

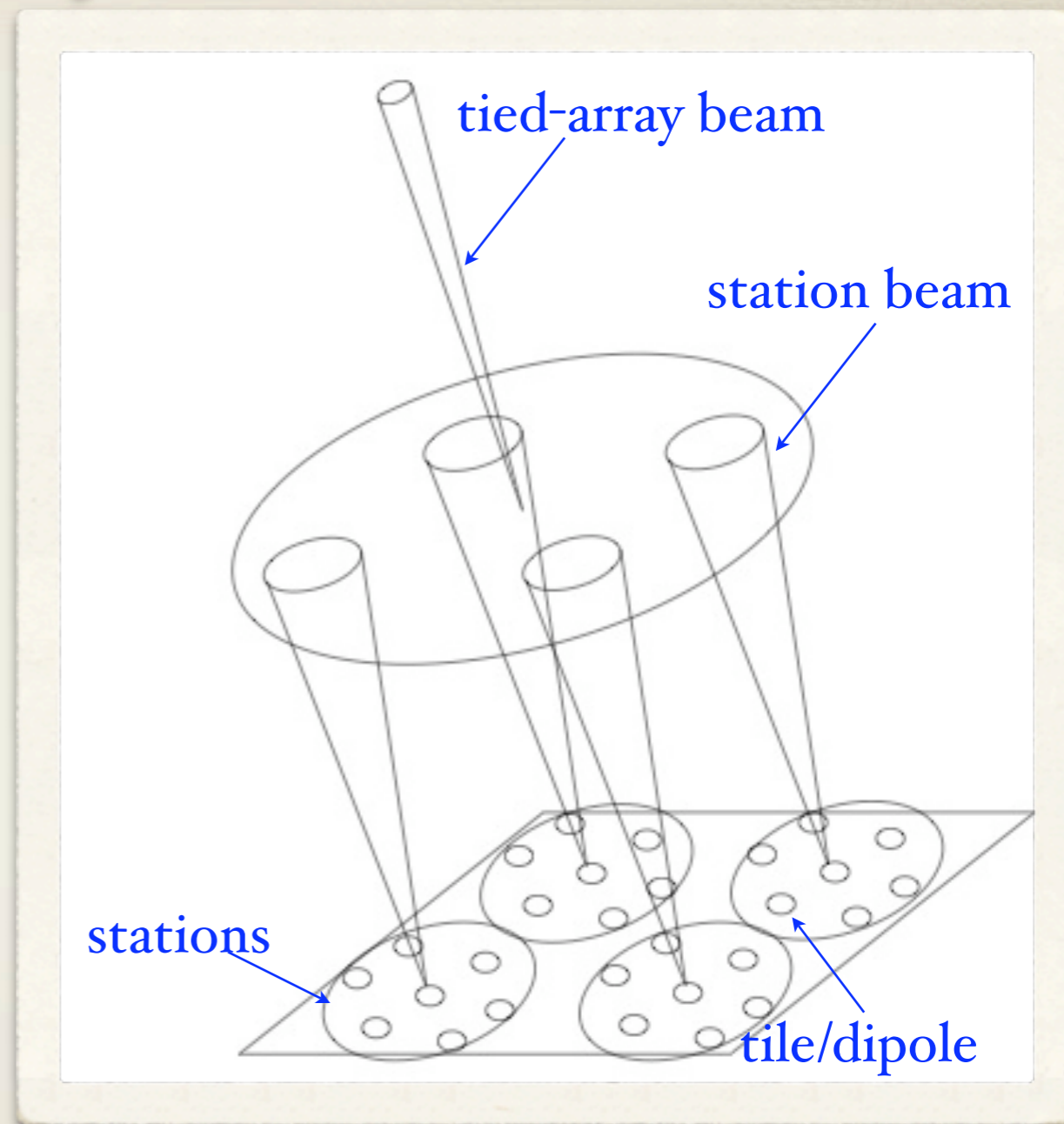
# NON IMAGING OBSERVATIONS WITH LOFAR

A brief look at timeseries data

Ben Stappers and the Pulsar Science  
Working Group

# Tied-Array Beam

- \* Sometimes also known as a pencil beam
- \* For pulsar surveys would like to “dump” data from the BG correlator every 50 us or so at about 20 kHz resolution.
- \* At least 10000 times the current output data rate!
- \* Effectively give up information from individual baselines to gain the higher time and frequency resolution.
- \* However in its vanilla mode it gives you a single very narrow beam on the sky!
- \* OK for a single source, not OK for pulsar surveys.



$$B = \sum_{i=0}^{N_{stations}} S_i w_i$$

$$\theta \approx \frac{60\lambda}{D_{core}} = 3.6'$$

# How do we increase the FoV?

- \* Form more beams, but to tile out the whole station beam is computationally demanding!

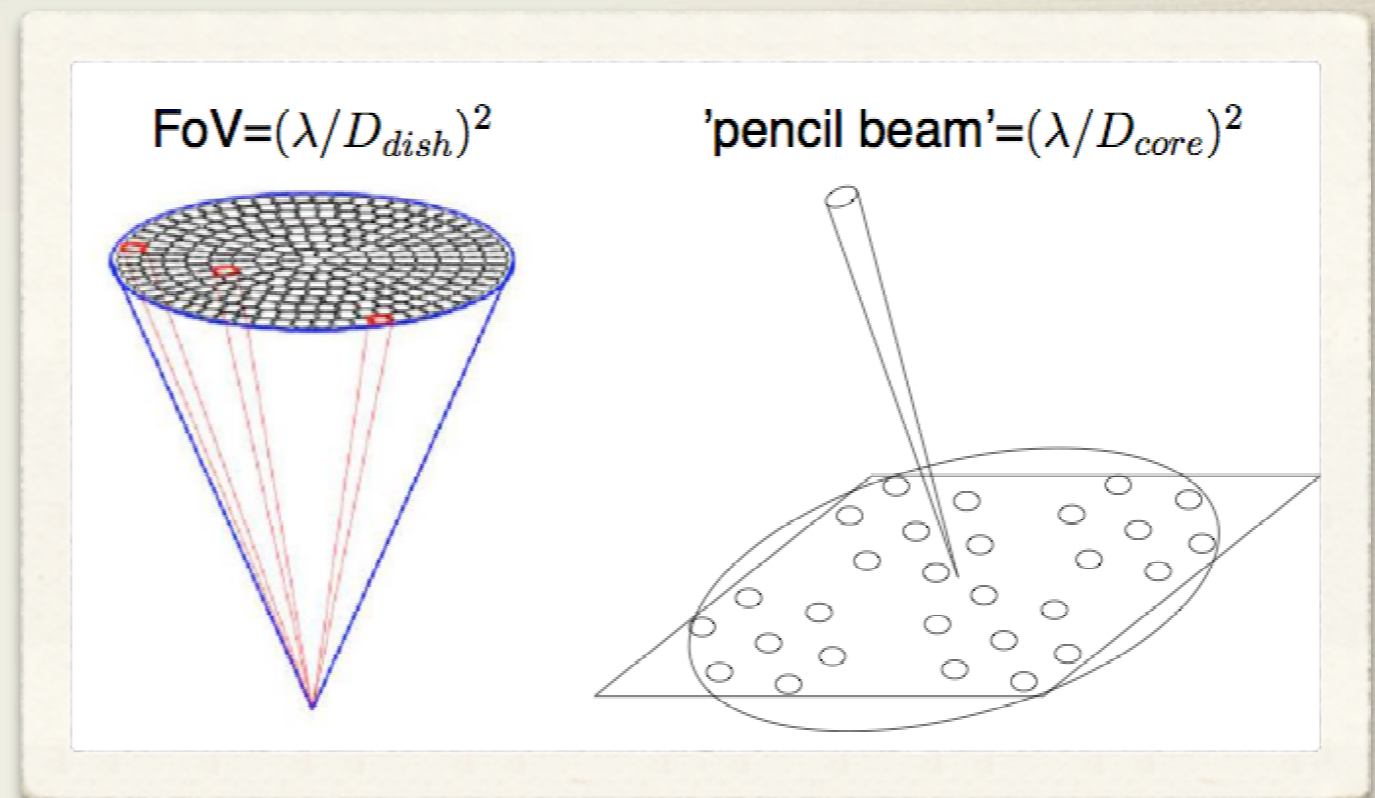
$$N_{pixels} = \left( \frac{D_{core}}{D_{station}} \right)^2 \approx 5000$$

$$B = \sum_{j=0}^{N_{pixels}} \sum_{i=0}^{N_{stations}} S_i w_{i,j}$$

- \* You also need to have a pulsar signal processing chain for each one!

- \* An alternative is to do an incoherent sum of the stations

$$B = \sum_{i=0}^{N_{stations}} |S_i|$$



- \* However lose sensitivity as:  $\sqrt{N_{stations}}$

- \* Can do a trade off between the two methods and find if we can form more than about 160 tied-array beams then we have a highly efficient pulsar survey.

