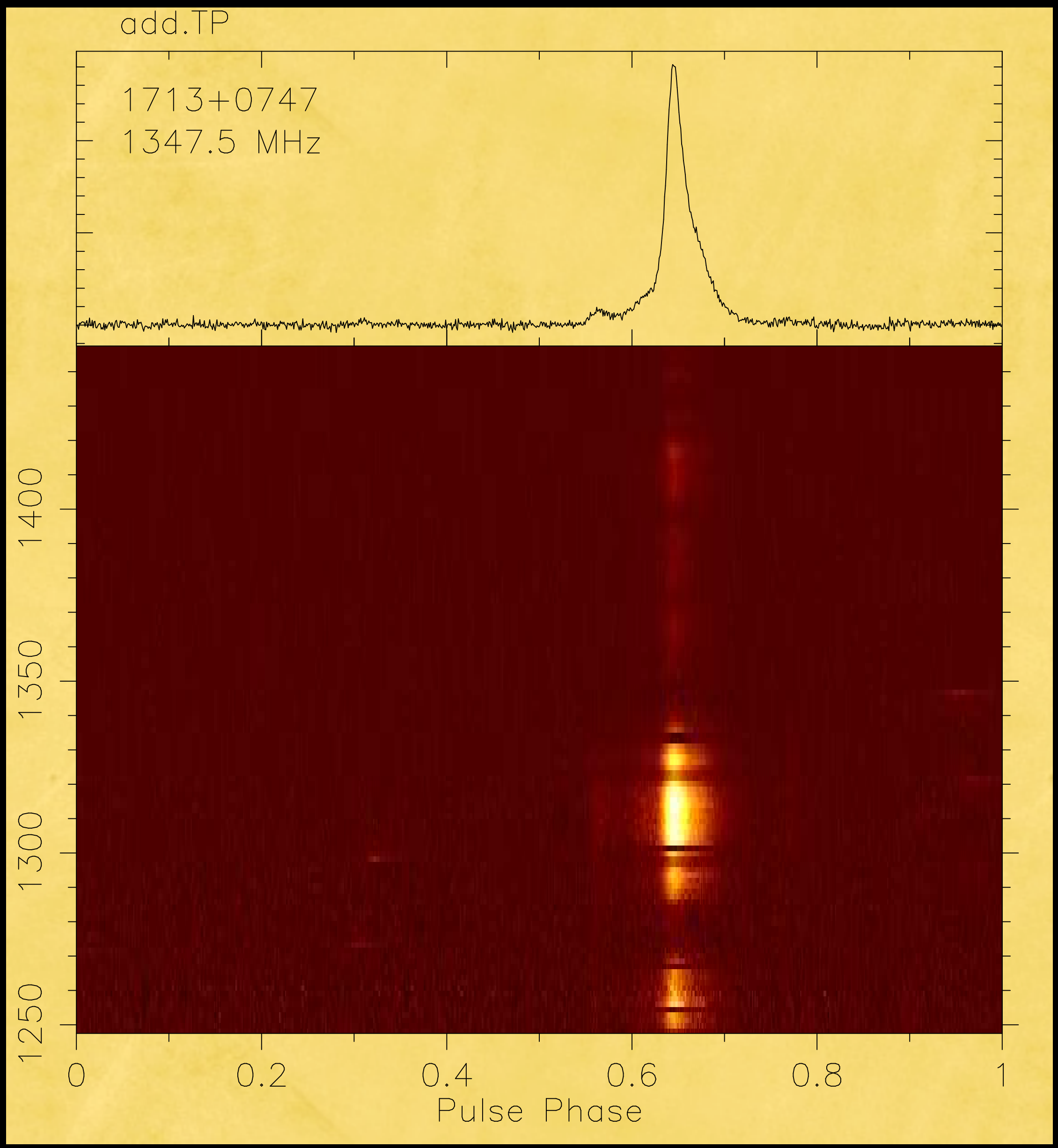
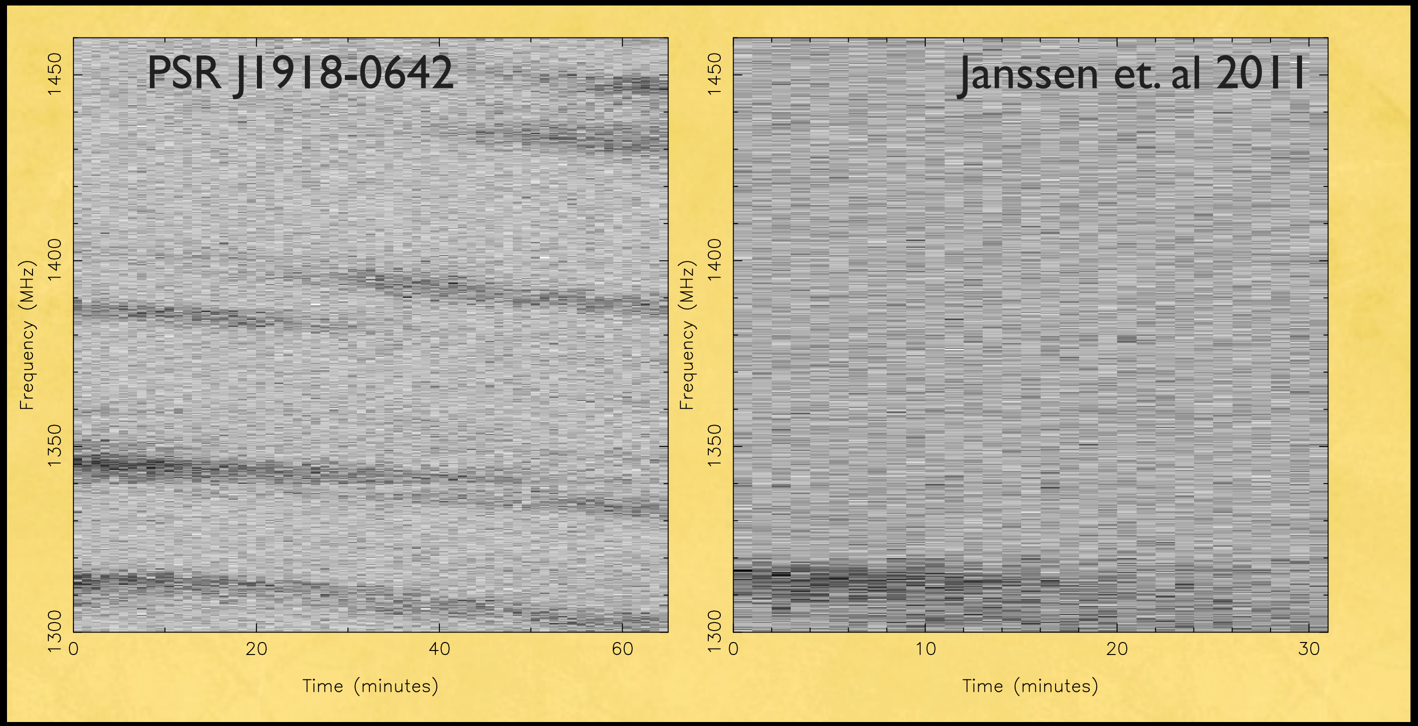
