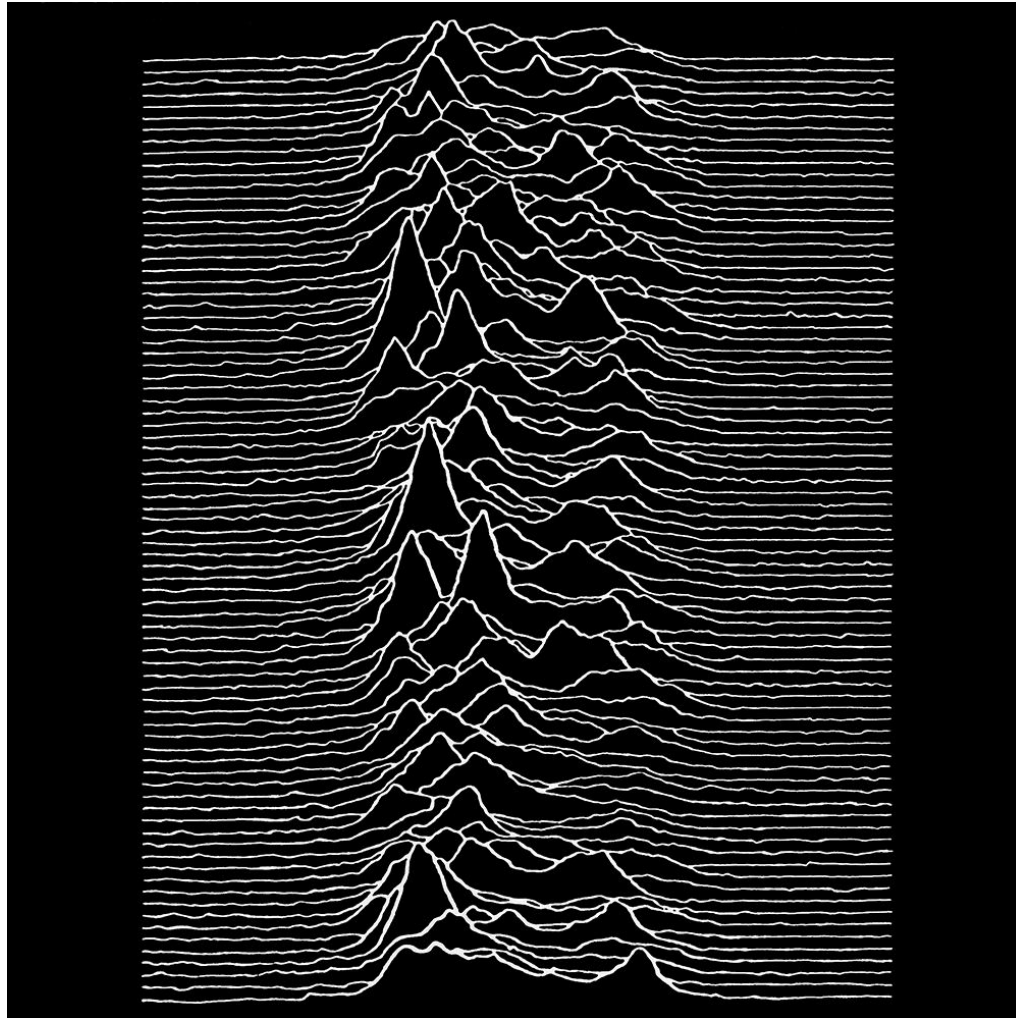


Phasing-up the EVN with SFXC

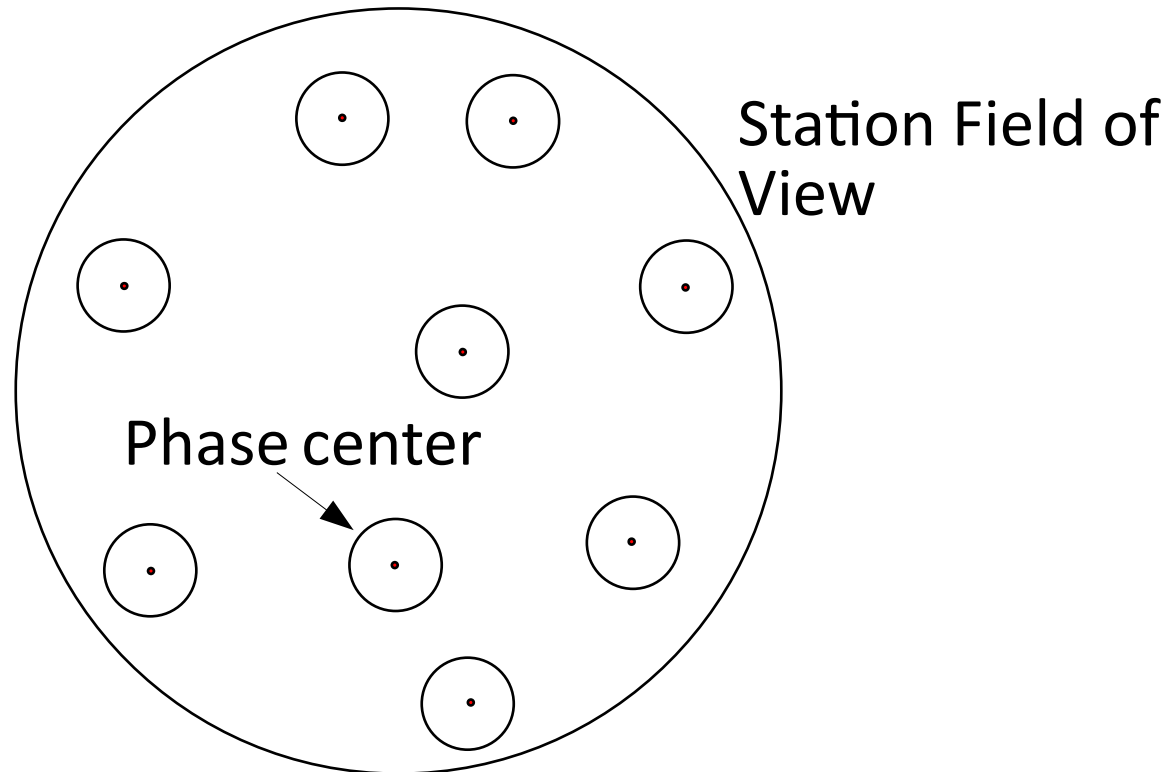
Aard Keimpema (keimpema@jive.nl)



SFXC

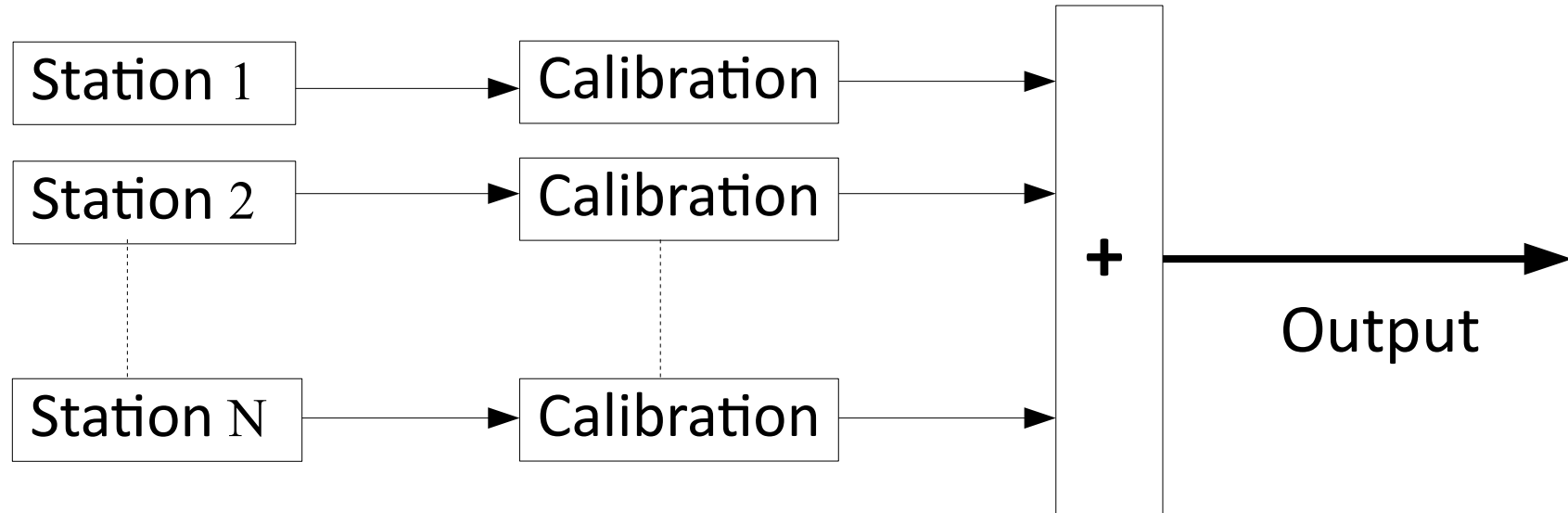
- Software correlator developed and maintained at JIVE
- Used for all correlation at JIVE
- Supported features include
 - Multiple simultaneous phase centers
 - Mixed bandwidth correlation
 - Pulsar binning / gating
 - **Coherent de-dispersion**
 - **Phased array mode**
- Licensed under the open source GPL v2 licence
- Available from the JIVE wiki
 - *<http://www.jive.nl/jivewiki/doku.php?id=sfxc>*

Multiple simultaneous phase centers



- Internally correlate at high temporal / spectral resolution
- Output a narrow field data set for each source in the beam
- On average 50% slowdown but each additional phase center comes at very little additional cost