# Dedispersion & the ISM

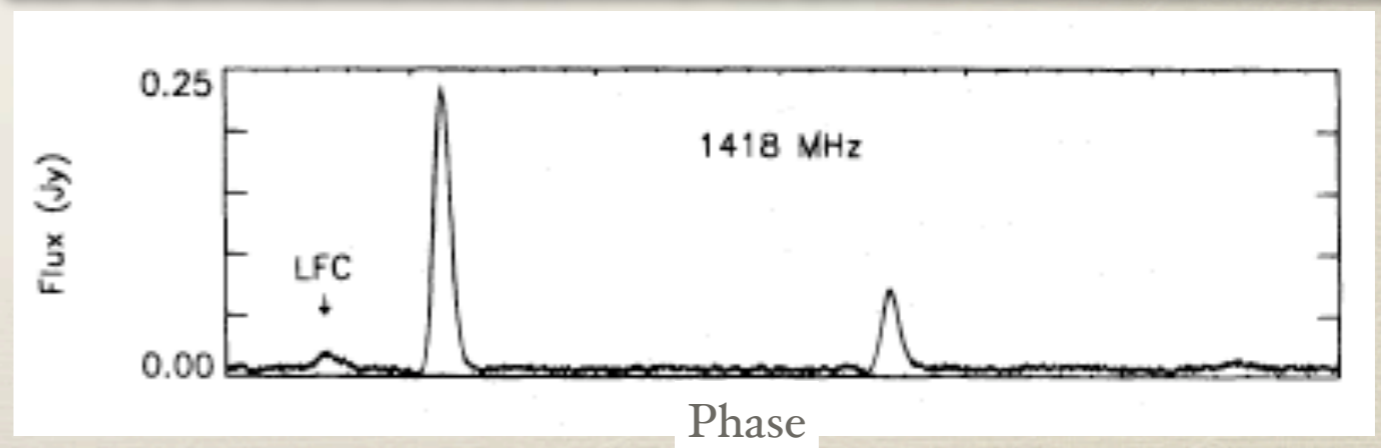
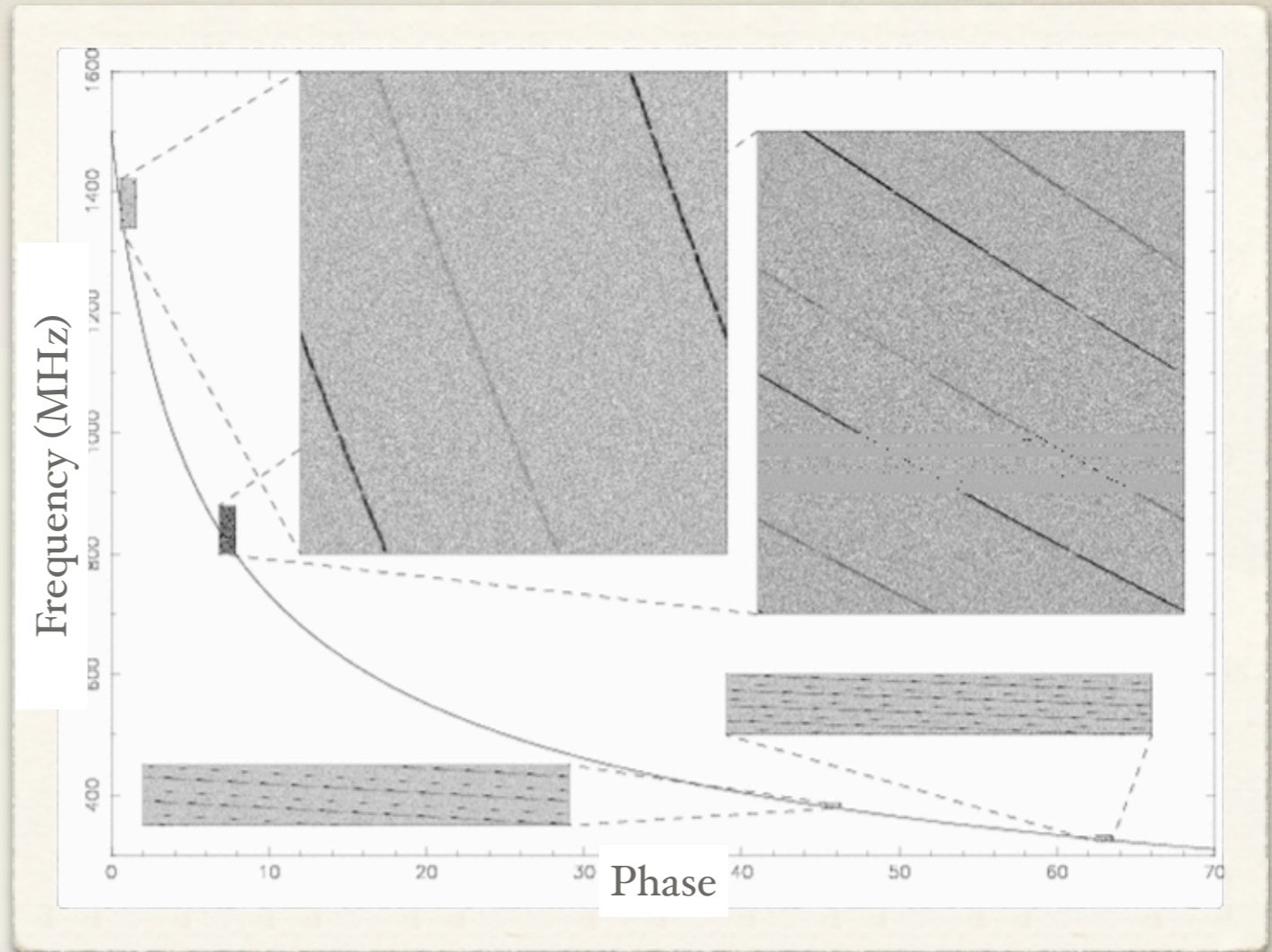
- \* Dispersion in the ISM is one of the main issues for the pulsar survey

$$\delta t = 8.3 \times 10^3 \frac{DM \times BW}{\nu^3}$$

Freq (MHz)	BW 32 MHz	BW 4 MHz	BW 200 kHz
150	7.8s	0.98 s	0.049s
25	1700s	212.7s	10.6s

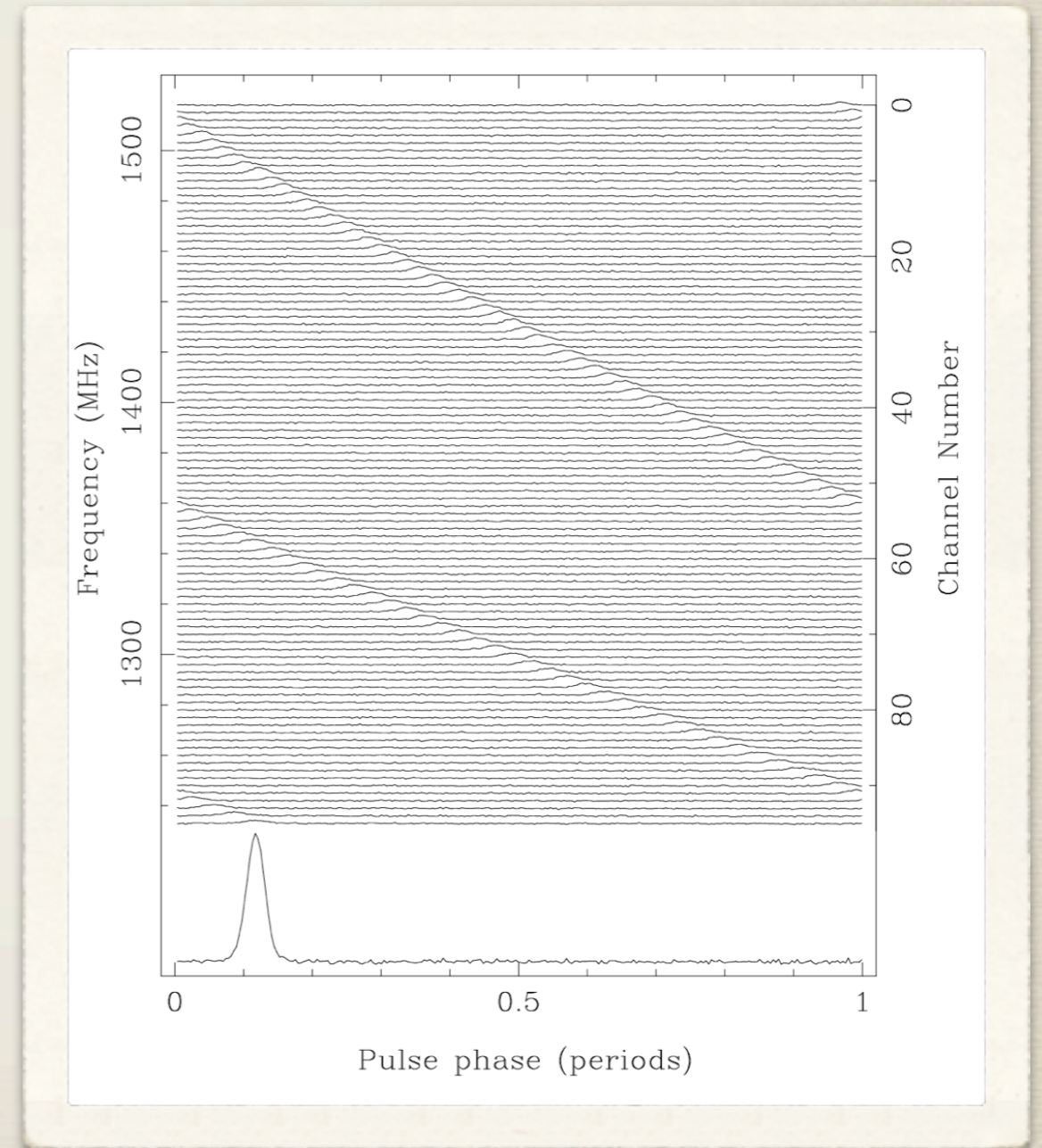
DM ~ 100 almost max

- \* Scattering is also a BIG problem but not something we can do about it ....YET.



