# Phasing-up the EVN with SFXC

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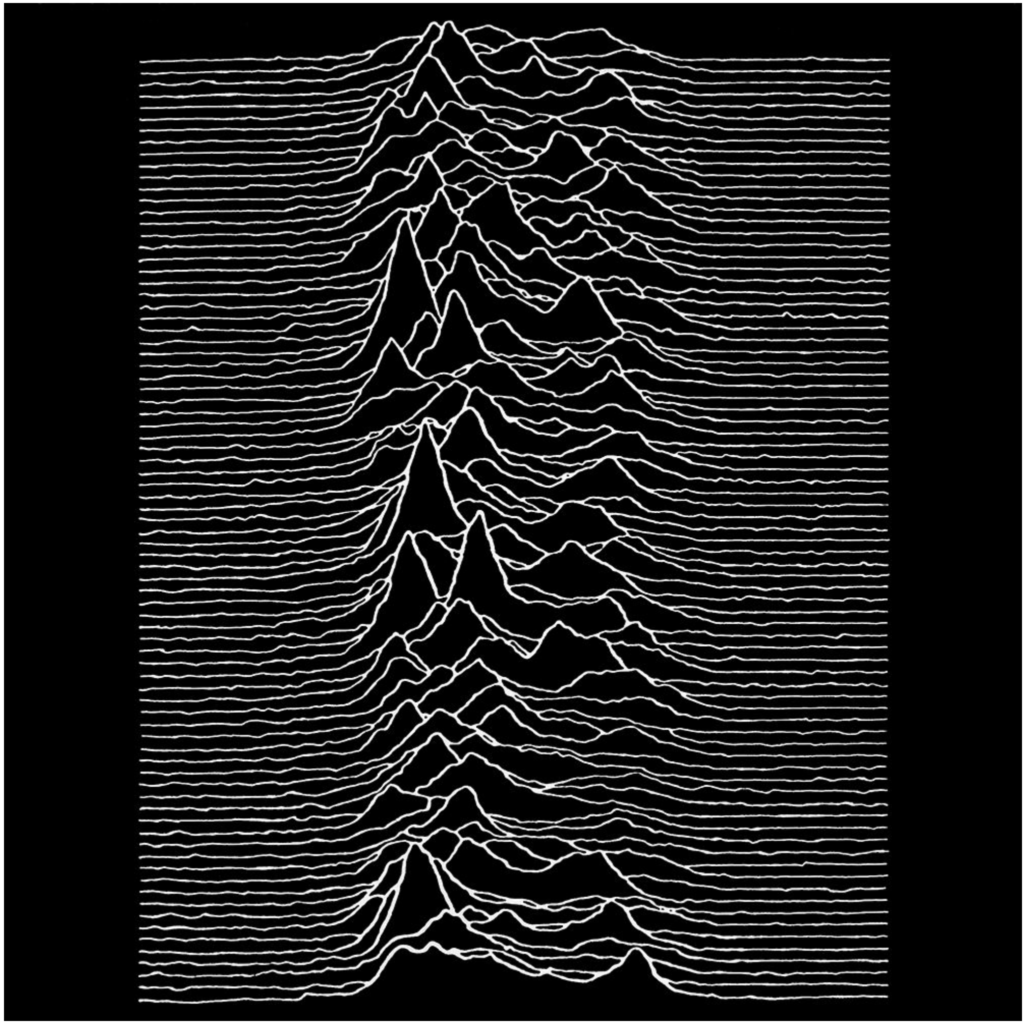
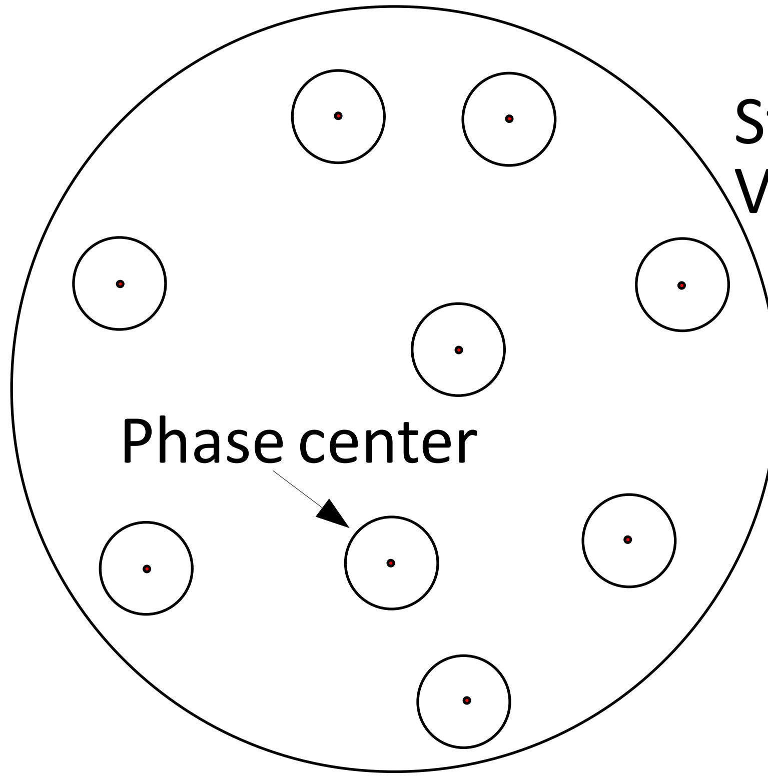


JOINT INSTITUTE FOR VLBI IN EUROPE

# SFXC

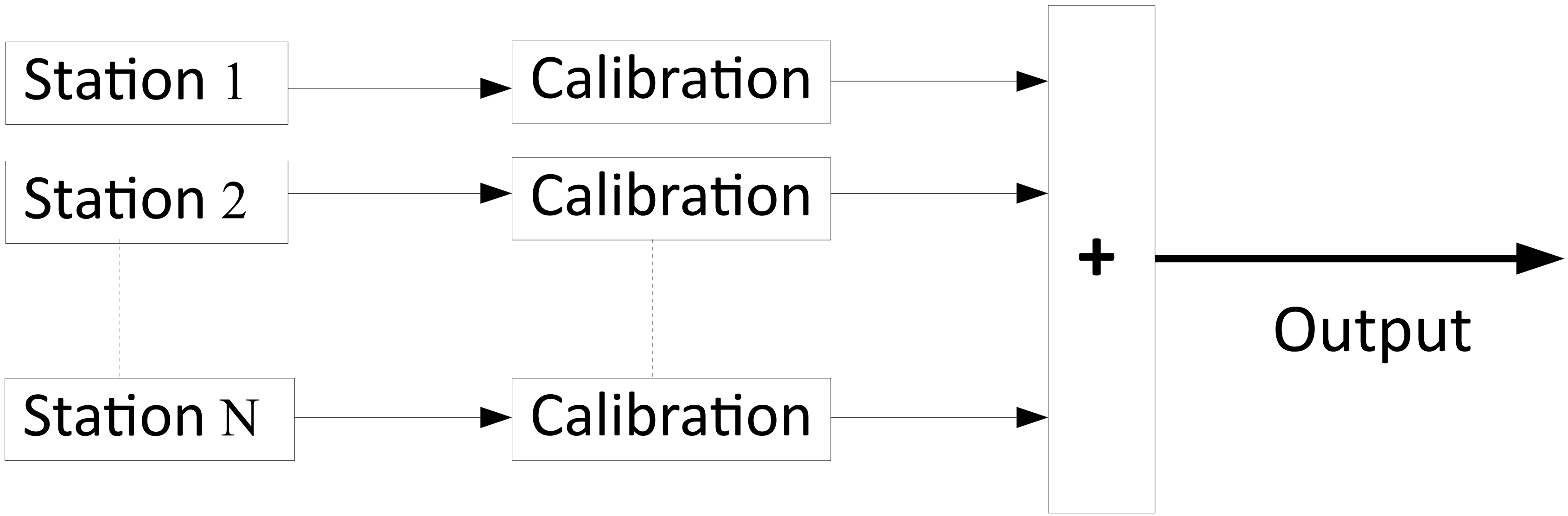
- Software correlator developed and maintained at JIVE
- Used for all correlation at JIVE
- Supported features include
  - Multiple simultaneous phase centers
  - Mixed bandwidth correlation
  - Pulsar binning / gating
  - Coherent de-dispersion
  - Phased array mode
- Licensed under the open source 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