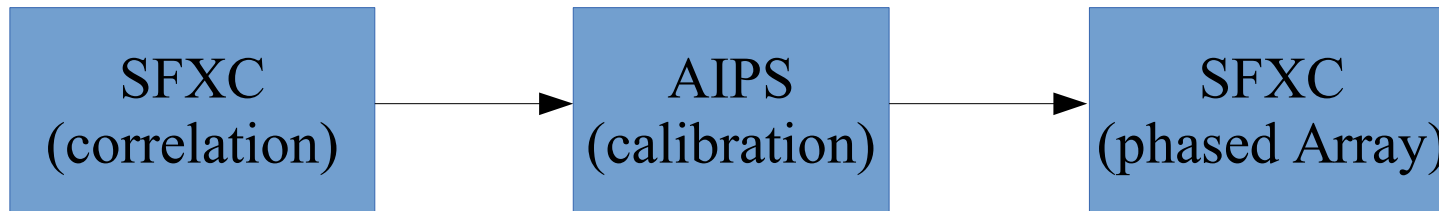
Phased Array Mode



- Phased array mode : coherently sum station signals
- SNR is proportional to total collecting area in the array
- Time domain pulsar science
 - Pulsar searching
 - Pulsar timing
 - Scintillation studies

Calibration

- Before signals can be coherently summed, phase and amplitude calibration solutions have to be provided

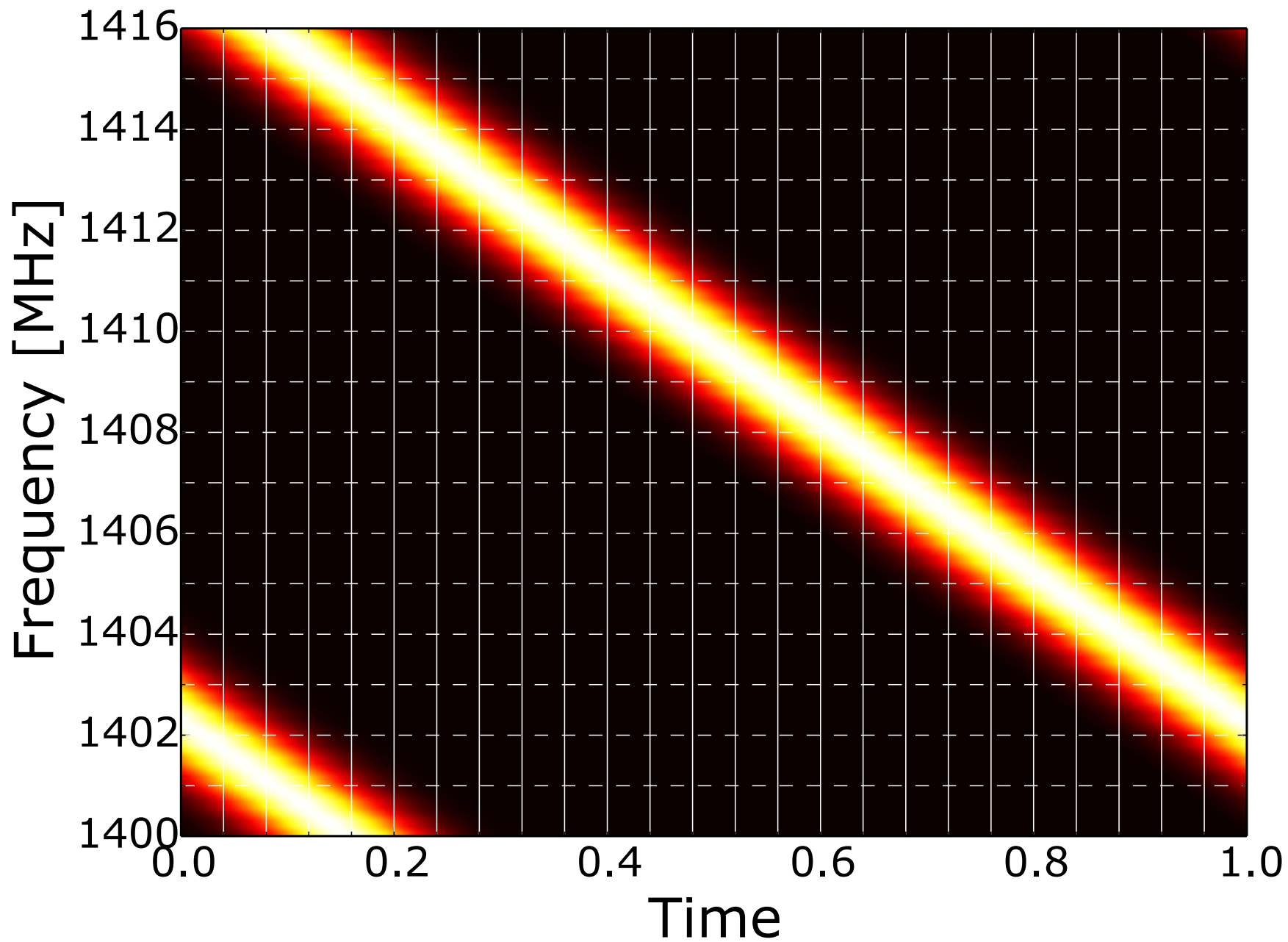


- Two pass process, data is first correlated like a regular VLBI experiment and the usual data reduction steps are performed in AIPS.
- Calibration (CL) and bandpass (BP) tables from AIPS are exported back to the correlator.
- Bad frequency channels are masked in BP table
- Calibration tables are then applied within SFXC.

Search mode data

- Compute power spectrum and accumulate this for short integration time

Search mode data



Search mode data

- Compute power spectrum and accumulate this for short integration time
- Output to either 8 bit PSRFITS or 32 bit SIGPROC filterbank format
- Data is re-quantized during conversion from single precision floating point to 8 bits
- Output from SFXC can be directly used in pulsar search toolkits such as SIGPROC and PRESTO

Implementation

- Search mode data can be computed from interferometric data

$$\begin{aligned} |f_1 + f_2 + \dots + f_n|^2 &= \sum_{i=0}^n |f_i|^2 + \sum_{i \neq j} f_i^* f_j + \sum_{i \neq j} f_i f_j^* \\ &= \sum_{i=0}^n |f_i|^2 + 2 \Re \left(\sum_{i \neq j} f_i f_j^* \right) \end{aligned}$$

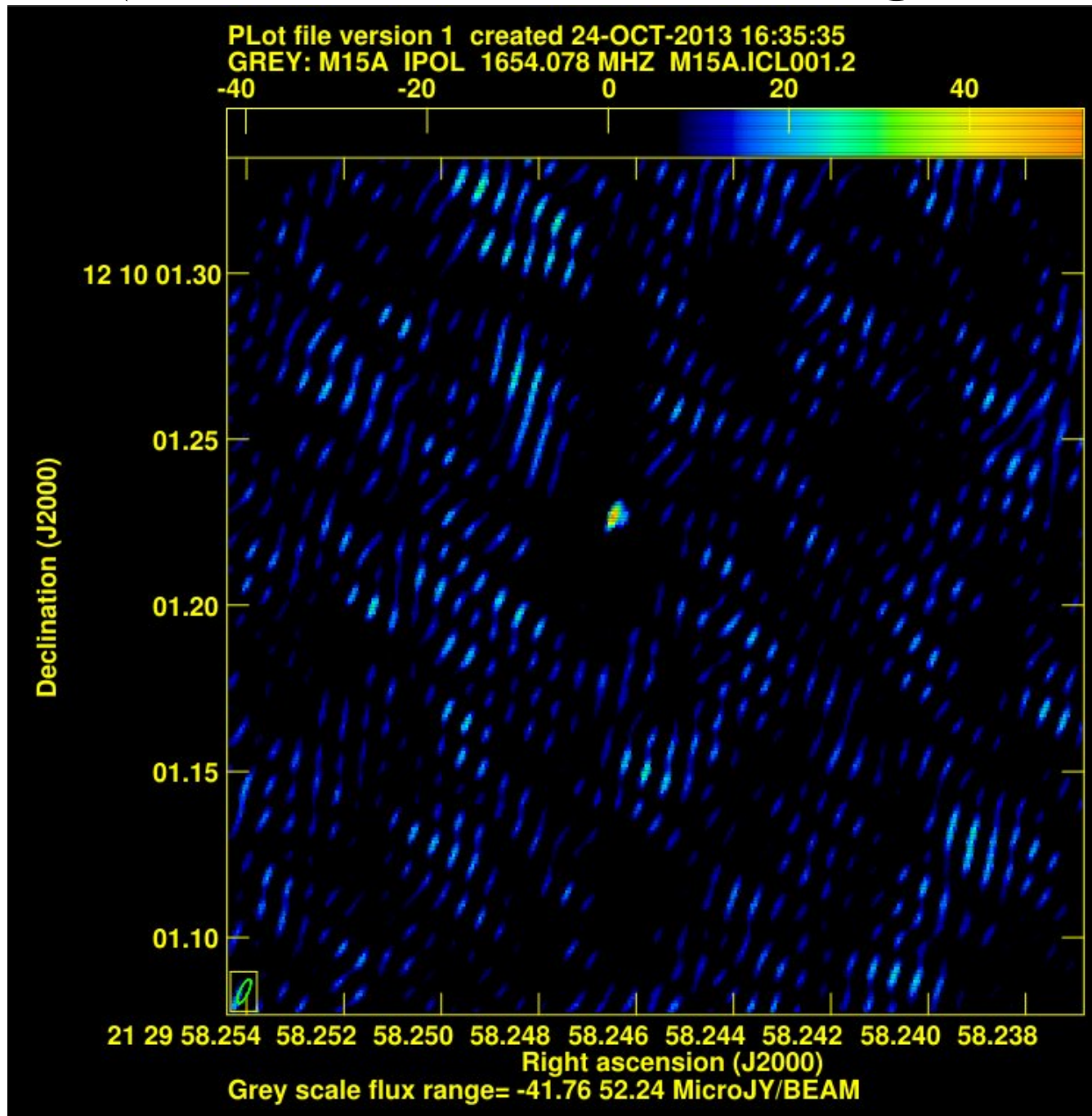
- **Efficient multiple phase center mode**
- Auto-correlations need online RFI mitigation
- Only cross terms are used
- SNR asymptotically approaches true phased array SNR

$$SNR_{true} \propto A \cdot N$$

$$SNR_{cross} \propto A \sqrt{N(N-1)}$$

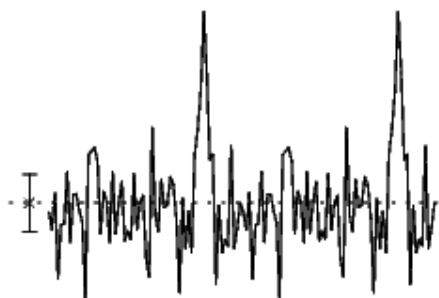
N = number of stations
A = area of antenna

M15A (Kirsten, Vlemmings, et al.)