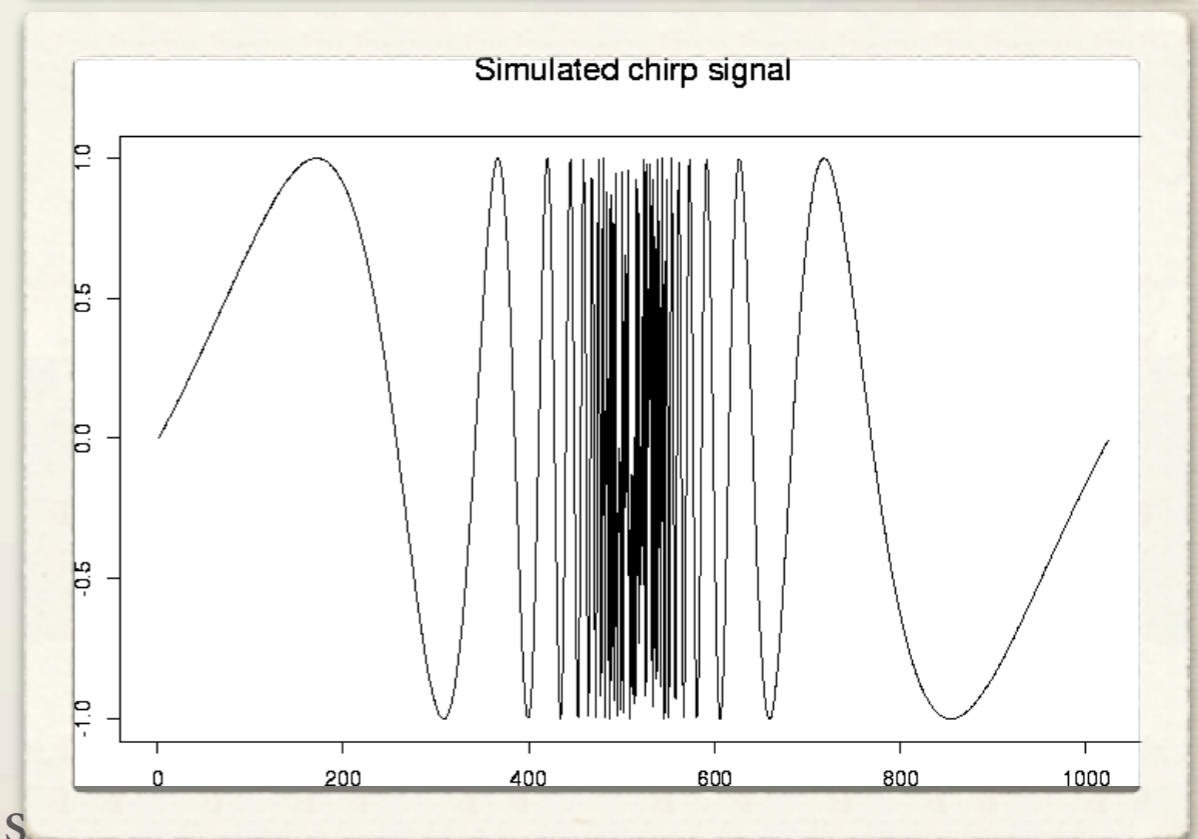
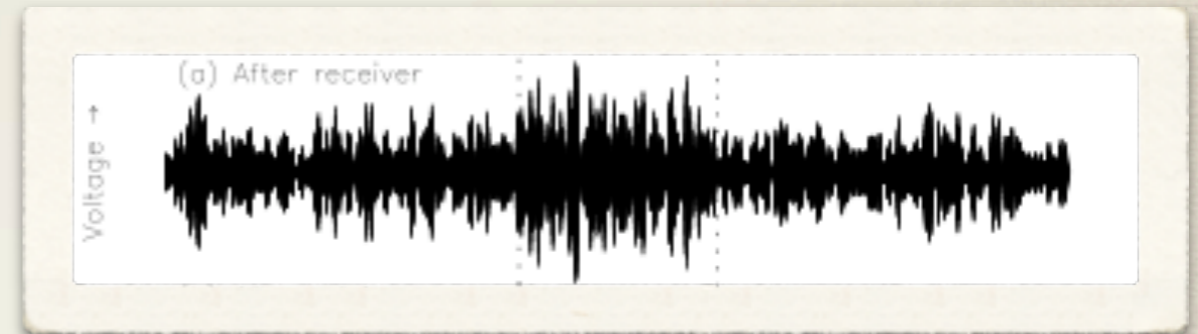
# Incoherent Dedispersion

- \* Traditional method is to break the data set up into a large number of fine channels.
- \* However there is a finite limit to this as the sampling time is proportional to  $1/(\text{channel BW})$
- \* With 32 channels across a 200 kHz subband we can reach a DM of 10 before the smearing equals the sampling rate
- \* Perhaps ok for surveys, but limits access to fastest pulsars.
- \* A hybrid approach may be needed.