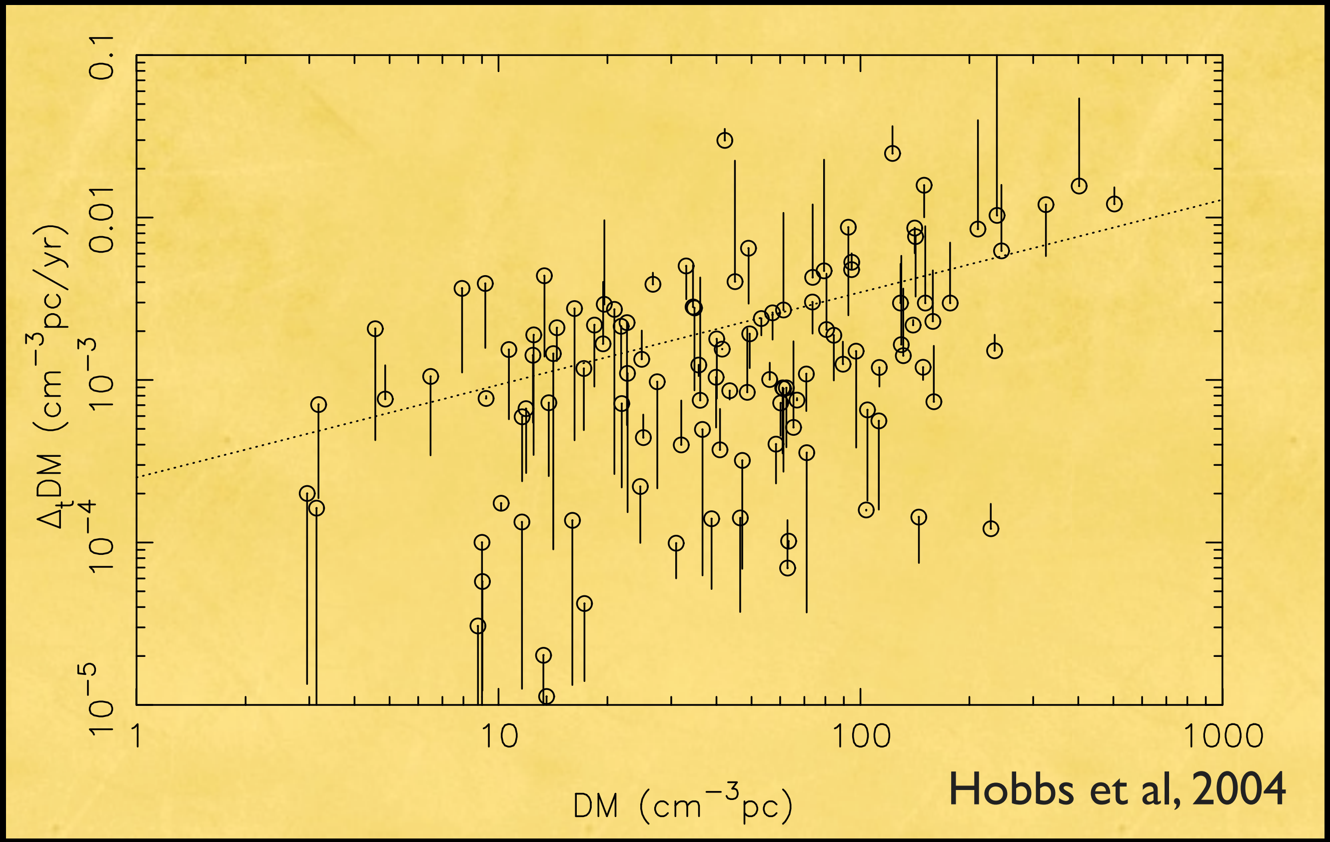
Scintillation ...