Stations = Jb, Gb

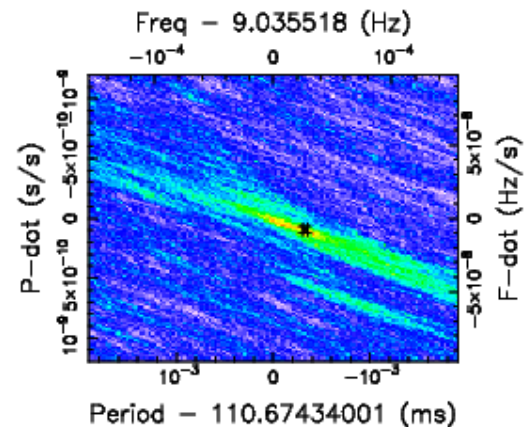
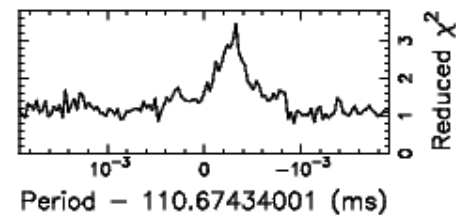
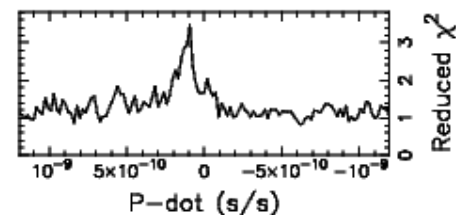
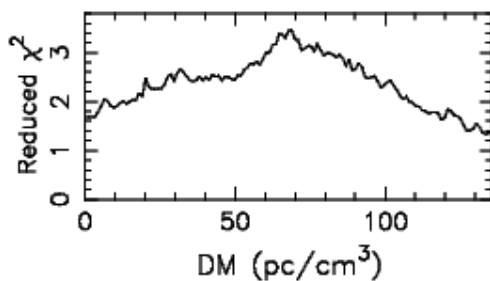
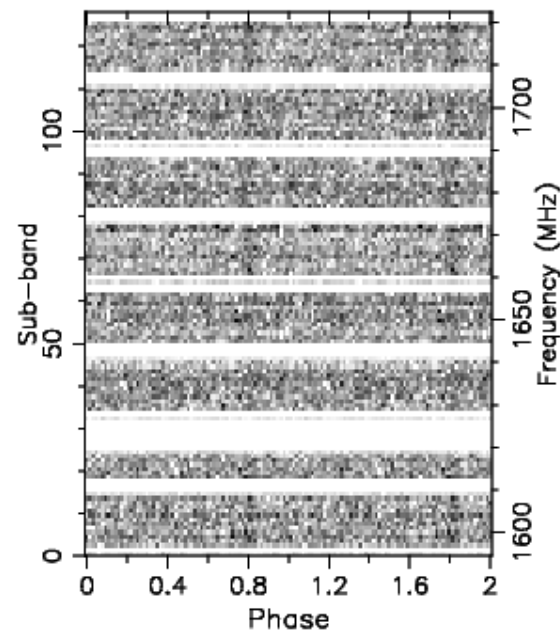
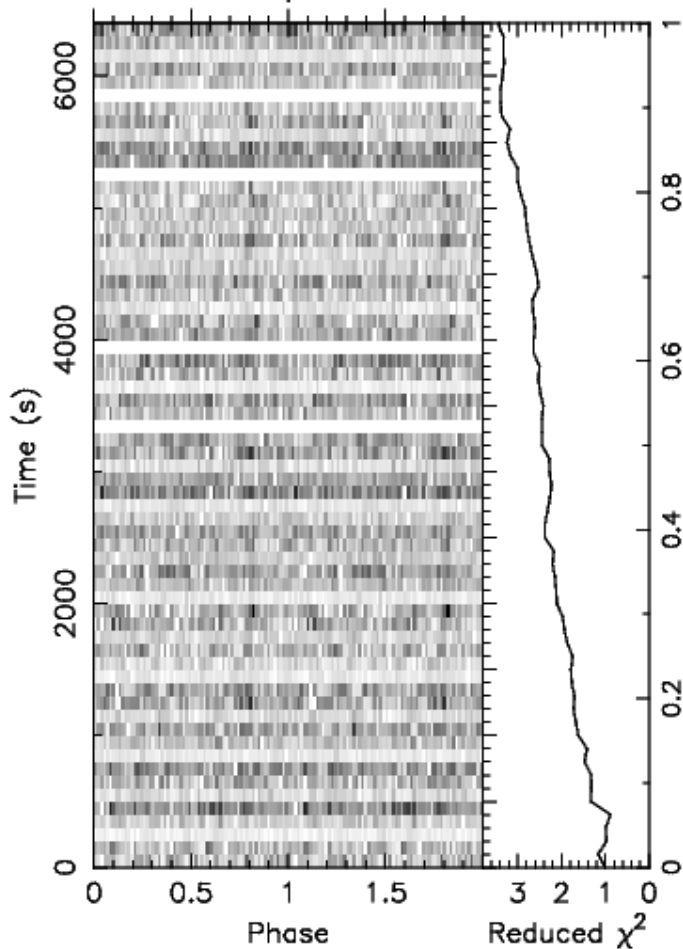
2 Pulses of Best Profile



Candidate: PSR_2129+1210A
 Telescope: Geocenter
 Epoch_{topo} = 55870.90973379630
 Epoch_{bary} = N/A
 T_{sample} = 0.0005
 Data Folded = 12800000
 Data Avg = 9.256e+04
 Data StdDev = 1143
 Profile Bins = 64
 Profile Avg = 1.851e+10
 Profile StdDev = 5.112e+05

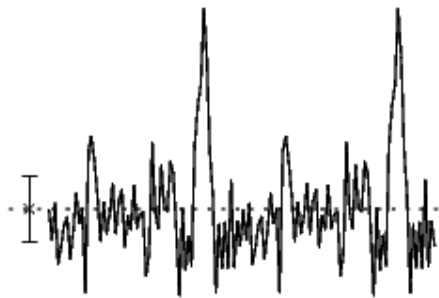
Search Information

RA_{J2000} = 21:29:58.2465 DEC_{J2000} = 12:10:01.2270
 Best Fit Parameters
 DOF_{eff} = 57.19 χ^2_{red} = 3.458 P(Noise) < 6.34e-19 (8.8 σ)
 Dispersion Measure (DM; pc/cm³) = 67.812
 P_{topo} (ms) = 110.674011(25) P_{bary} (ms) = N/A
 P'_{topo} (s/s) = 9.3(3.0)x10⁻¹¹ P'_{bary} (s/s) = N/A
 P''_{topo} (s/s²) = 0.0(3.1)x10⁻¹⁴ P''_{bary} (s/s²) = N/A
 Binary Parameters
 P_{orb} (s) = N/A e = N/A
 a₁sin(i)/c (s) = N/A ω (rad) = N/A
 T_{peri} = N/A