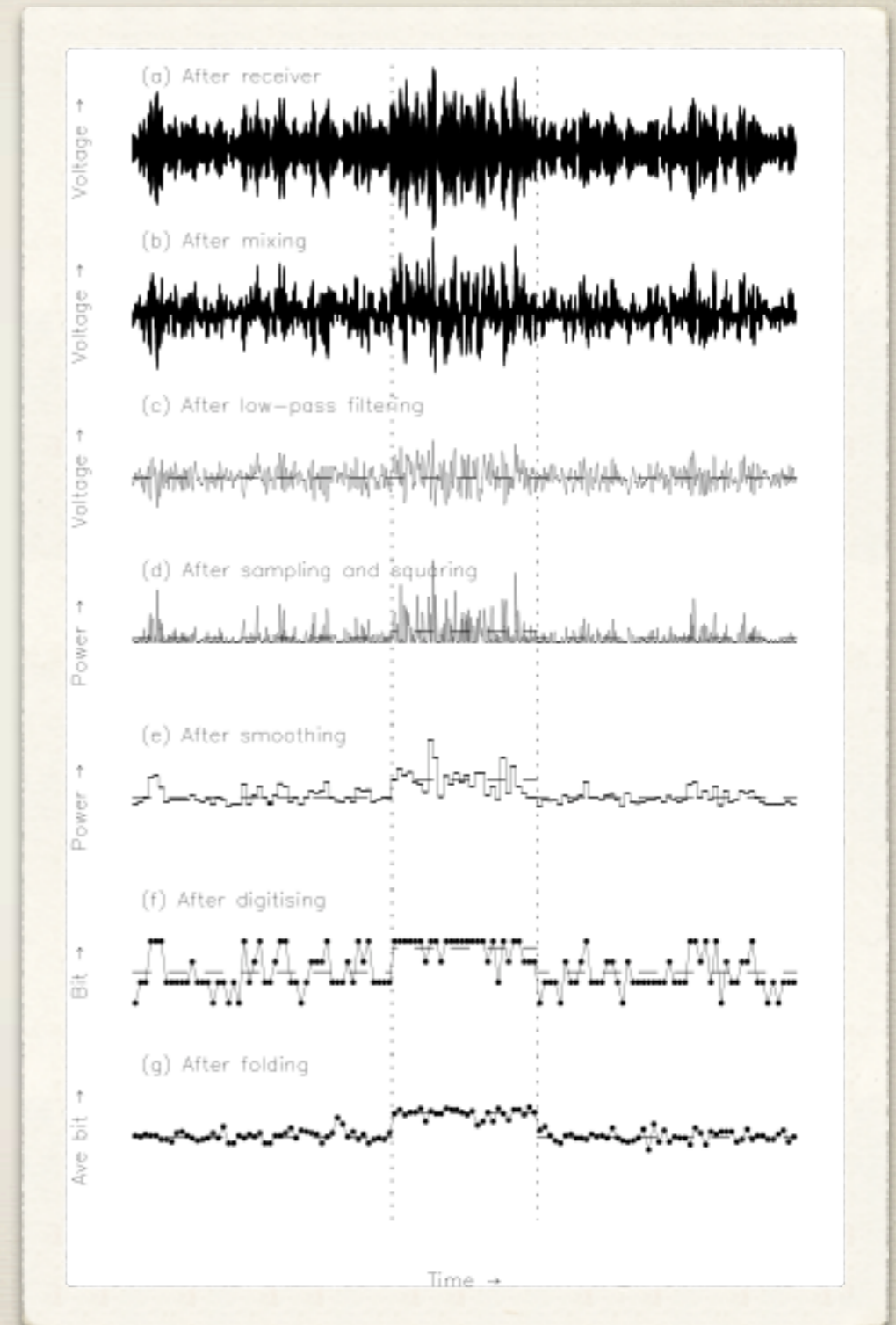
# Coherent Dedispersion

- \* The ISM can be modelled as a filter.
- \* Modifies the phase of the pulsed signal as it passes through it.
- \* Can model this as a so-called chirp function, one where the frequency varies with time.
- \* Applying this filter to the data “coherently” removes the dispersion delay
- \* Gives you back the timeseries with the same time resolution you put in.
- \* Computationally costly
- \* Applied regularly to known pulsar observations
- \* Not yet to surveys as need to do for all DMs!



# Time Domain Data

- \* Typically less interested in the spatial information
- \* Sacrifice this in order to get either/or higher time resolution
- \* Data usually comes as a cube of **time, frequency, polarisation**
- \* In native mode the maximum time resolution is  $1/\text{subband}$  ~ 5 microseconds
- \* With tricks can get to higher resolution
- \* Generally will apply an FFT to get to higher frequency resolution and sacrifice time resolution.
- \* Greater RFI rejection capabilities
- \* Essential for dispersion correction.



# Two Major Observing Modes

## Survey Mode

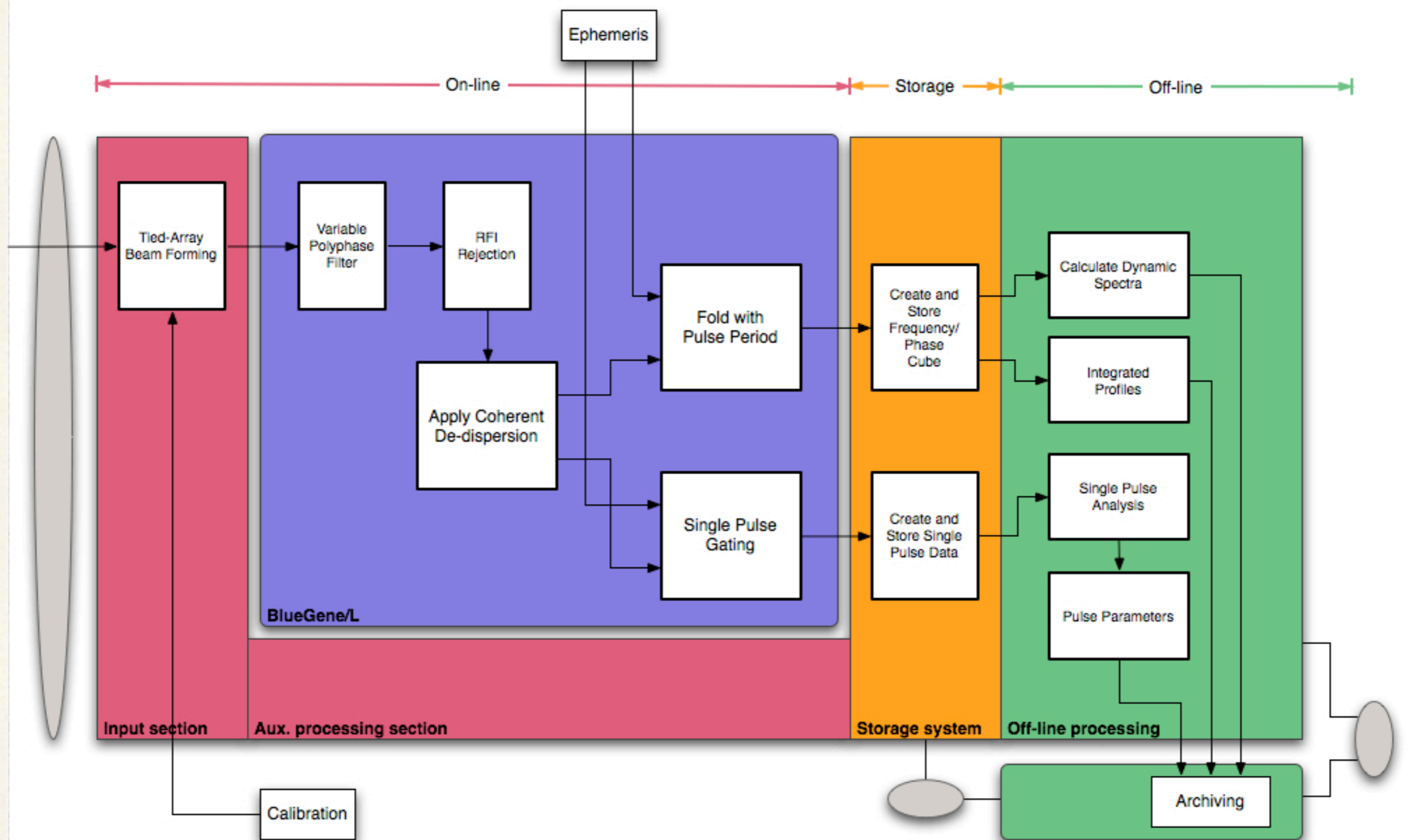
- \* Observe the entire sky at least once to search for new pulsars and other radio emitting neutron stars
- \* Large number of beams on the sky so many signal chains
- \* Requires high time and frequency resolution
- \* Will use incoherent dedispersion
- \* Significant computational load on both BlueGene and offline cluster if using multiple tied-array beams

## Known Pulsar Mode

- \* Observe large numbers of known pulsars to determine their pulse characteristics, spectral and timing properties
- \* Typically only one, or a handful of objects observed at once
- \* May require higher time and frequency resolution than survey mode
- \* Will use coherent dedispersion
- \* Modest computational load on BG and on offline cluster



# Known Pulsar Mode



# Calibration: Phases & Clocks

\* One of the key aspects of the tied-array mode is that we need to sum the station signals in phase.

\* This means that we need to correct for:

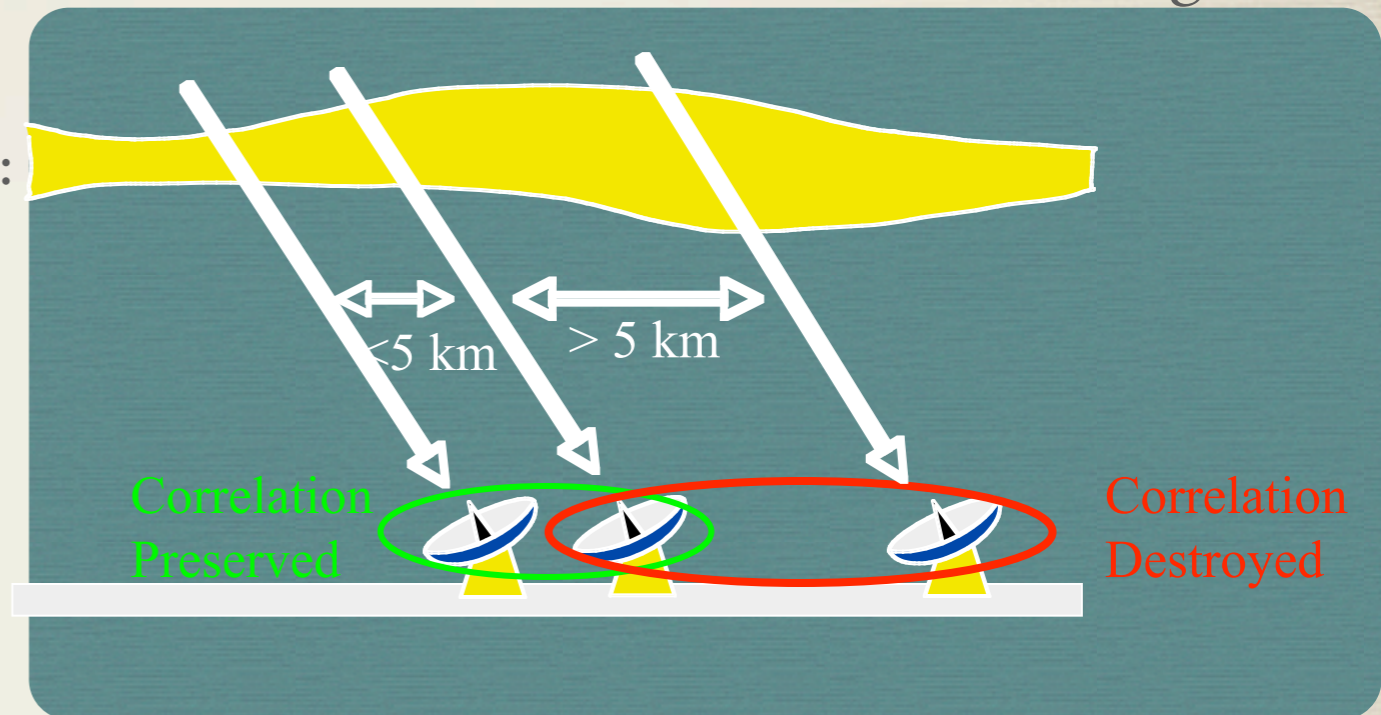
\* geometric phase “easy”

\* instrumental phase “stable?”