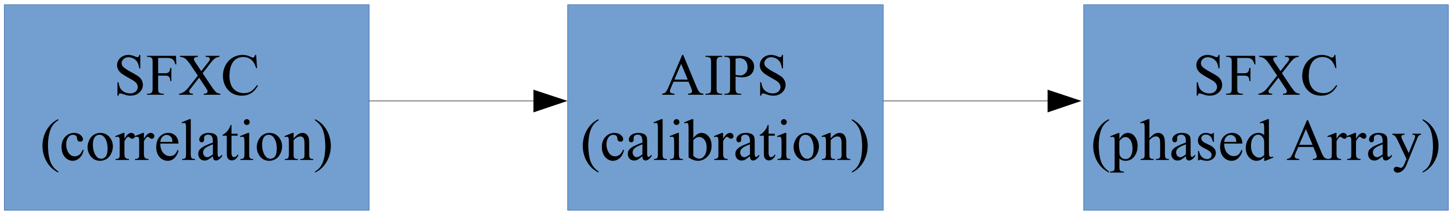
# Phased Array Mode




- 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
  - Scintilation studies

# Calibration

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

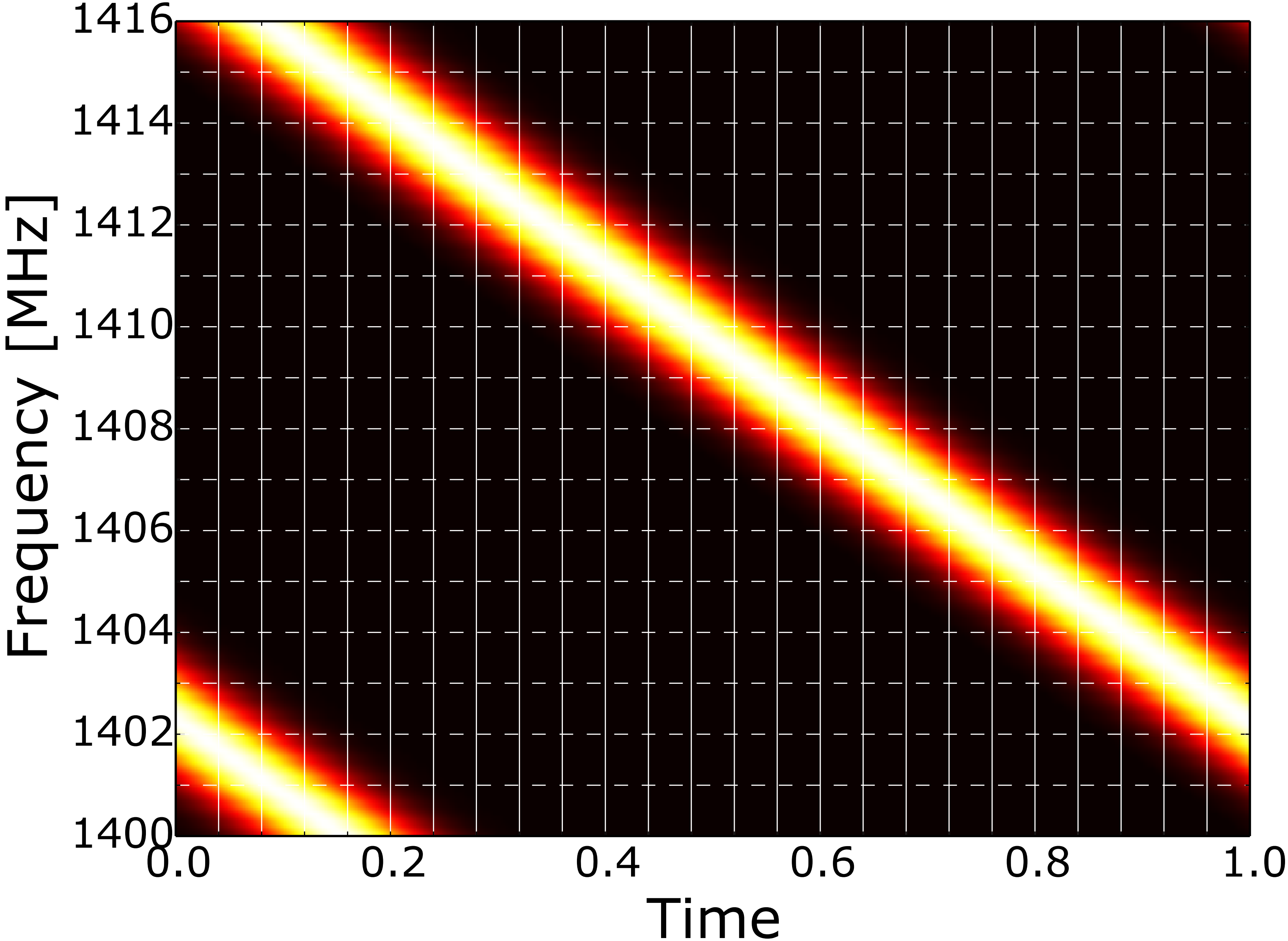


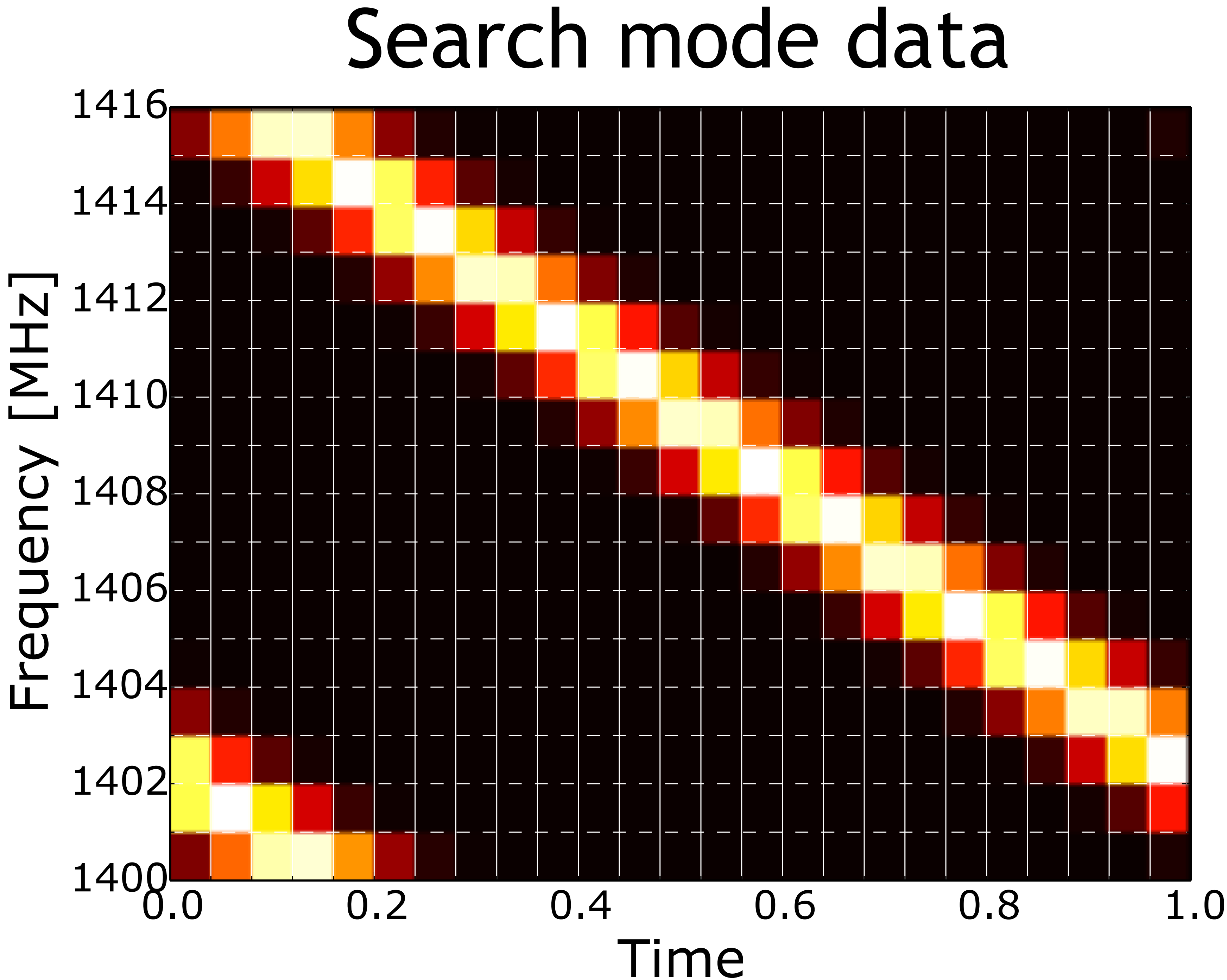

- Two pass process, data is first correlated like a regular VLBI experiment and the usual data reduction steps are performed in AIPS.
- Calibration (CL) and bandpass (BP) tables from AIPS are exported back to the correlator.
- Bad frequency channels are masked in BP table
- Calibration tables are then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