- scintiles -- blobs in time-frequency space
- scintillation can push signal out of band
- solution is to use very large bandwidths
- scattering - arise from diffraction/refraction
- can be used to model the ISM

Better DM estimates ...



- 274 pulsars, over 25yrs of data
- DM does change for some pulsars
- empirical fit ~ 0.57

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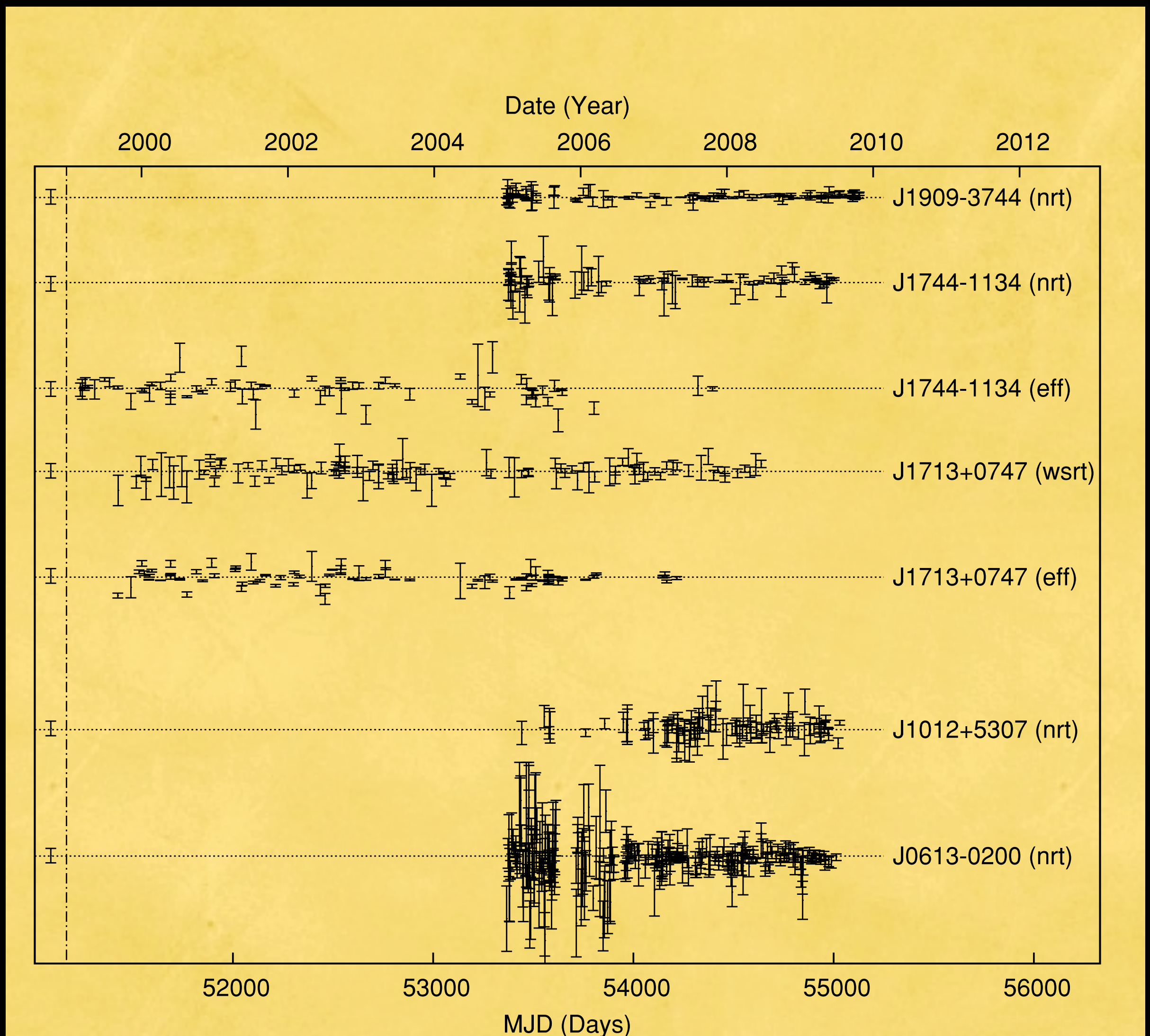