\* ionospheric phase “hard”

\* clock “phase” “??”

simultaneous  
imaging data



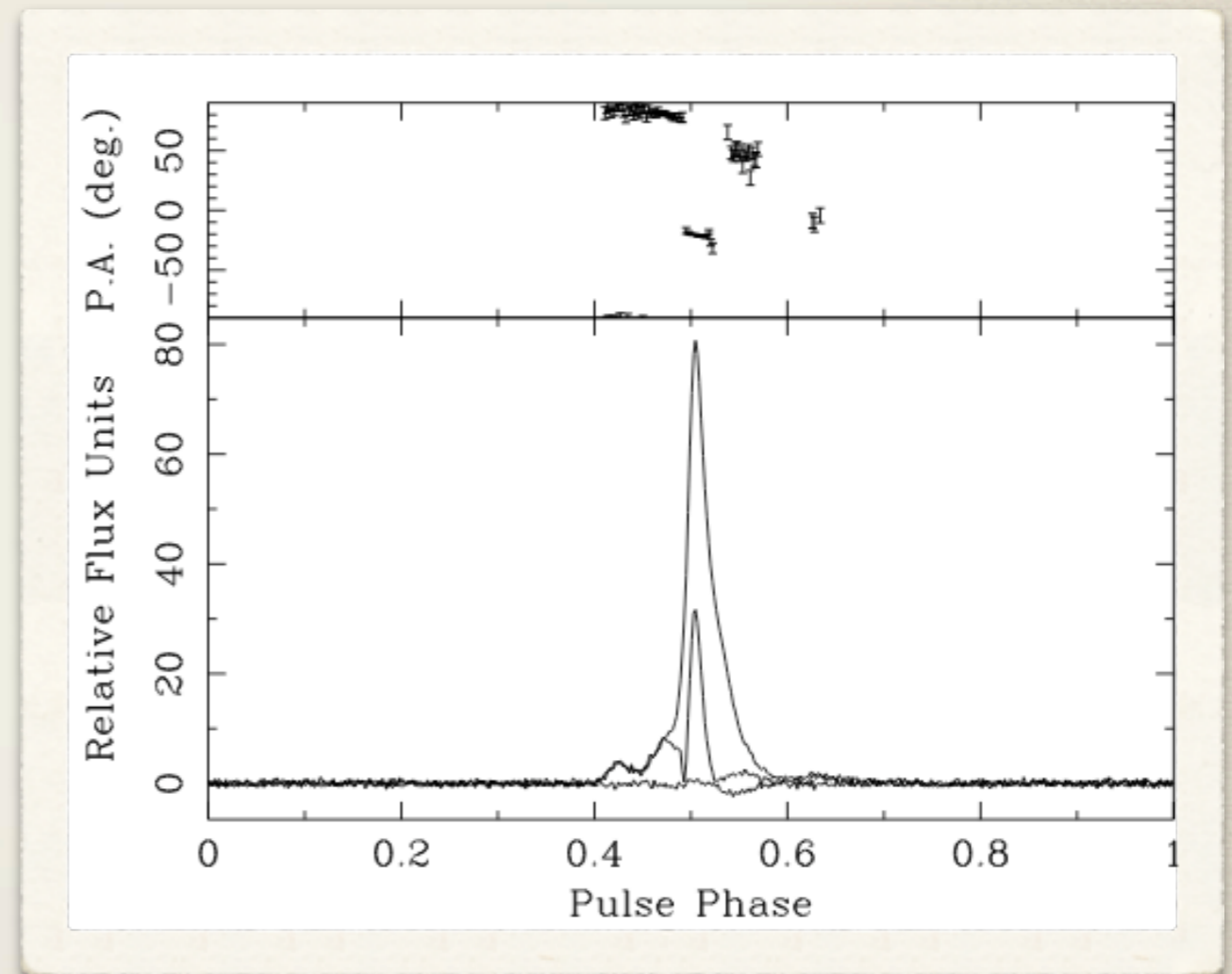
\* This requires that we be able to track these phases during the observation

\* Need to do it in real, or close to real, time as we cannot correct for this after as we have already formed the sum.

\* Observations with the WSRT in the HB frequency range show that it is possible to calibrate relatively infrequently, but we have not yet done a detailed study of the degree of correlation, or coherent summing, as a function of time. Difficult as pulsars are not stable flux sources.

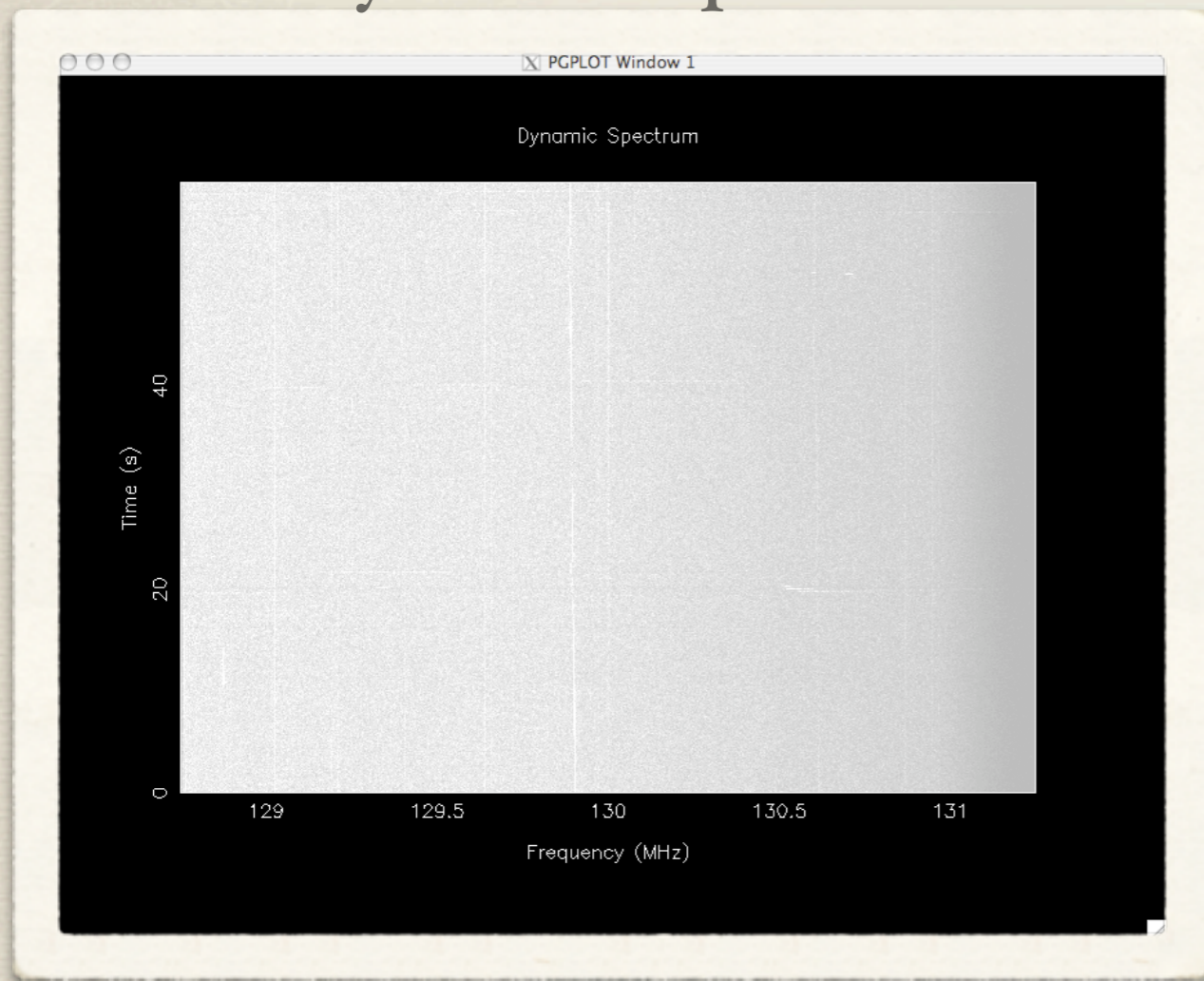
# Polarisation

- \* We want to study polarisation for three main reasons:
  - \* Pulsar properties
  - \* RM studies in the ISM
  - \* Calibration sources
- \* Requires an extra layer on top of the phasing up procedure
- \* Work in close collaboration with the magnetism KSP.