# Search mode data

- Compute power spectrum and accumulate this for short integration time

# Search mode data




Search mode data
Frequency [MHz]
1416
1414
1412
1410
1408
1406
1404
1402
1400
0.0
0.2
0.4
0.6
0.8
1.0
Time

# 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

$$|f_1+f_2+\ldots+f_n|^2=\sum_{i=0}^{n}|f_i|^2+\sum_{i\neq j}f_i^*f_j+\sum_{i\neq j}f_if_j^*$$

$$=\sum_{i=0}^{n}|f_i|^2+2\Re\left(\sum_{i\neq j}f_if_j^*\right)$$

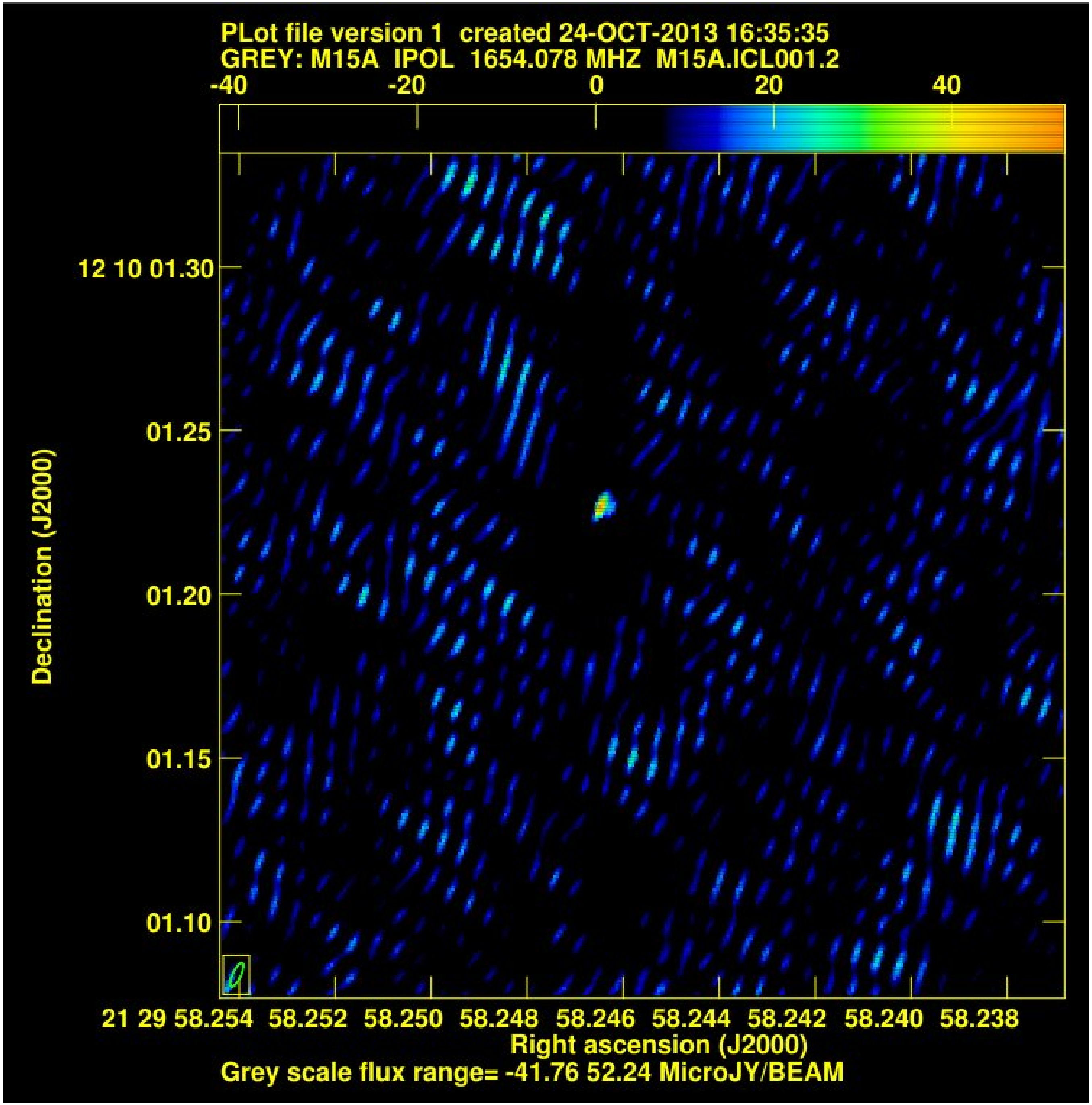
- **Efficient multiple phase center mode**
- Auto-correlations need online RFI mitigation
- Only cross terms are used
- SNR asymptotically approaches true phased array SNR