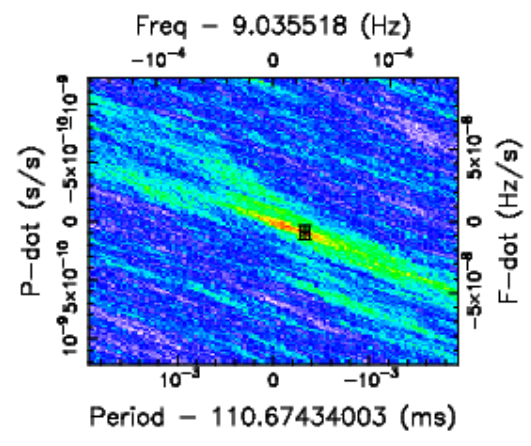
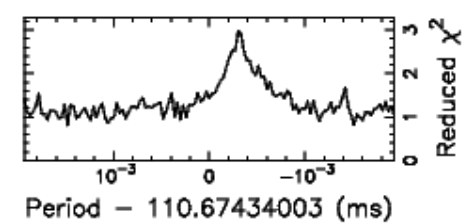
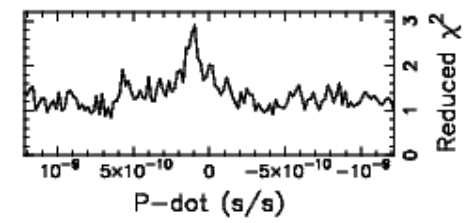
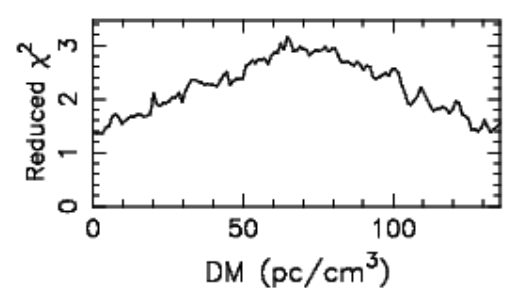
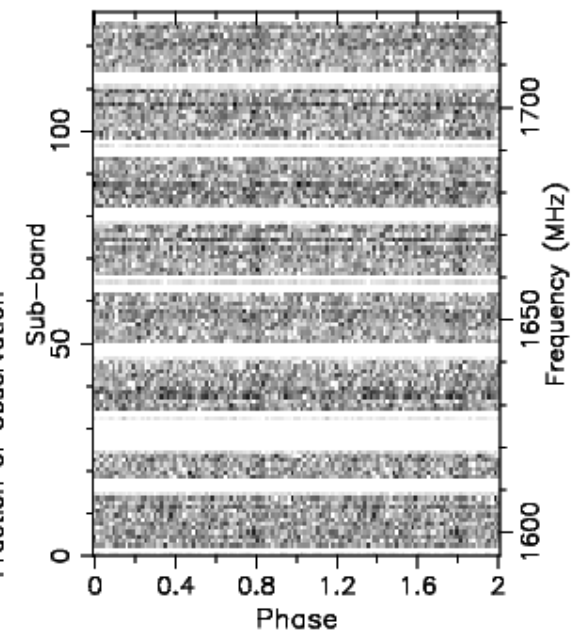
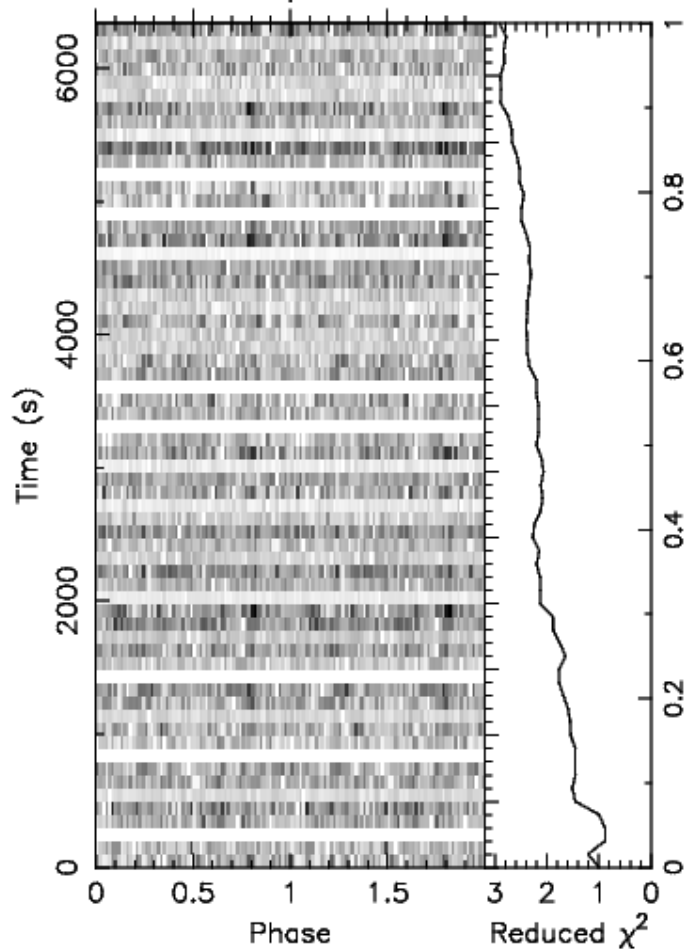
Stations = Jb,Gb,On,Tr,Wb(1)

2 Pulses of Best Profile



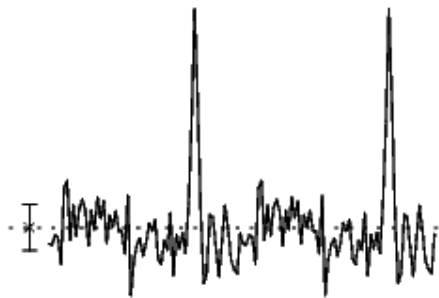
Candidate: PSR_2129+1210A
 Telescope: Geocenter
 Epoch_{topo} = 55870.91003472222
 Epoch_{bary} = N/A
 T_{sample} = 0.0005
 Data Folded = 12672000
 Data Avg = 9.136e+04
 Data StdDev = 1105
 Profile Bins = 64
 Profile Avg = 1.809e+10
 Profile StdDev = 4.918e+05

Search Information
 RA_{J2000} = 21:29:58.2465 DEC_{J2000} = 12:10:01.2270
 Best Fit Parameters
 DOF_{eff} = 57.19 χ^2_{red} = 2.906 P(Noise) < 1.21e-13 (7.3 σ)
 Dispersion Measure (DM; pc/cm³) = 67.812
 P_{topo} (ms) = 110.674008(47) P_{bary} (ms) = N/A
 P'_{topo} (s/s) = 9.5(5.8)x10⁻¹¹ P'_{bary} (s/s) = N/A
 P''_{topo} (s/s²) = 0.0(5.9)x10⁻¹⁴ P''_{bary} (s/s²) = N/A
 Binary Parameters
 P_{orb} (s) = N/A e = N/A
 a₁sin(i)/c (s) = N/A ω (rad) = N/A
 T_{peri} = N/A



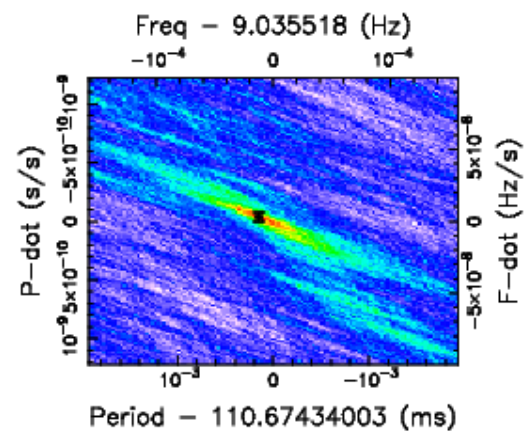
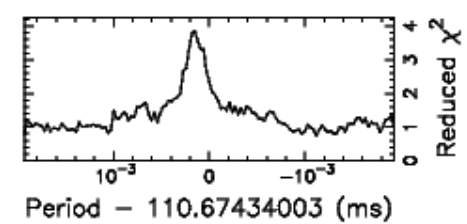
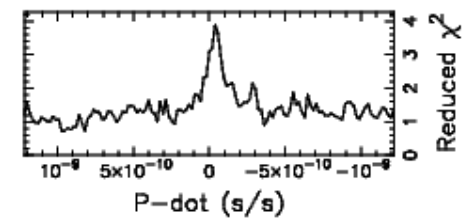
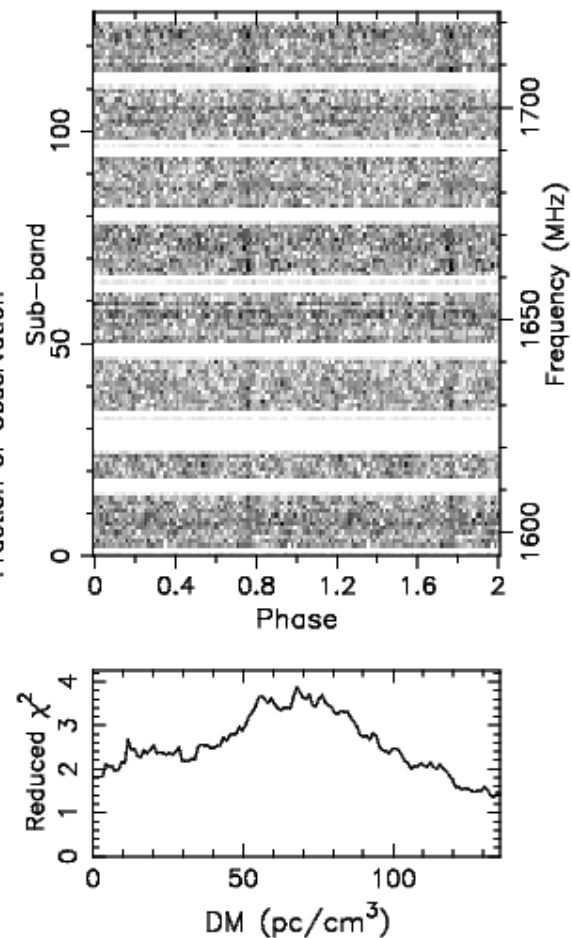
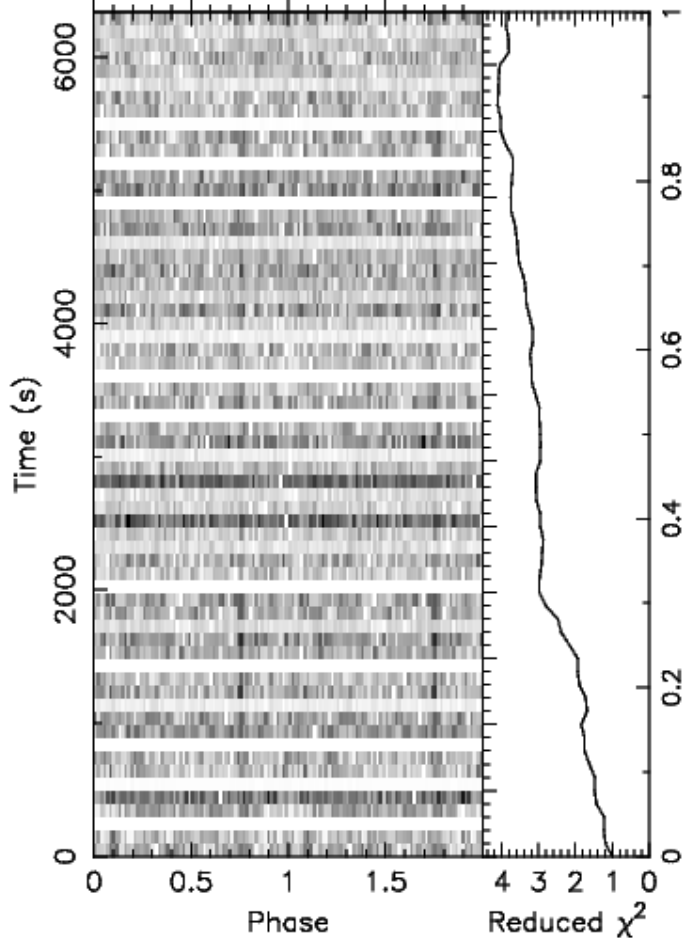
Stations = Ef, Jb, Gb, On, Tr, Wb(1)