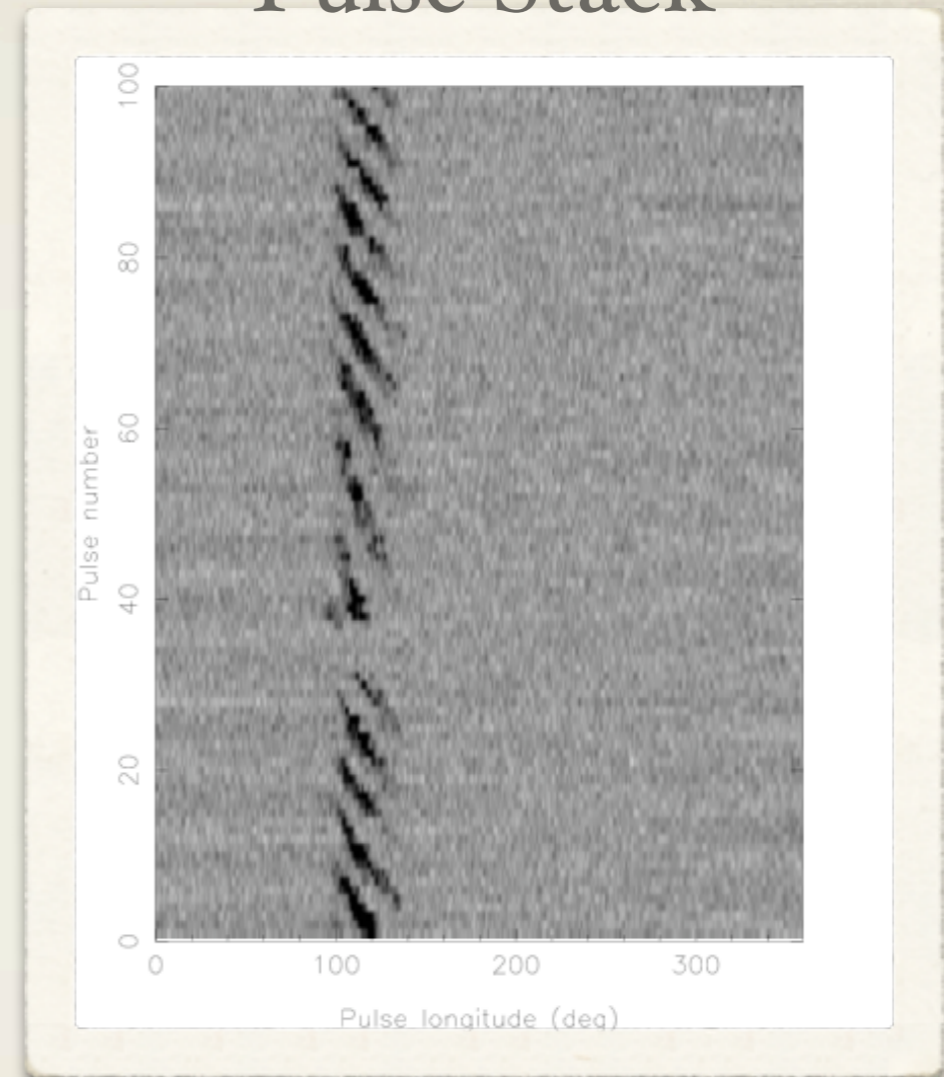
# Data Products

## Dynamic Spectra



- \* Useful for RFI studies
- \* Studies of ISM
- \* Also useful for Flare Stars/Planets

## Pulse Stack

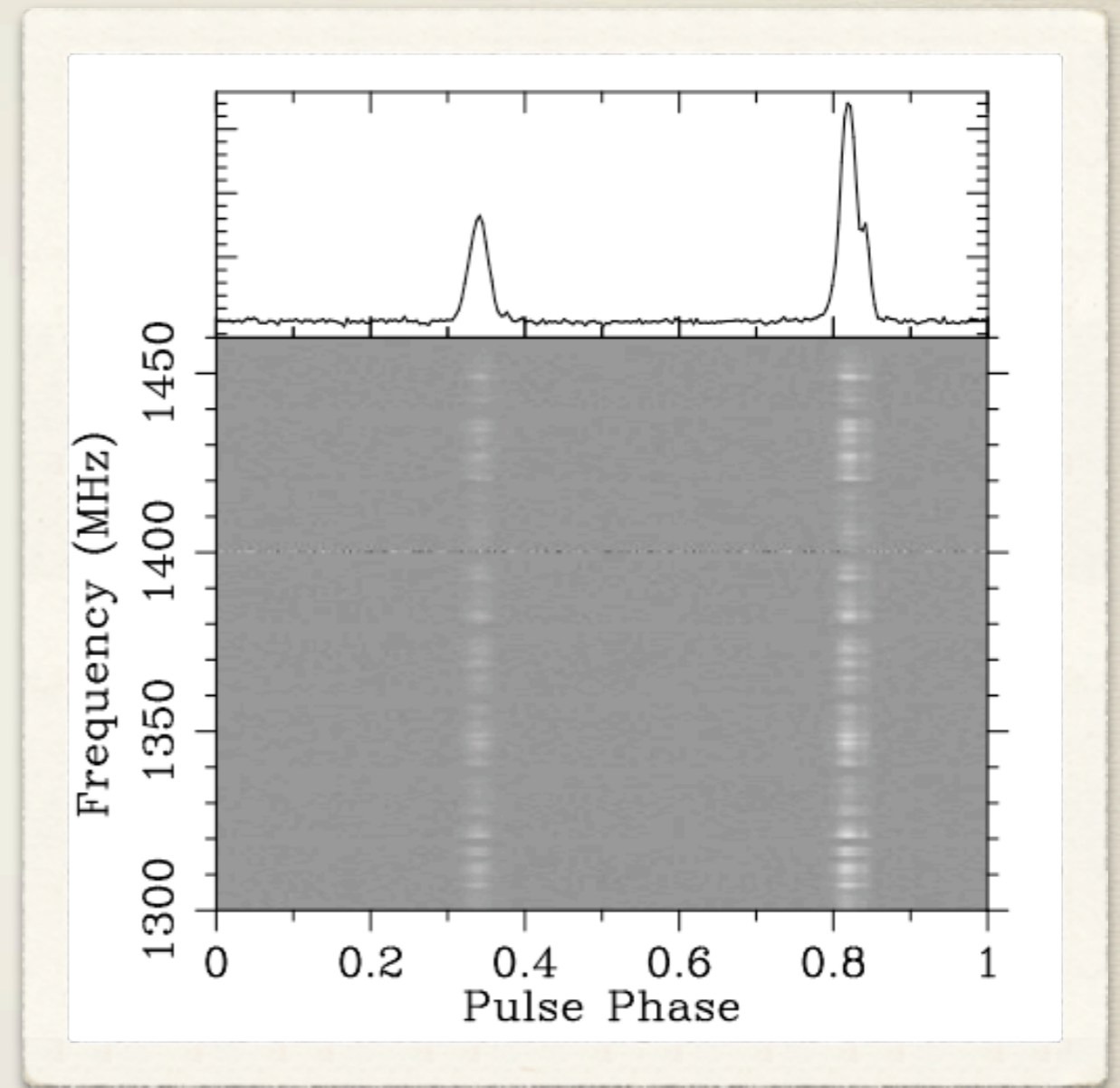
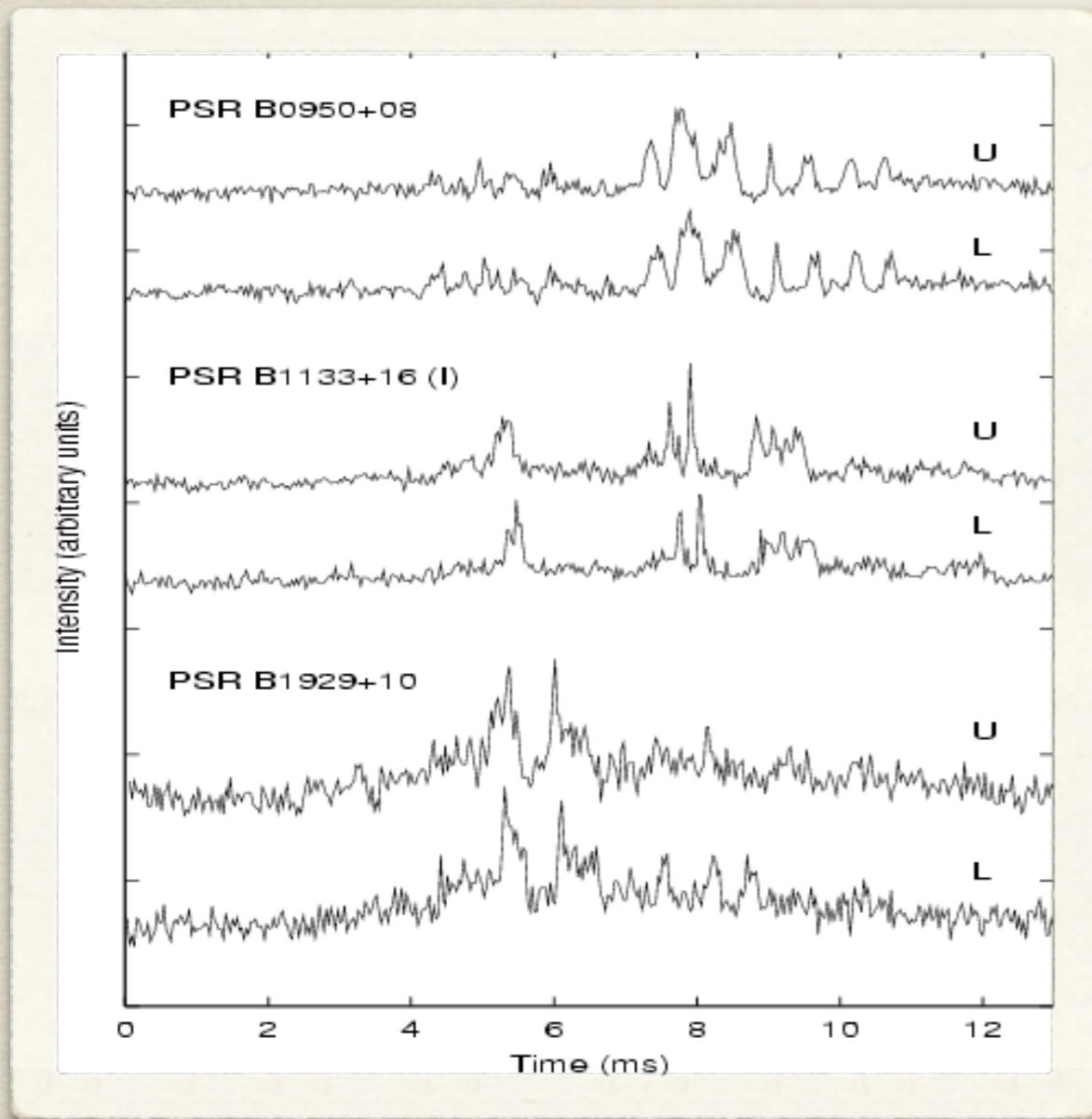