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

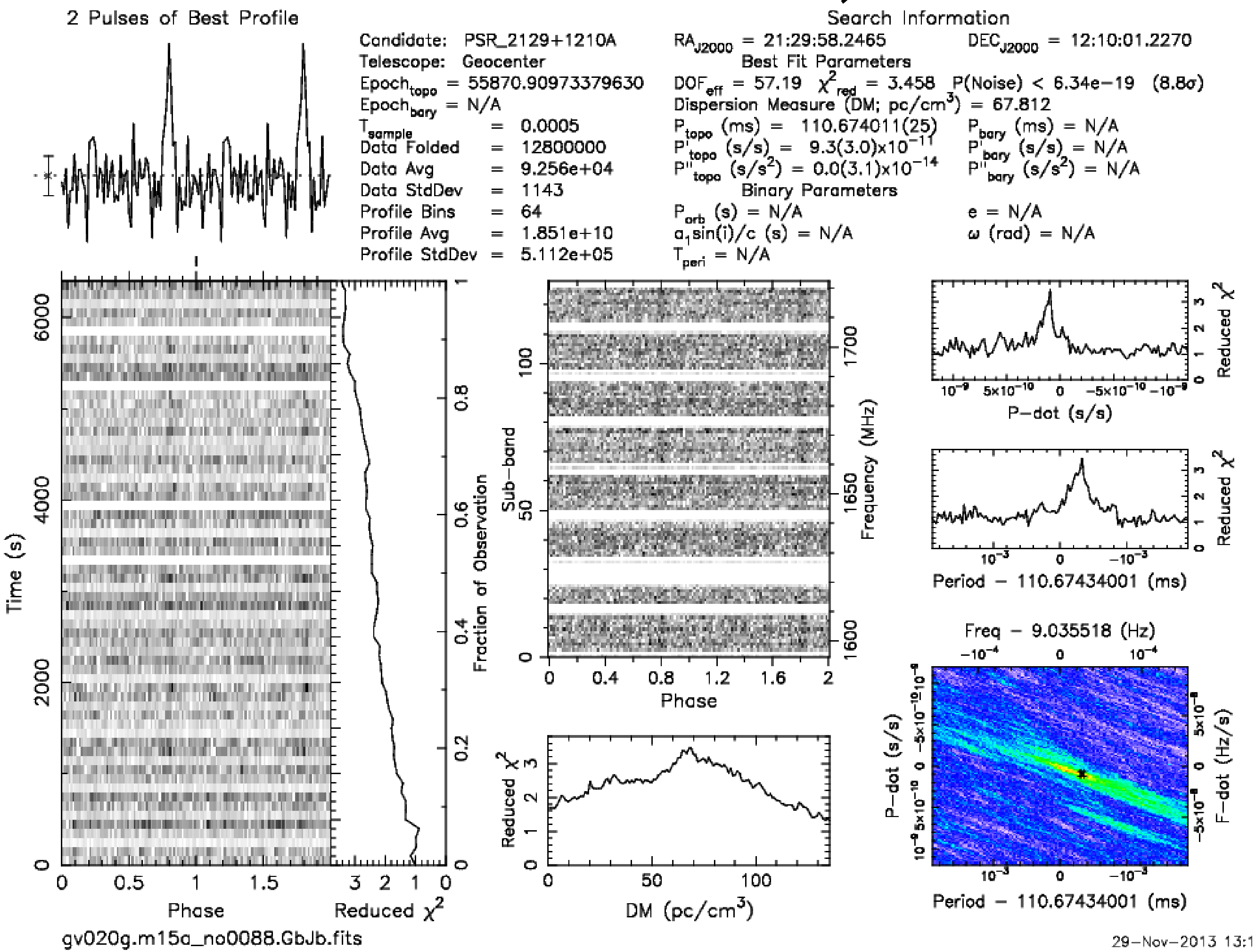
$$SNR_{cross}\propto A\sqrt{N(N-1)}$$

*N = number of stations*
*A = area of antenna*

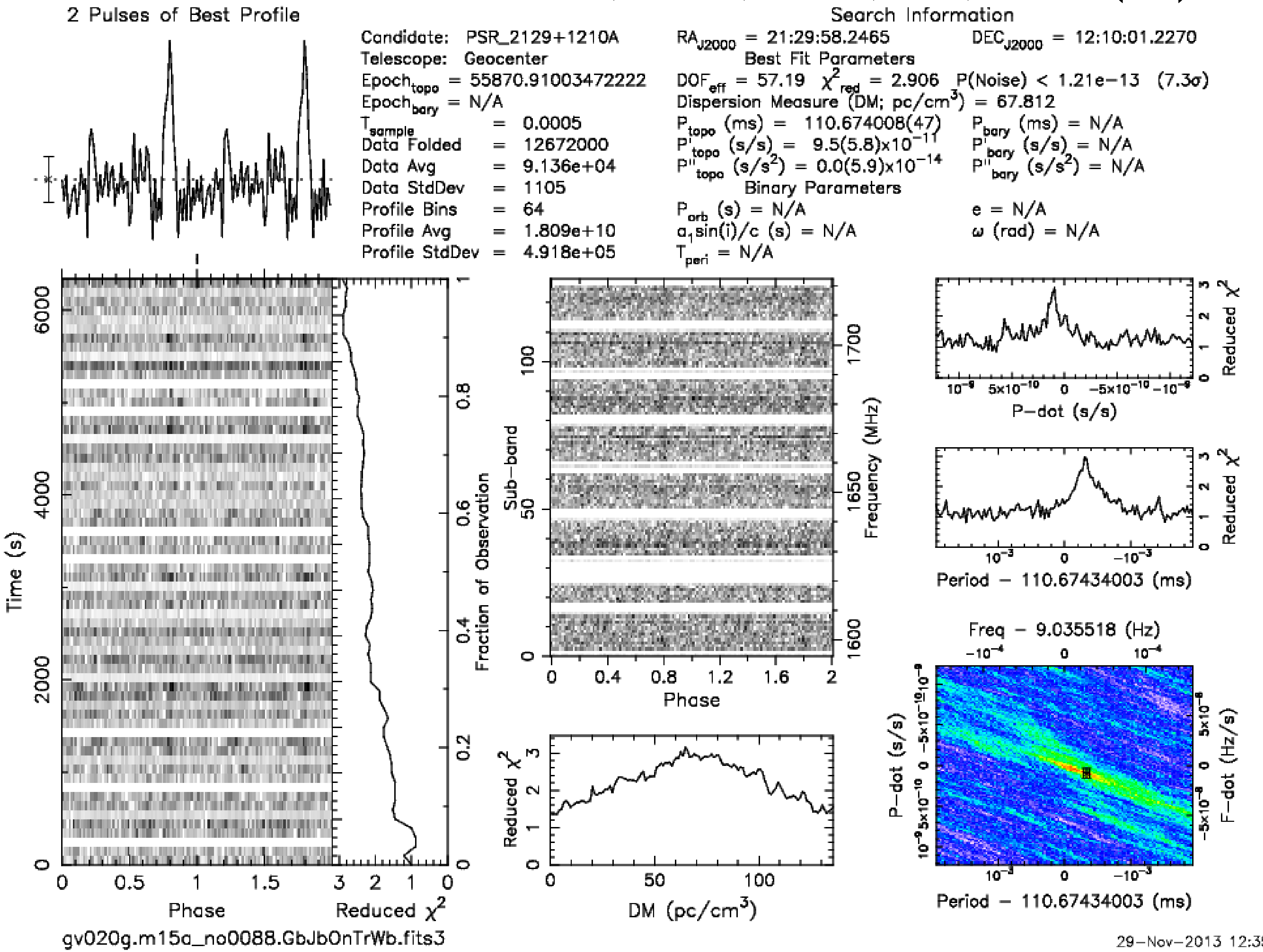
# M15A (Kirsten, Vlemmings, et al.)