2 Pulses of Best Profile



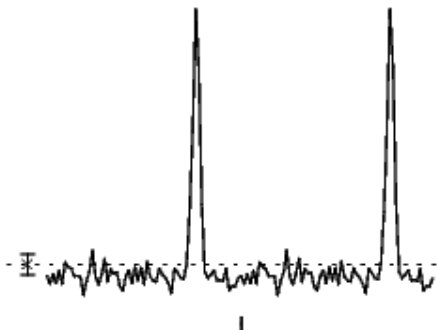
Candidate: PSR_2129+1210A
 Telescope: Geocenter
 Epoch_{topo} = 55870.91012731481
 Epoch_{bary} = N/A
 T_{sample} = 0.0005
 Data Folded = 12672000
 Data Avg = 8.999e+04
 Data StdDev = 1095
 Profile Bins = 64
 Profile Avg = 1.782e+10
 Profile StdDev = 4.874e+05

Search Information
 RA_{J2000} = 21:29:58.2465 DEC_{J2000} = 12:10:01.2270
 Best Fit Parameters
 DOF_{eff} = 57.19 χ^2_{red} = 3.872 P(Noise) < 4.1e-23 (9.8 σ)
 Dispersion Measure (DM; pc/cm³) = 67.812
 P_{topo} (ms) = 110.674491(31) P_{bary} (ms) = N/A
 P'_{topo} (s/s) = -3.8(3.8)x10⁻¹¹ P'_{bary} (s/s) = N/A
 P''_{topo} (s/s²) = 0.0(3.9)x10⁻¹⁴ P''_{bary} (s/s²) = N/A
 Binary Parameters
 P_{orb} (s) = N/A e = N/A
 a₁sin(i)/c (s) = N/A ω (rad) = N/A
 T_{peri} = N/A



Stations = Ar,Ef,Jb,Gb,On,Tr,Wb(1)

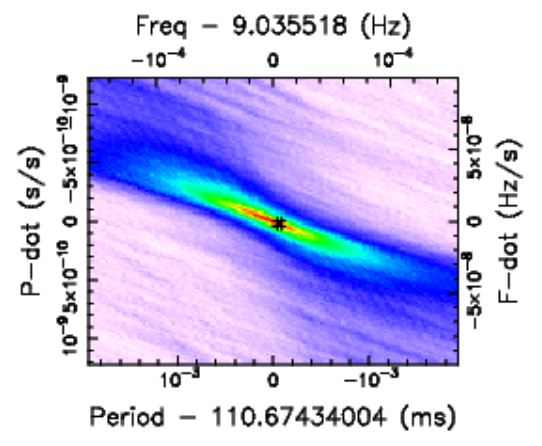
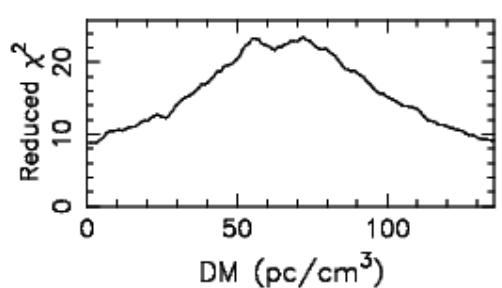
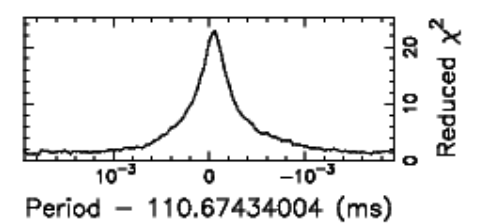
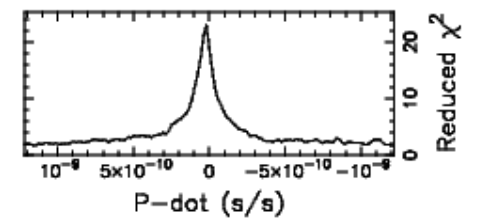
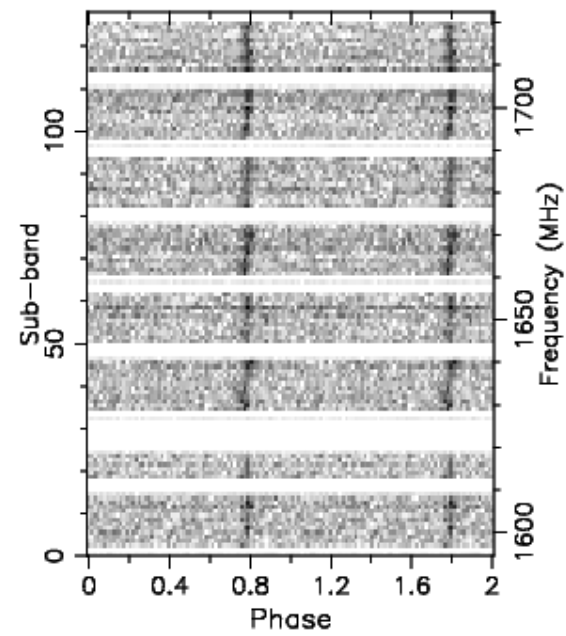
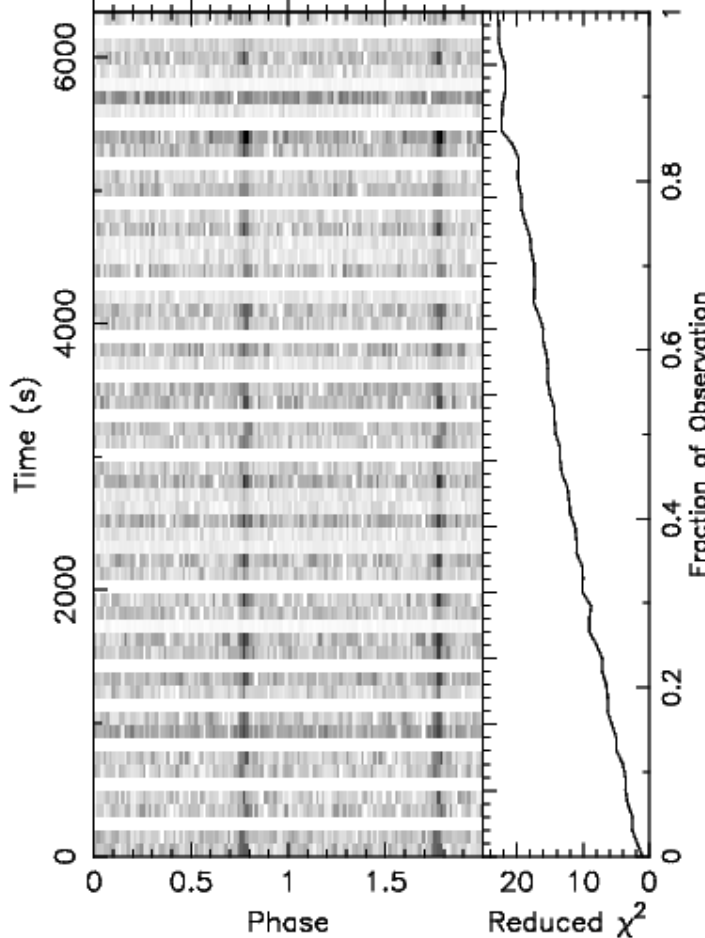
2 Pulses of Best Profile



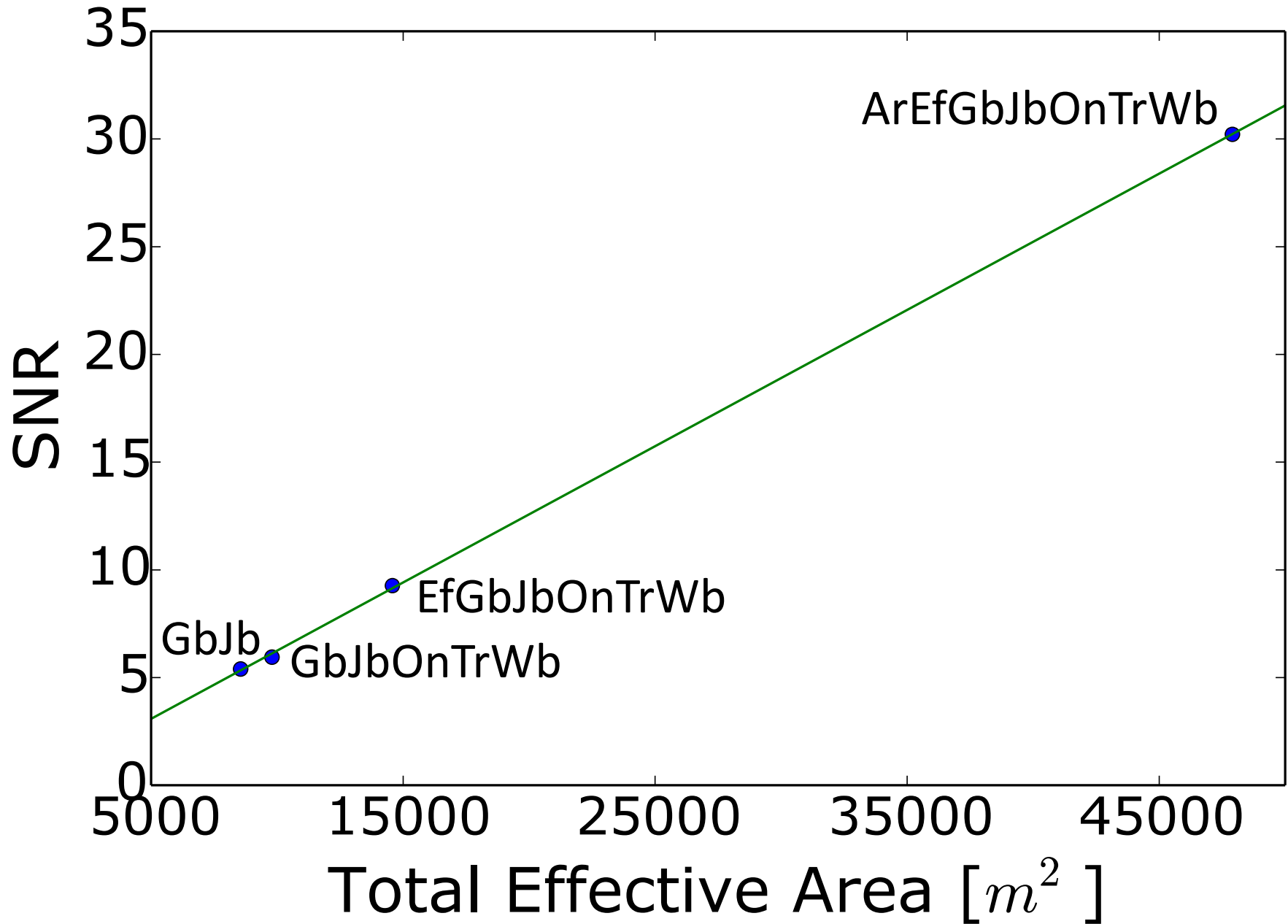
Candidate: PSR_2129+1210A
 Telescope: Geocenter
 Epoch_{topo} = 55870.91025462963
 Epoch_{bary} = N/A
 T_{sample} = 0.0005
 Data Folded = 12672000
 Data Avg = 8.974e+04
 Data StdDev = 1033
 Profile Bins = 64
 Profile Avg = 1.777e+10
 Profile StdDev = 4.594e+05