- \* Properties of the individual pulses
- \* Variations such as nulling/drift
- \* Also identify mode changes

# Data Products

Very High Time Resolution

Timing Observations



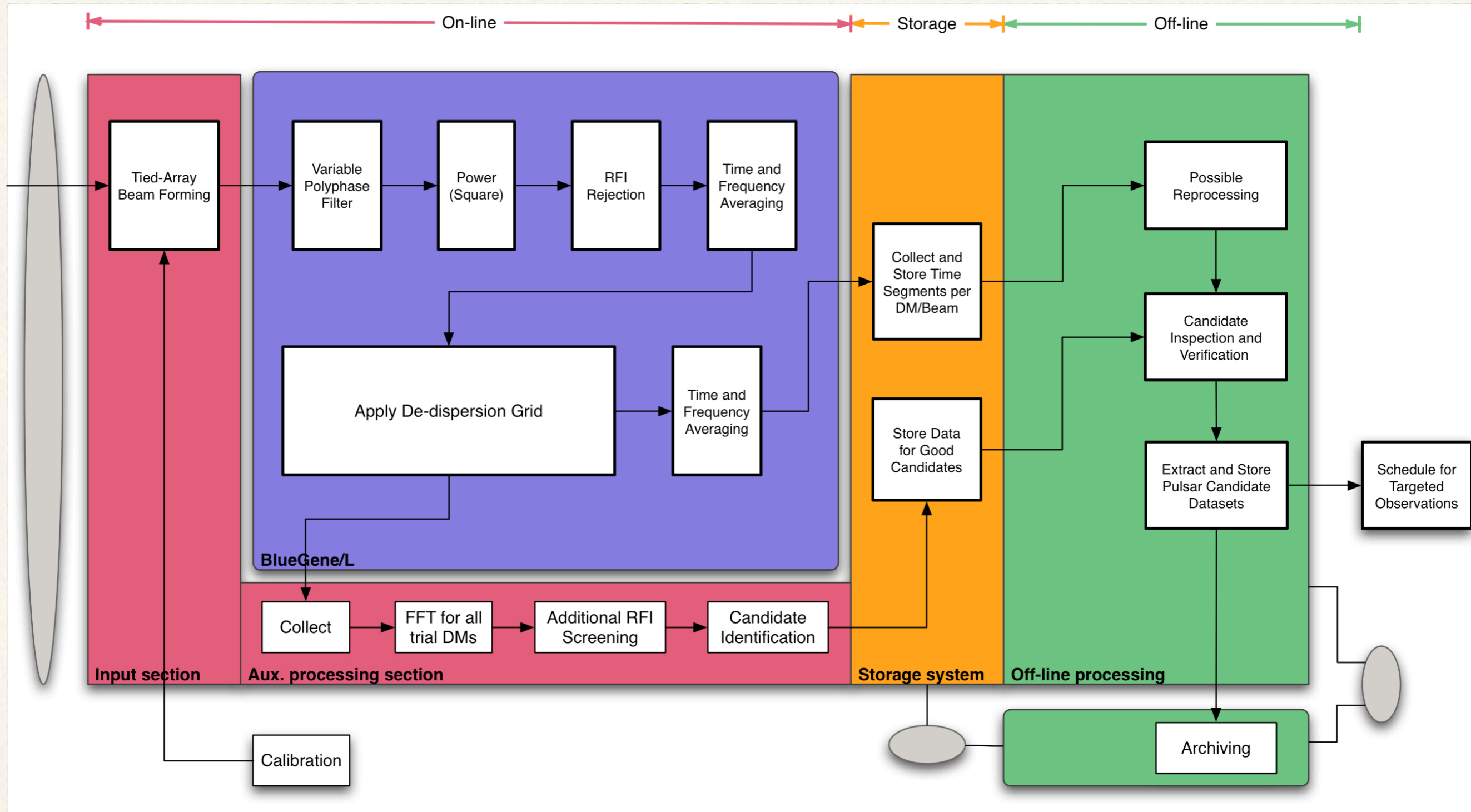
\* Study effects below microseconds that are seen in pulsars

\* High SNR observations of pulsars to measure the pulse time or arrivals and thus use them as clocks.