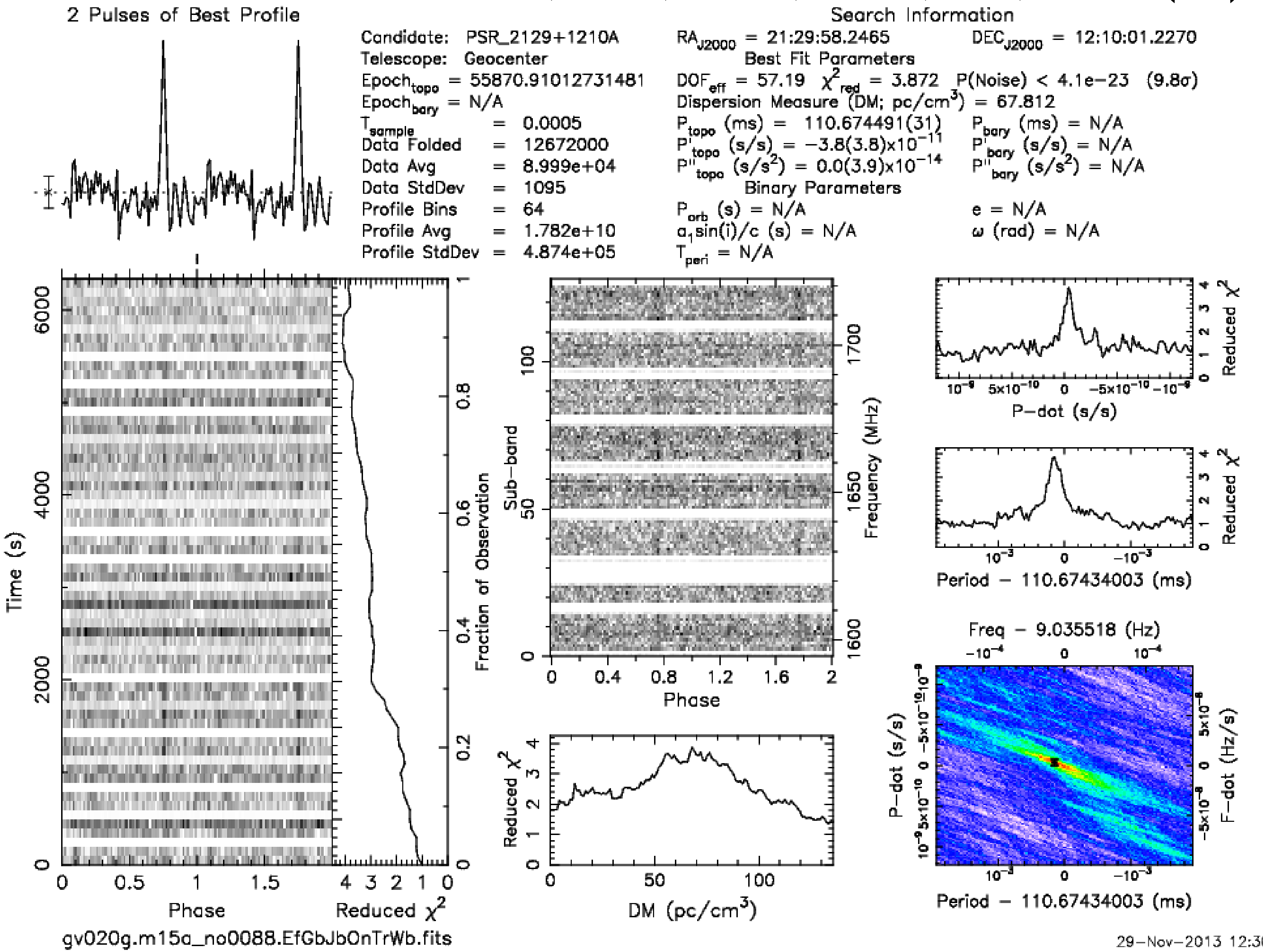
# Stations = Jb,Gb



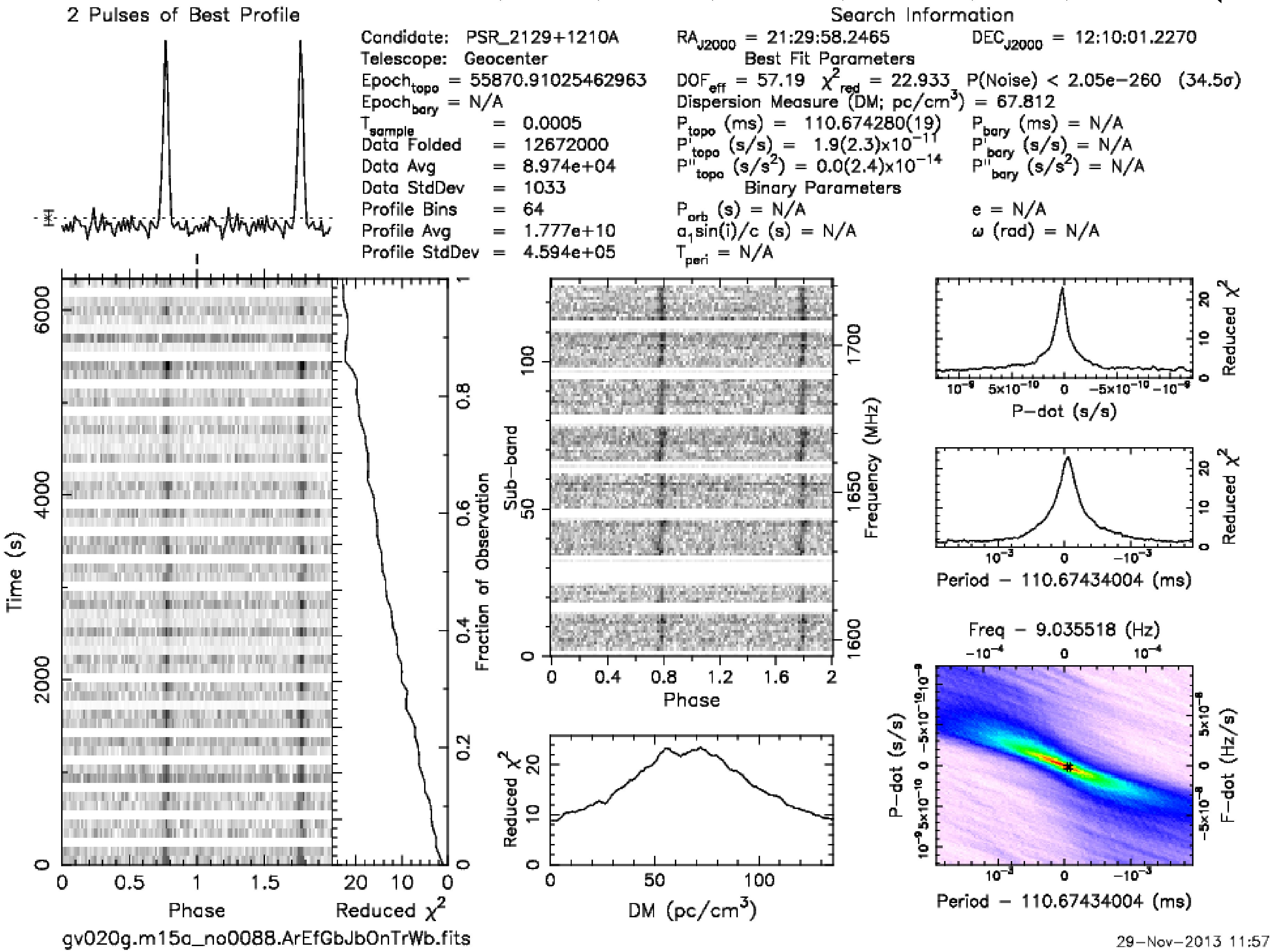
# Stations = Jb,Gb,On,Tr,Wb(1)