Search Information

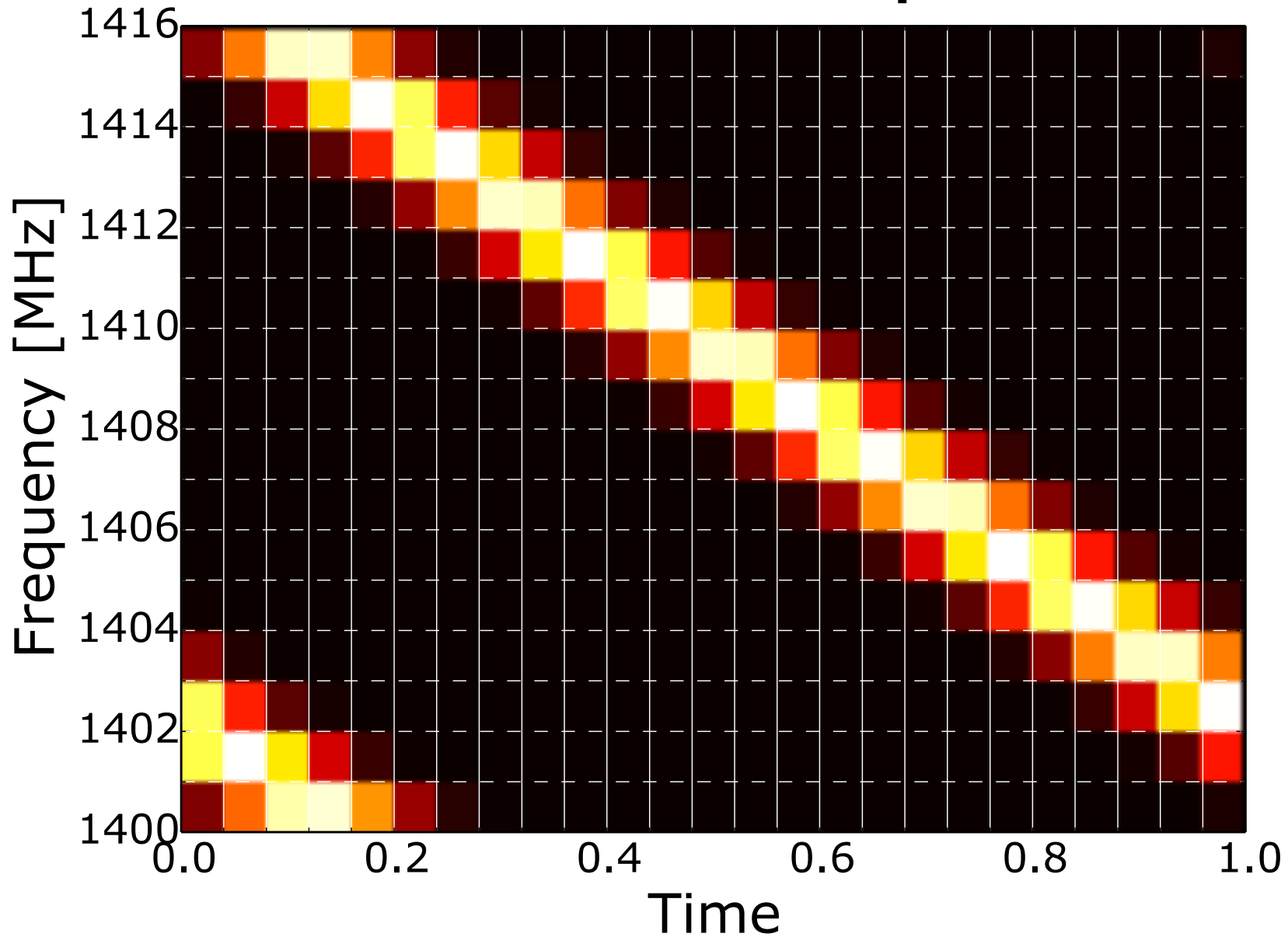
RA_{J2000} = 21:29:58.2465 DEC_{J2000} = 12:10:01.2270
 Best Fit Parameters
 DOF_{eff} = 57.19 χ^2_{red} = 22.933 P(Noise) < 2.05e-260 (34.5 σ)
 Dispersion Measure (DM; pc/cm³) = 67.812
 P_{topo} (ms) = 110.674280(19) P_{bary} (ms) = N/A
 P'_{topo} (s/s) = 1.9(2.3)x10⁻¹¹ P'_{bary} (s/s) = N/A
 P''_{topo} (s/s²) = 0.0(2.4)x10⁻¹⁴ P''_{bary} (s/s²) = N/A
 Binary Parameters
 P_{orb} (s) = N/A e = N/A
 a₁sin(i)/c (s) = N/A ω (rad) = N/A
 T_{peri} = N/A