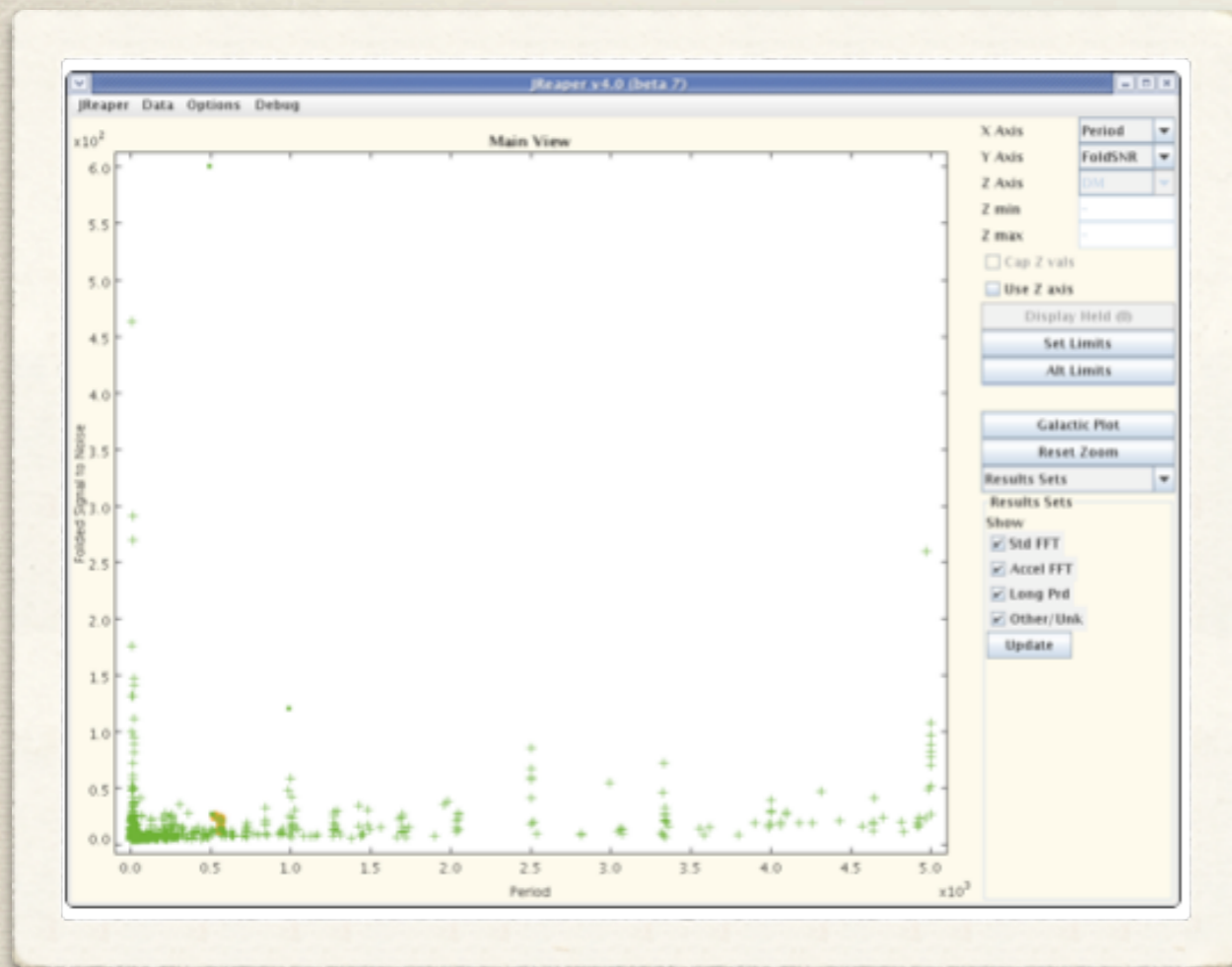
# Processing & Data Rates

- \* In general it will be a lower data rate as we will typically not need as high time/frequency resolution.
- \* However we can consider a maximum which would be a “baseband” observation to obtain the highest time resolution possible.
- \* This would be 162 channels each of 195.3 kHz in width, Nyquist sampled and 2 polarisations. As the coherent dedispersion will already have been done on BG the data will have expanded to be floats. Data Rate = 506 MBytes/s (cf. Current pulsar machine on WSRT receives 640 MBytes/s).
- \* This needs to be multiplied by the number of beams we might want to observe simultaneously, but it will typically only a handful.
- \* In general data rates will be factors of 10 lower than this.
- \* Processing power will also be low as majority of processing done on BG. Will be of the order of a dozen processors or so, small compared to survey requirements.

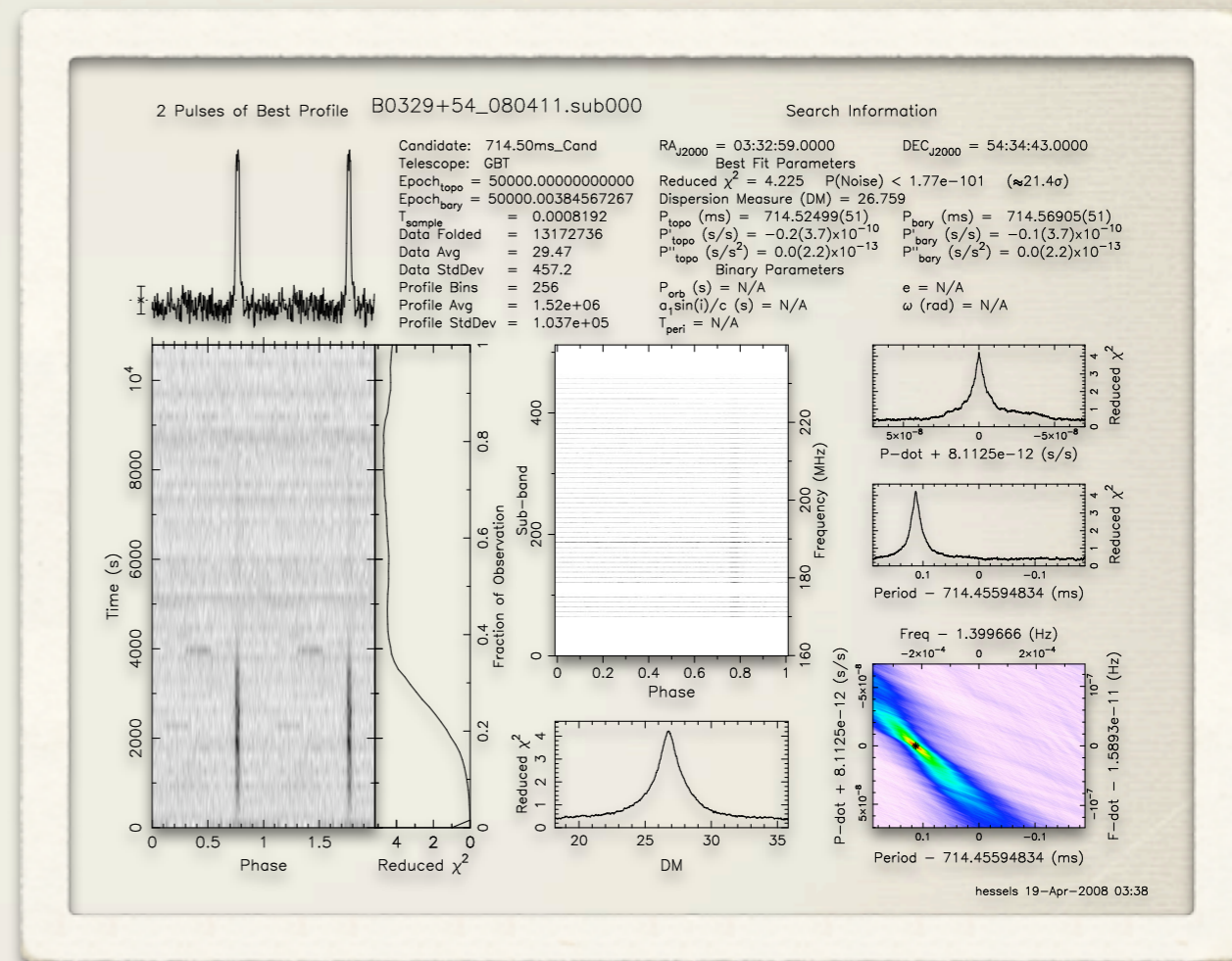
# Pulsar Survey Mode



# Data Products



\* Lots of pulsar candidates!



\* New pulsars!!!!



# Processing & Data Rates

- \* Assume a total bandwidth of 4 beams and 8 station beams on the sky
- \* 22 subbands, each divided into 32 channels with 150 us sampling = 8 MBytes/s/SB
- \* Total Data Rate for just 8 station beam signals is 32 MBytes /s
- \* But we want as many Tied-Array beams as possible: BG/P max output/rack ~ 50 Gbits/s, typical 10 minute pointing is thus 3.7 Tbytes.
- \* Perhaps can move some of the processing to the BG/P but needs to be a lot because the dedispersion stage actually expands the amount of data significantly.
- \* There is potential for processing this data in real time on the “offline” cluster though.

# Processing & Data Rates

$$N_{\text{oa}} = N_{\text{DM}} N_{\text{acc}} \times 5 N_{\text{samp}} \log_2(N_{\text{samp}})$$

- \* Assume again pointings of about 10 minutes, or  $N_{\text{samp}} = 2^{16}$
- \*  $N_{\text{acc}}$  is the number of accelerations and applies to binary searches, which for now we will ignore
- \* The number of trial dispersion measures we need to use is still to be determined fully but is likely to be of the order of 1,000.
- \*  $N_{\text{oa}} = 5.2$  Gops per beam.
- \* If we now also take into consideration a possible 200 beams or so then you see that we get into the realm of Tops.
- \* This is small compared to the SKA, and doesn't need to be in real time!

# Commissioning: Piggy Backing on MS<sup>3</sup>

- \* MS<sup>3</sup> provides an excellent platform to also commission many aspects of the pulsar processing pipeline
- \* For very low computational cost in BG it is possible to form the incoherent sum of the available stations simultaneously with obtaining the MS<sup>3</sup> data.
- \* The resultant signal can then be passed to our pulsar survey software, testing the dedispersion algorithms, interference rejection algorithms, search algorithms, processing speed etc....
- \* Not the only commissioning time needed as ultimately need to implement the full tied-array mode with the resultant multiplication in data rates etc...
- \* Some of this may be possible when MS<sup>3</sup> is not observing.
- \* However provides an excellent starting point and will also tell us a lot about the existing Northern hemisphere pulsar population.

# Conclusions

- \* The Tied-Array mode provides some additional challenges for LOFAR signal processing
- \* However it enables a large range of science not only radio pulsars but amongst other things; known radio transients, e.g. XRBs, flare stars, planets, both solar and extra-solar, and the Sun.
- \* If you have some projects requiring only timeseries data then come and talk with us, the Pulsar SWG in the Transients KSP, Jason, Joeri and me and we can make sure that the tools that are being developed can incorporate your requirements. Or at least we will commission you to provide those tools!
- \* The MS<sup>3</sup> will allow provide an excellent opportunity to commission aspects of the timelines for pulsars, and other short timescale variable sources.
- \* More details of where we are now will be presented by Jason in the following talk.