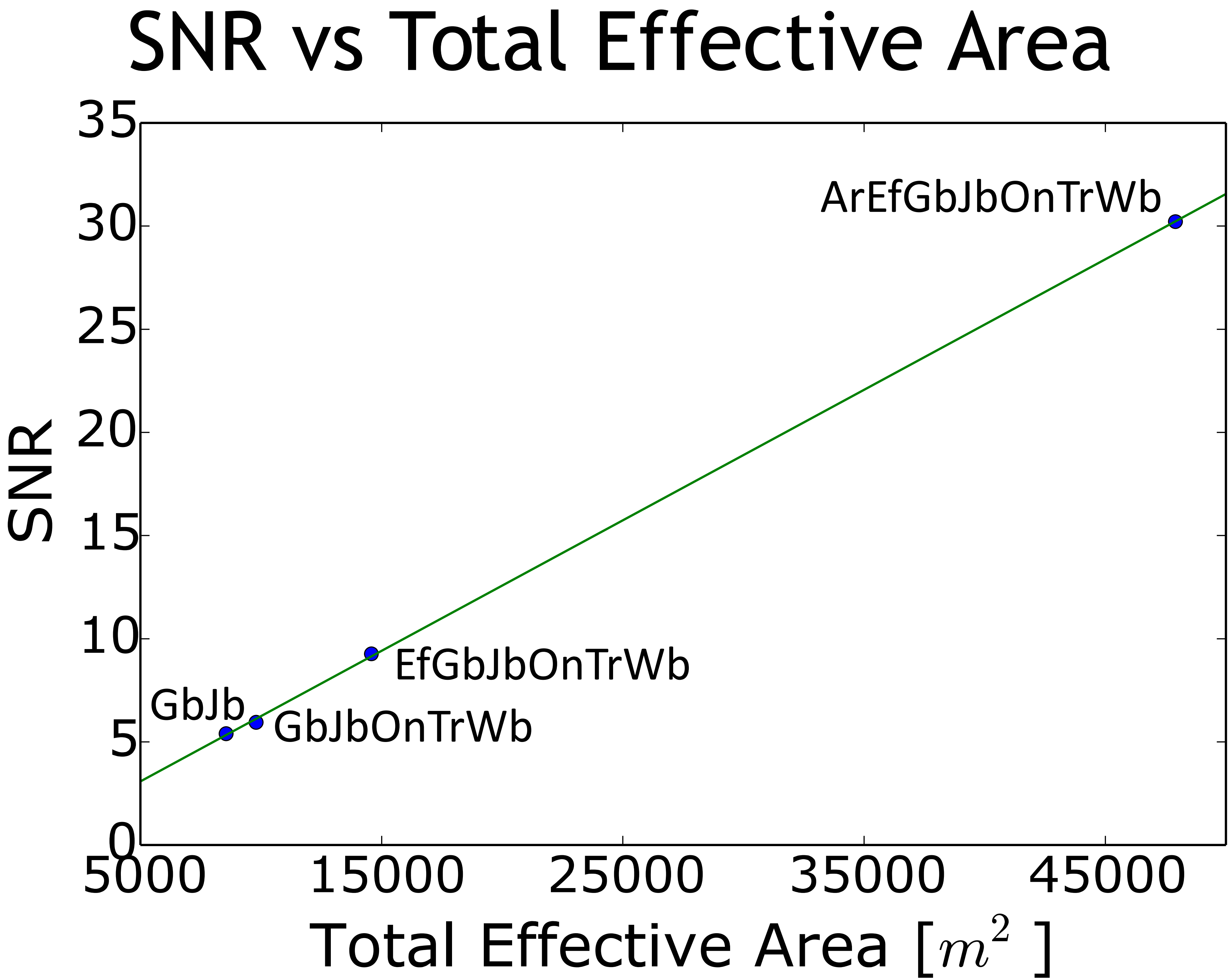


# Stations = Ef,Jb,Gb,On,Tr,Wb(1)

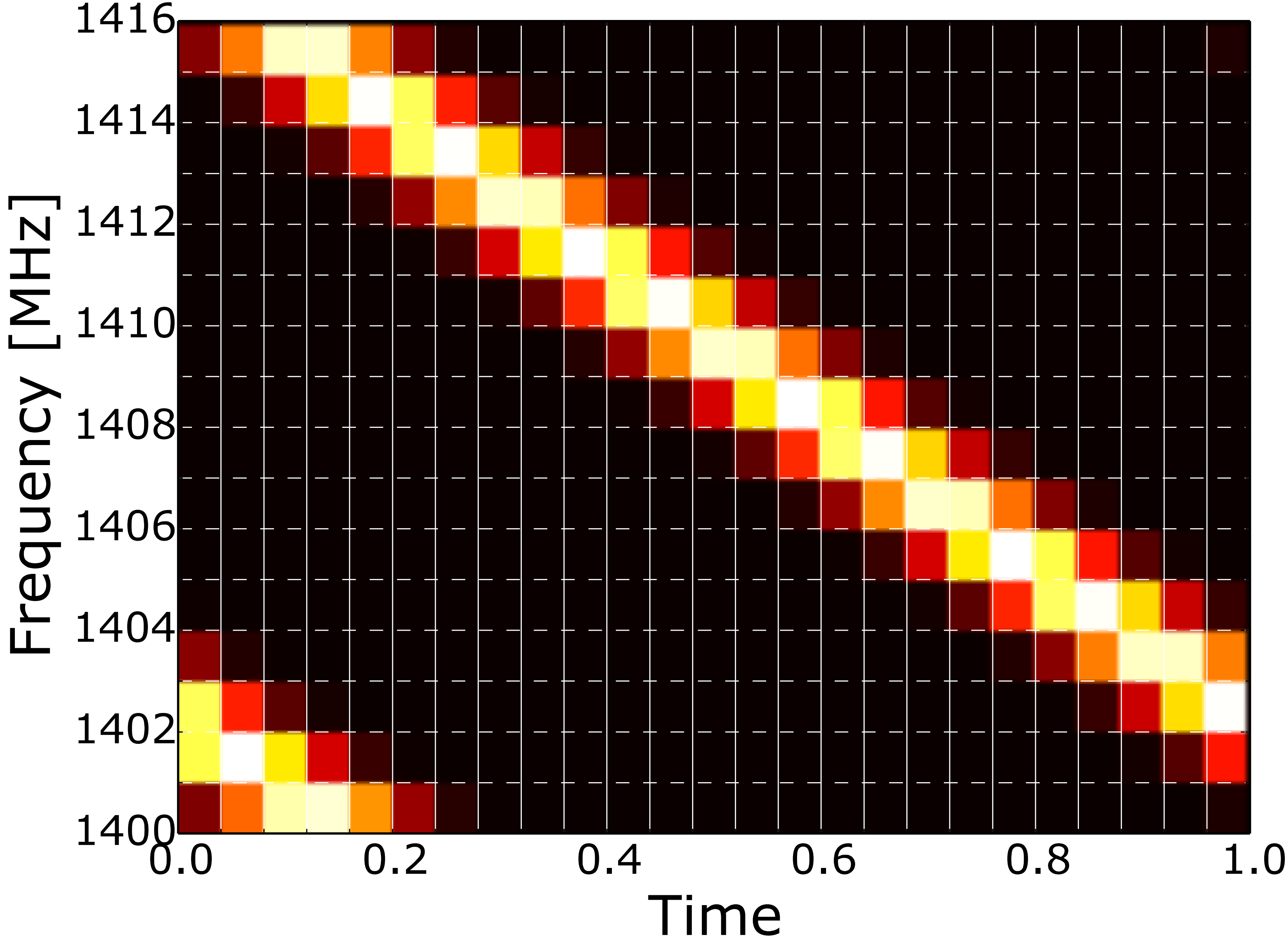


# Stations = Ar,Ef,Jb,Gb,On,Tr,Wb(1)



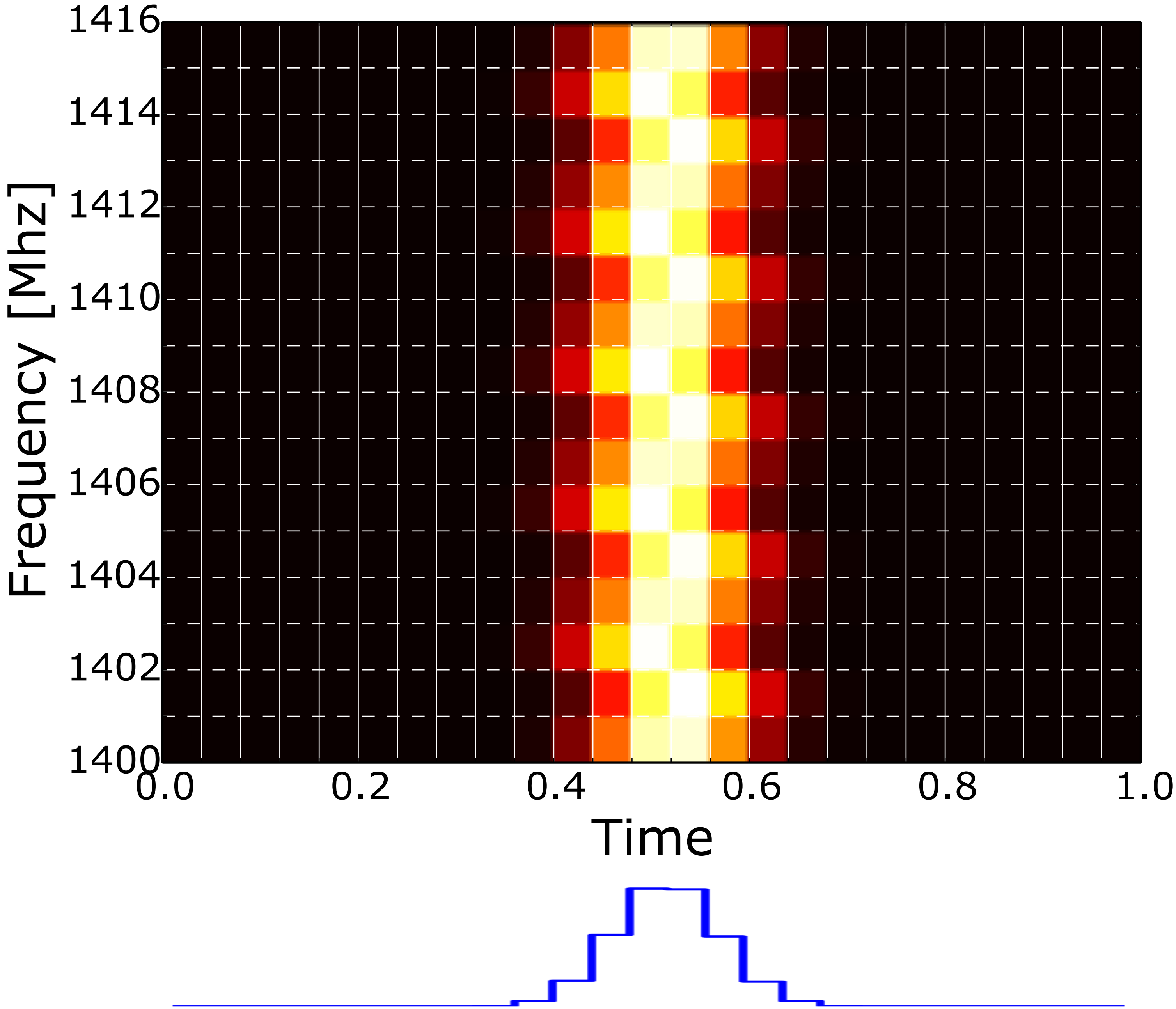

SNR vs Total Effective Area
SNR
Total Effective Area [$m^2$]
0
5
10
15
20
25
30
35
5000
15000
25000
35000
45000
GbJb
GbJbOnTrWb
EfGbJbOnTrWb
ArEfGbJbOnTrWb