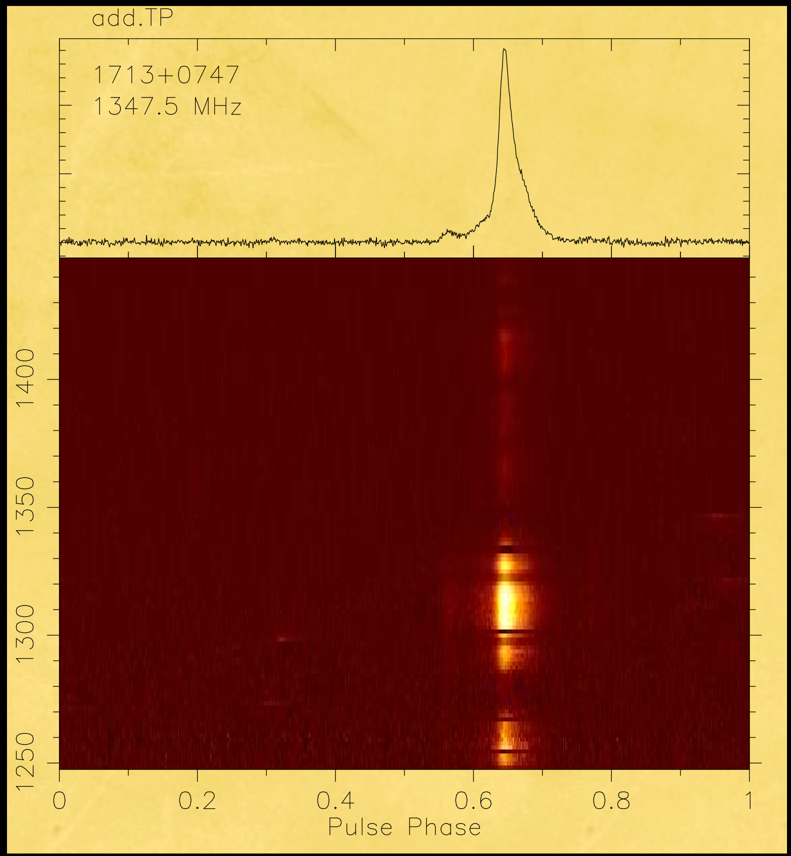
High precision timing



van Haasteren et. al , 2011

- current best limit on GWB $h_c = 6 \times 10^{-15}$
- many more pulsars with < 100ns residuals
- plus other tests of gravity!



Conclusions

- UBB receiver and backend are nearly complete
- System shows a great promise
- more issues are under control - RFI/Tsys
- At least ~2-3 improvement in EPTA residuals

Full Digital Approach