SNR vs Total Effective Area

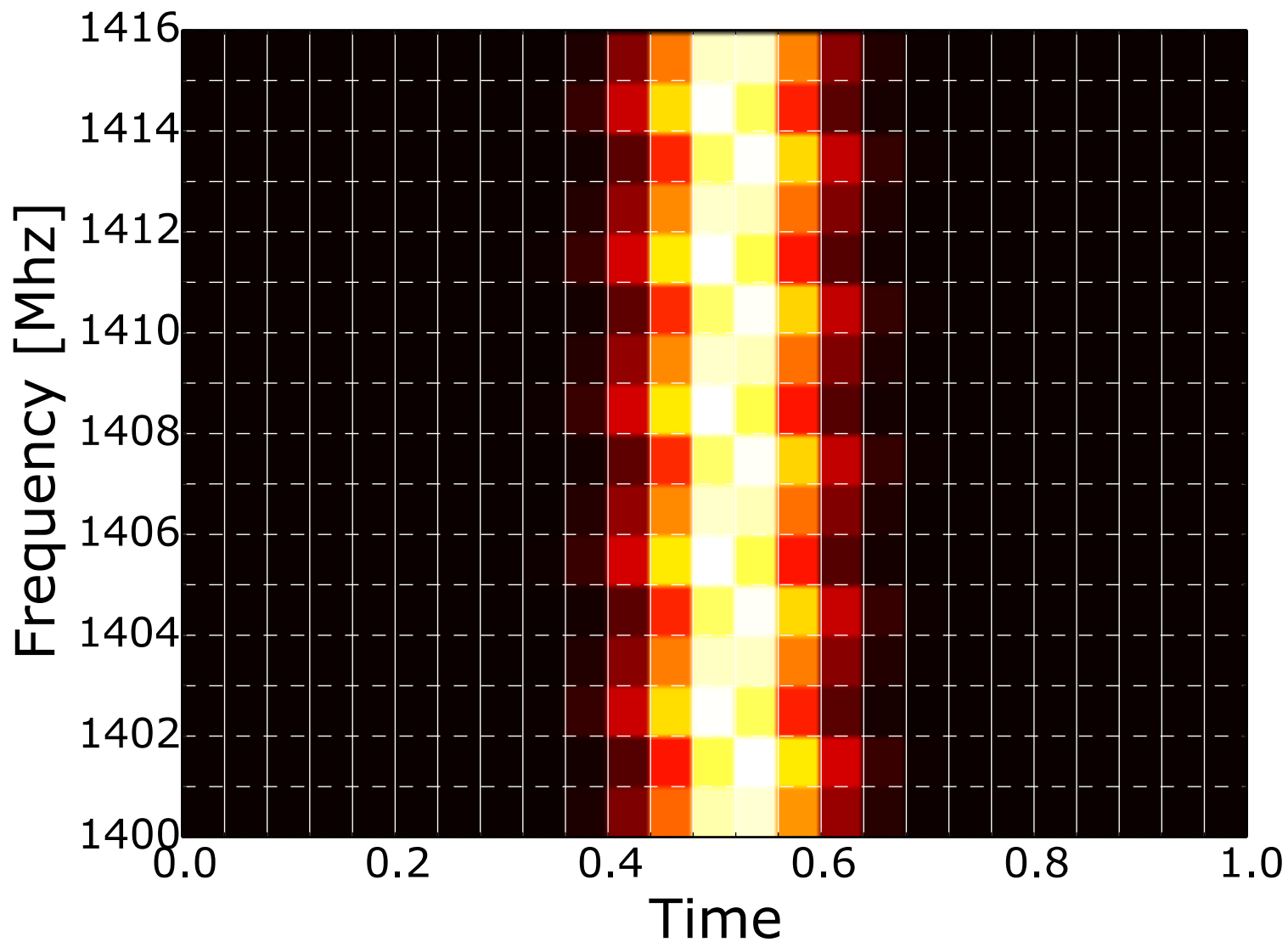


Incoherent de-dispersion

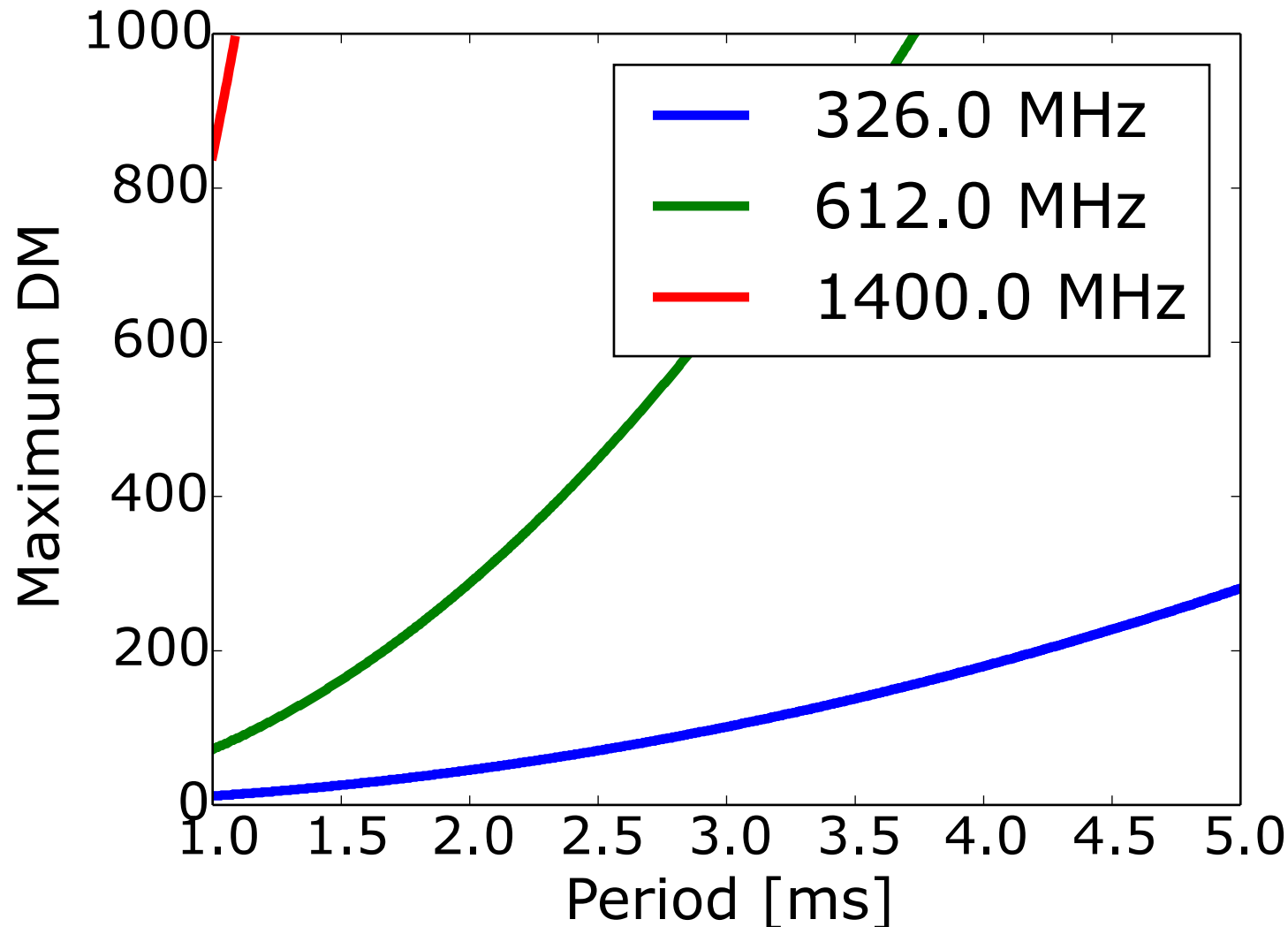


Dispersive delay : $\Delta t \approx 4.15 \times 10^6 \times DM \times (\nu_1^{-2} - \nu_2^{-2}) [ms]$

Incoherent de-dispersion



Limits to incoherent dedispersion



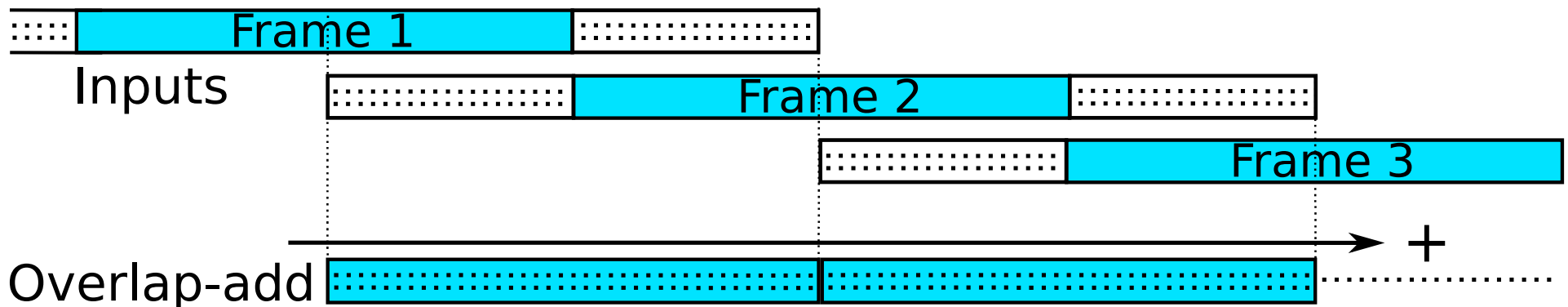
- Maximum dispersion measure for which dispersive delay and FFT length are within half a pulse width.
- Pulse width is 5% of pulse period

Coherent de-dispersion

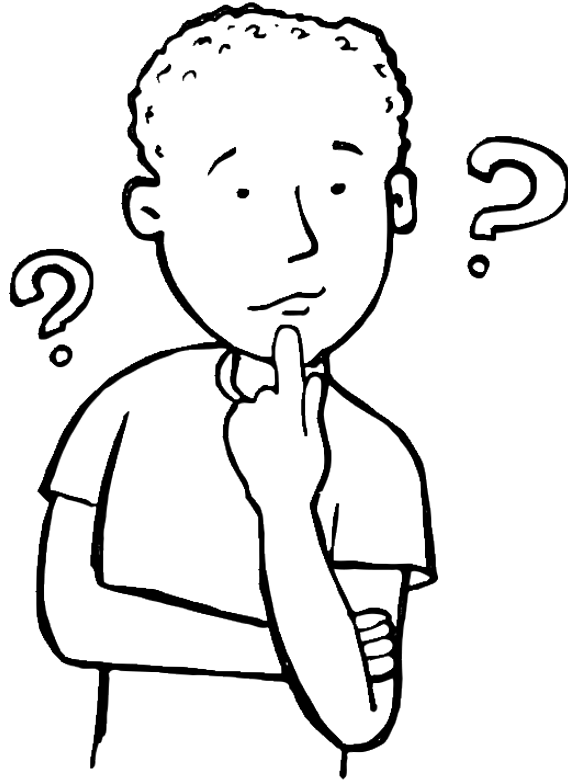
- Dispersive delay can be exactly removed by applying a filter $H(\nu)$ with transfer function

$$H(\nu_0 + \nu) = \exp\left(\frac{-i 2\pi DM \nu^2}{2.41 \times 10^{-10} \nu_0^2 (\nu_0 + \nu)}\right)$$

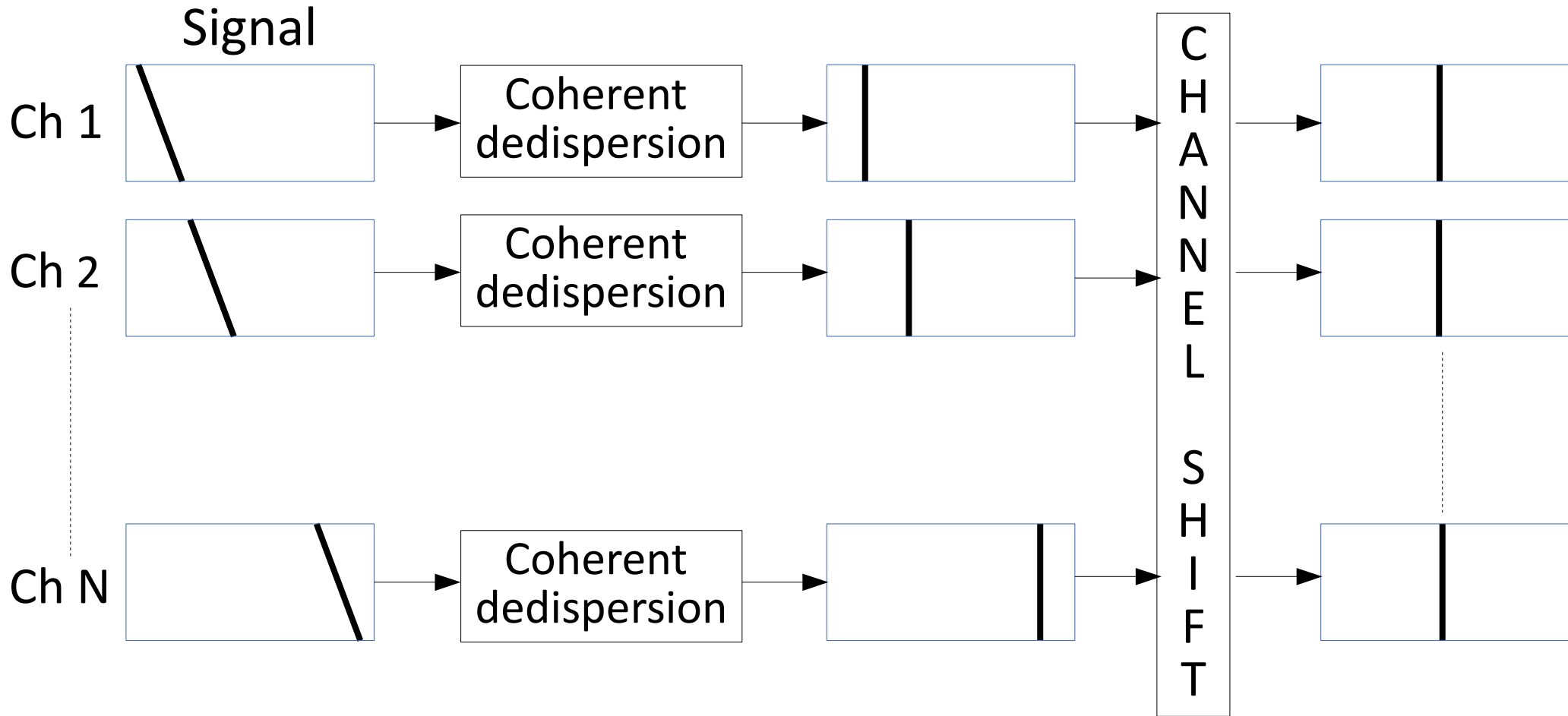
- Filter is applied in overlap – add structure



Questions?