# Incoherent de-dispersion

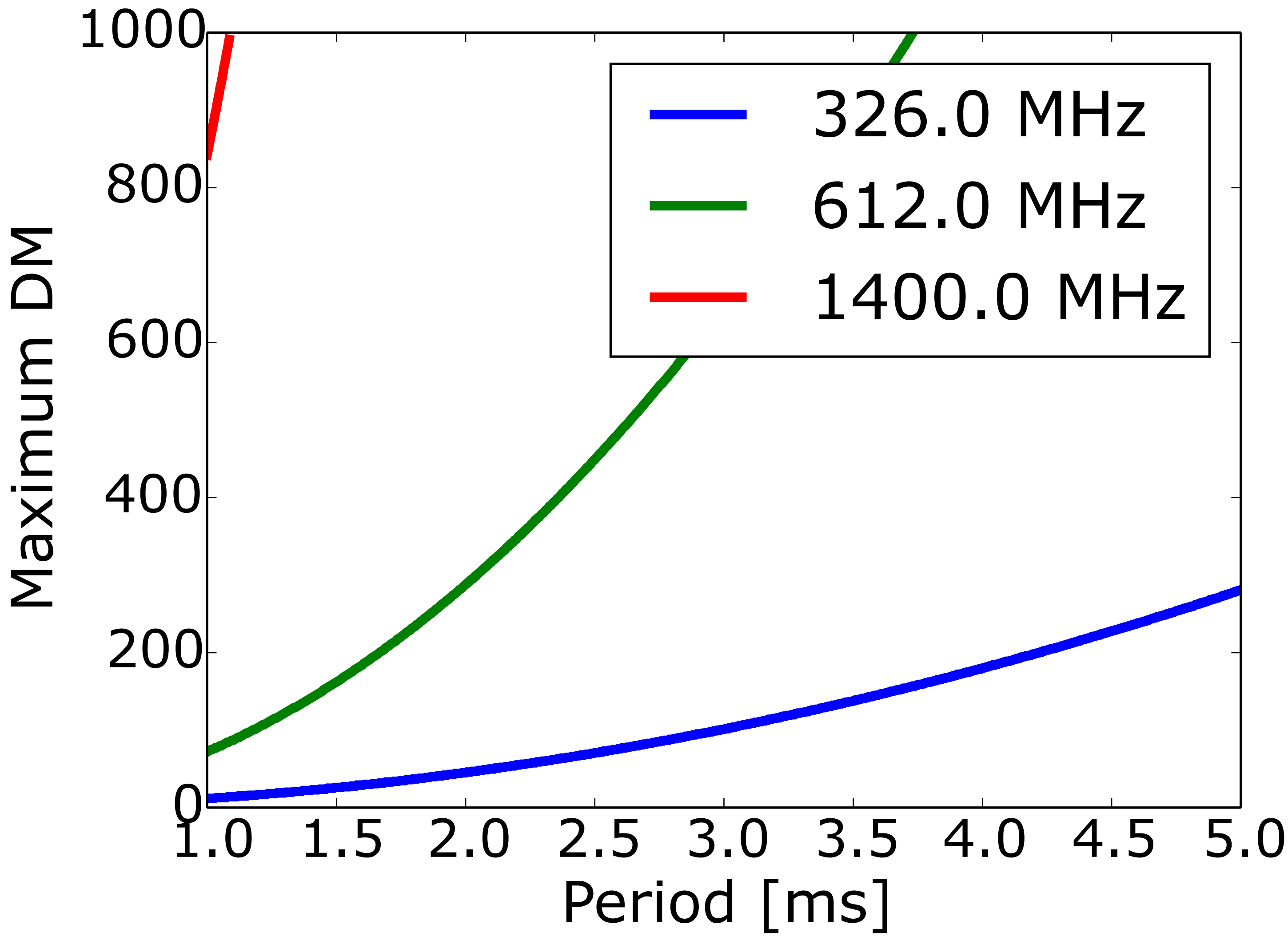



Dispersive delay : $\Delta t \approx 4.15 \times 10^6 \times DM \times \left(\nu_1^{-2} - \nu_2^{-2}\right) [ms]$

# Incoherent de-dispersion



# Limits to incoherent dedispersion



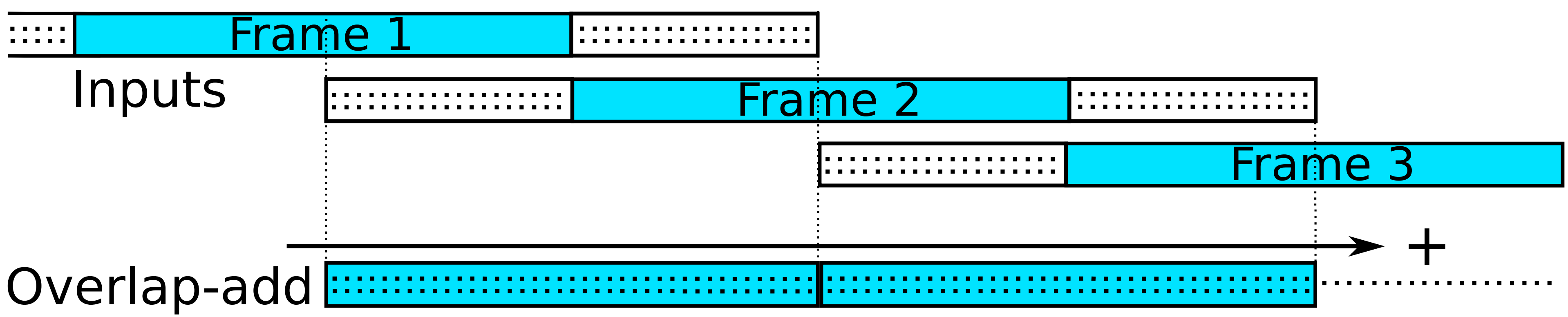

- Maximum dispersion measure for which dispersive delay and FFT length are within half a pulse width.
- Pulse width is 5% of pulse period

# Coherent de-dispersion

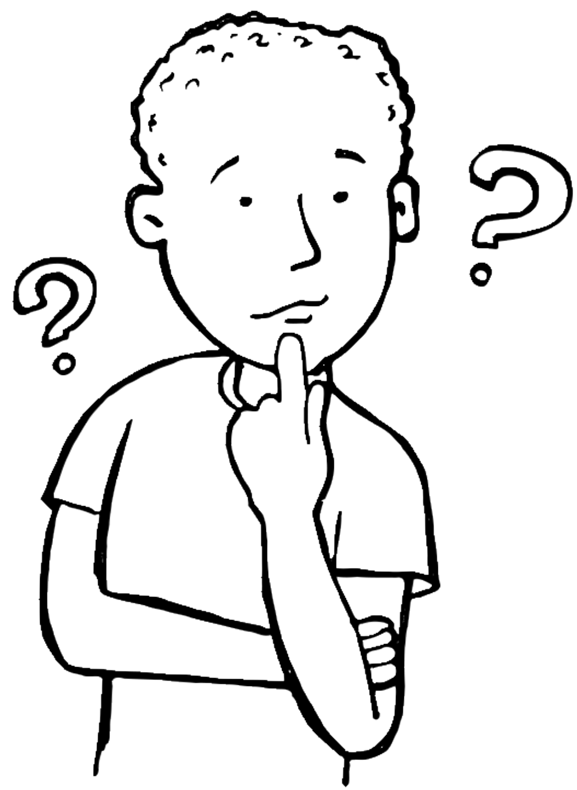
- Dispersive delay can be exactly removed by applying a filter H(υ) with transfer function

$$H(\nu_0+\nu)=\exp\left(\frac{-i\,2\pi\,DM\,\nu^2}{2.41\times10^{-10}\,\nu_0^2(\nu_0+\nu)}\right)$$