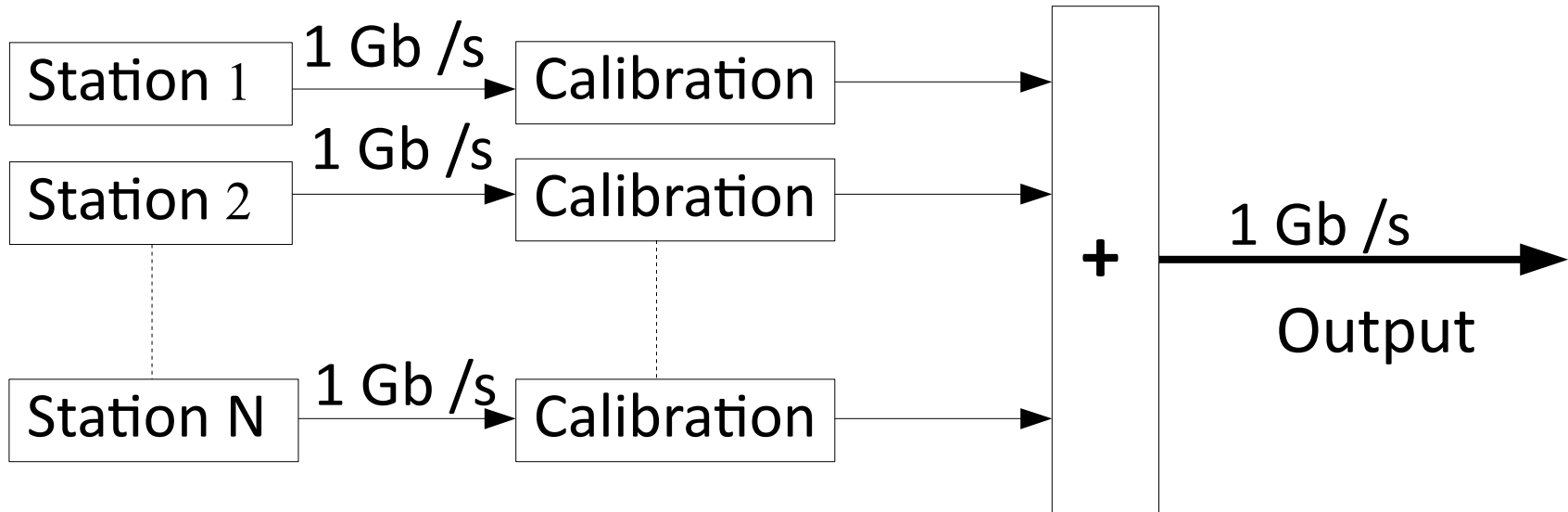


Coherent filterbank



After applying the de-dispersion filter there is still an offset between channels that needs to be compensated

Data rate decimation



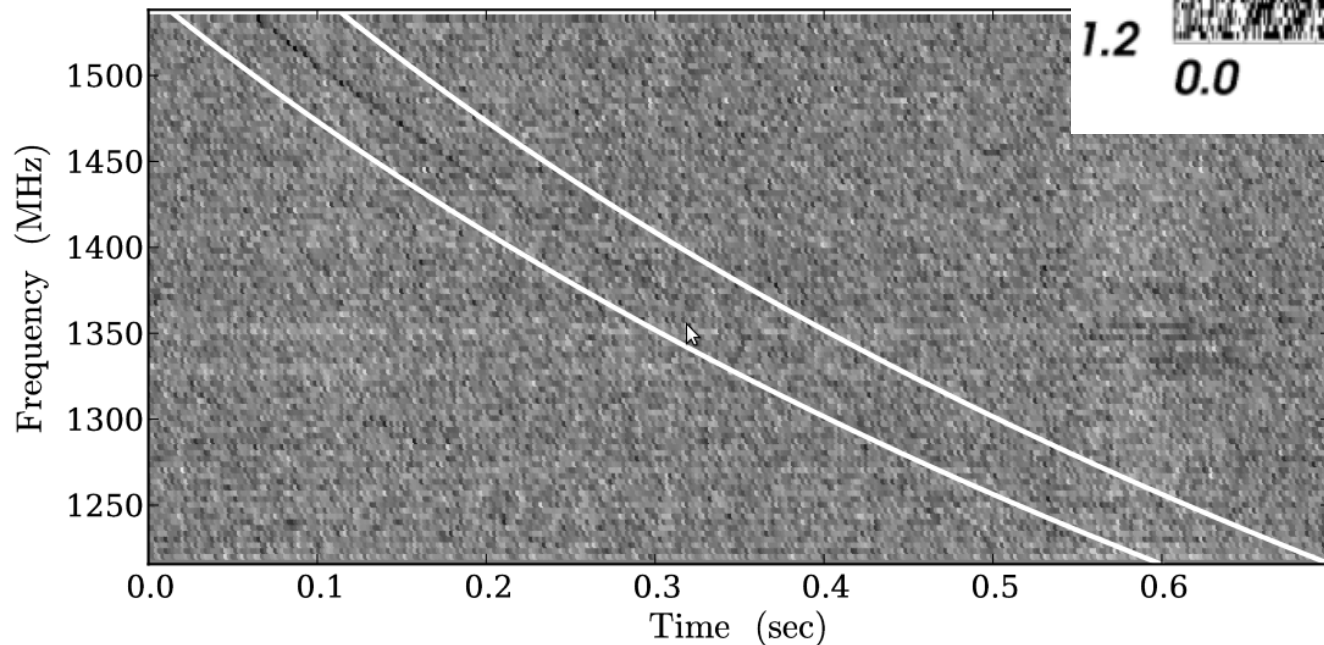
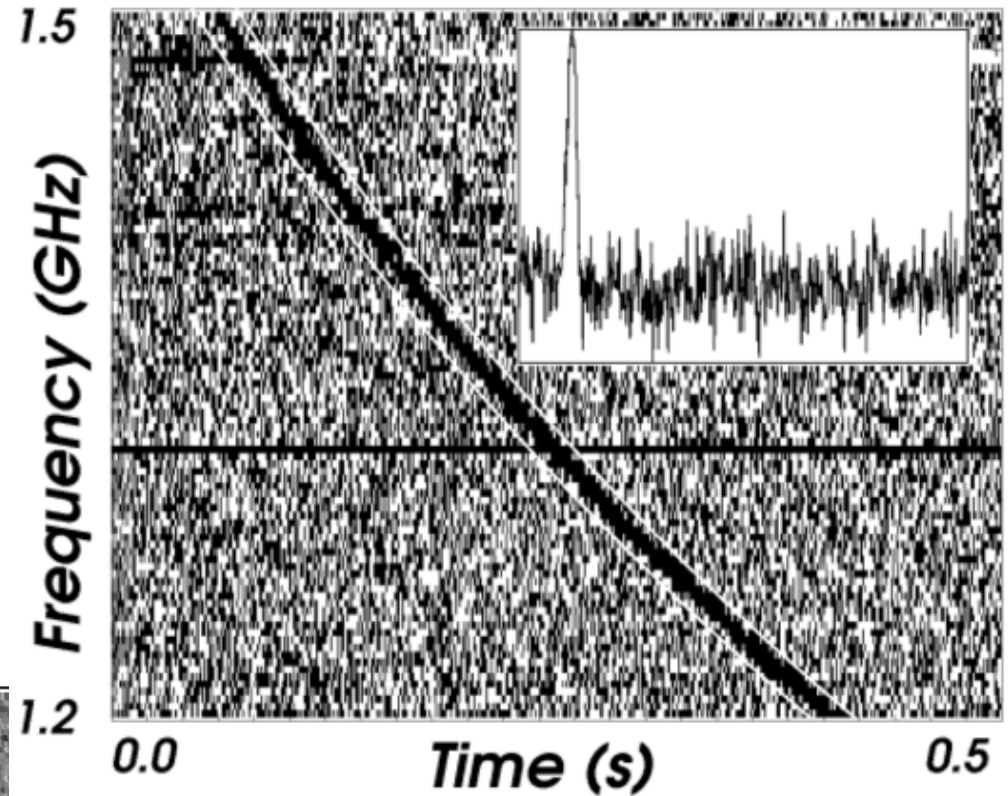
- Voltage data has very high data rate
- For known pulsars data rate can be reduced by folding pulsar inside the correlator (*planned feature*)
- Impractical for finding new pulsars

Fast radio bursts

Lorimer burst (Parks)

- Flux density 30 Jy
- Pulse width < 5 ms
- DM = 375

Lorimer et al, science 318, 777 (2007)



Arecibo burst

- Flux density 0.4 Jy
- Pulse width 3ms
- DM = 557

Spitler et al., ApJ 790, 101 2014