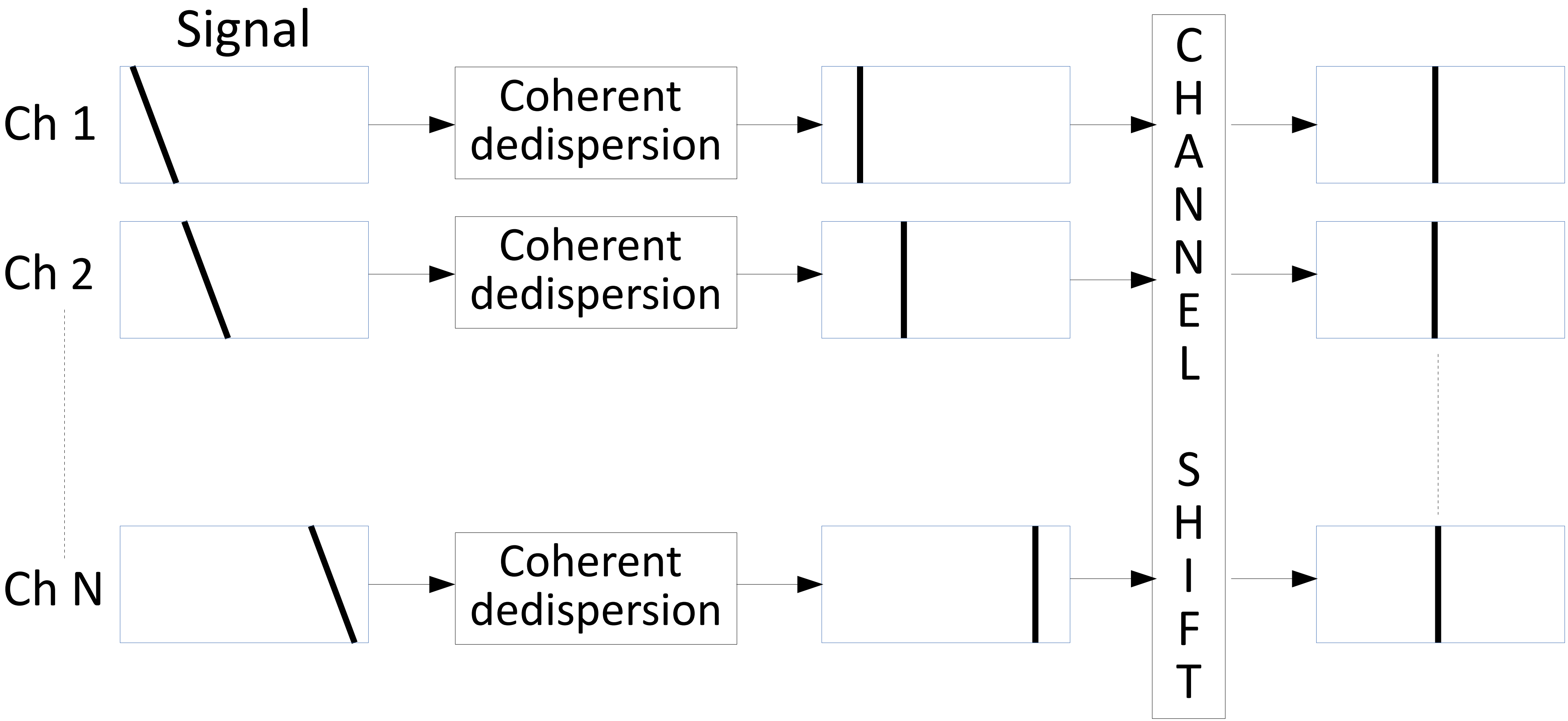
- Filter is applied in overlap – add structure



# Questions?

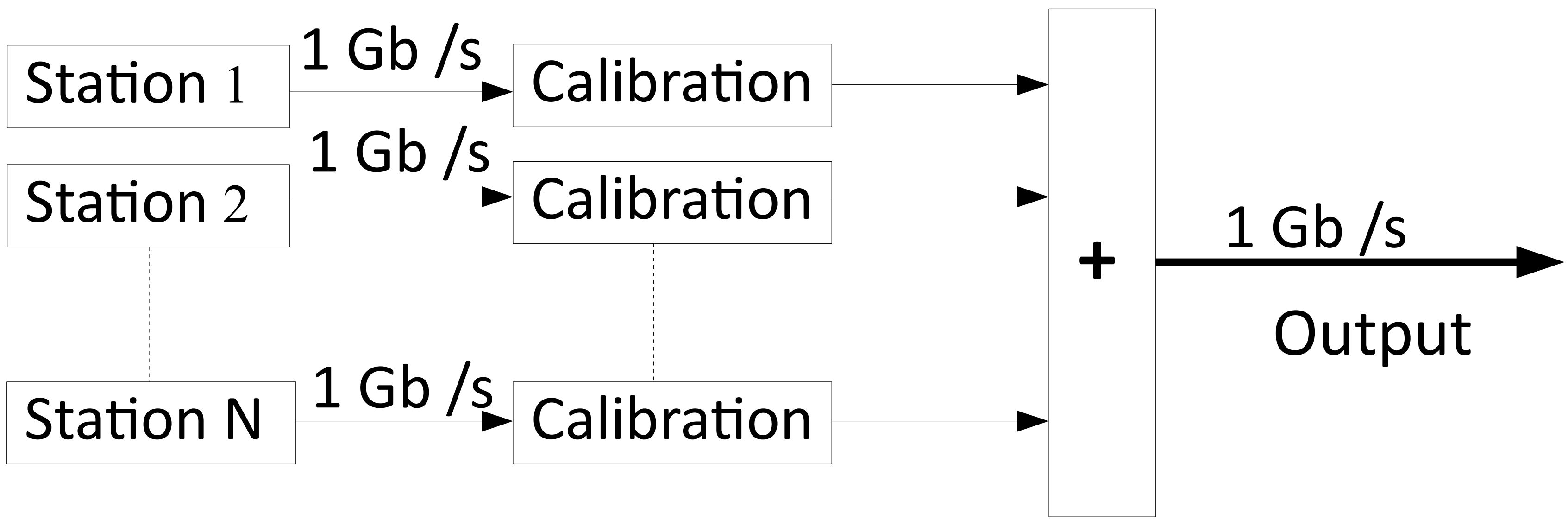


# Coherent filterbank




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

# Data rate decimation

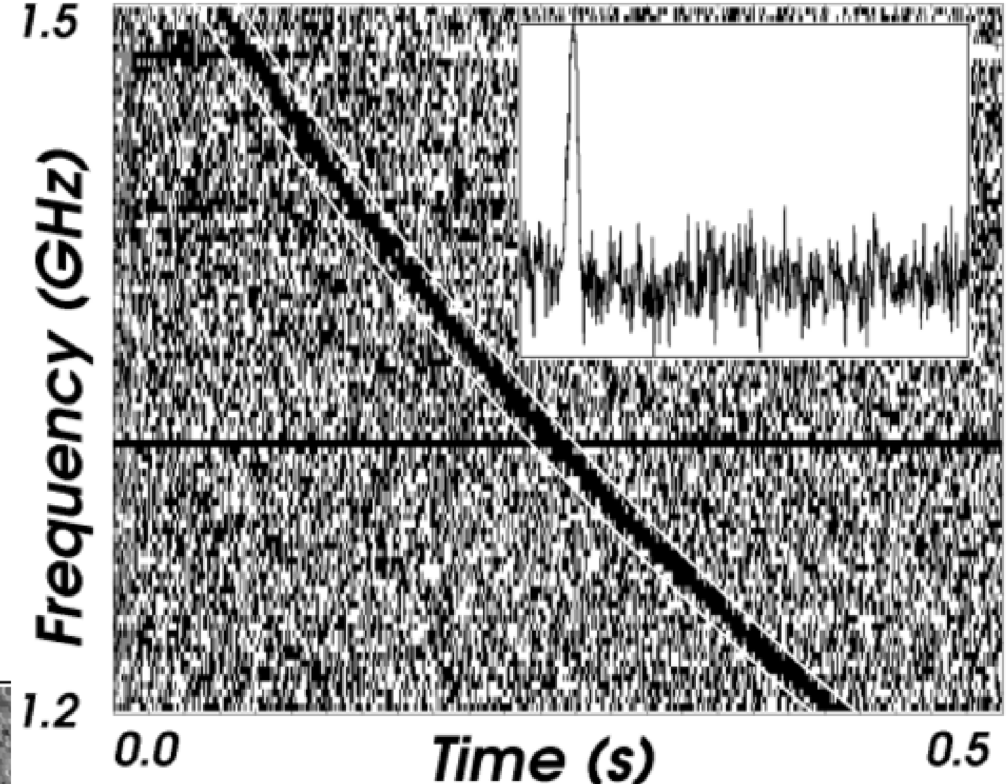


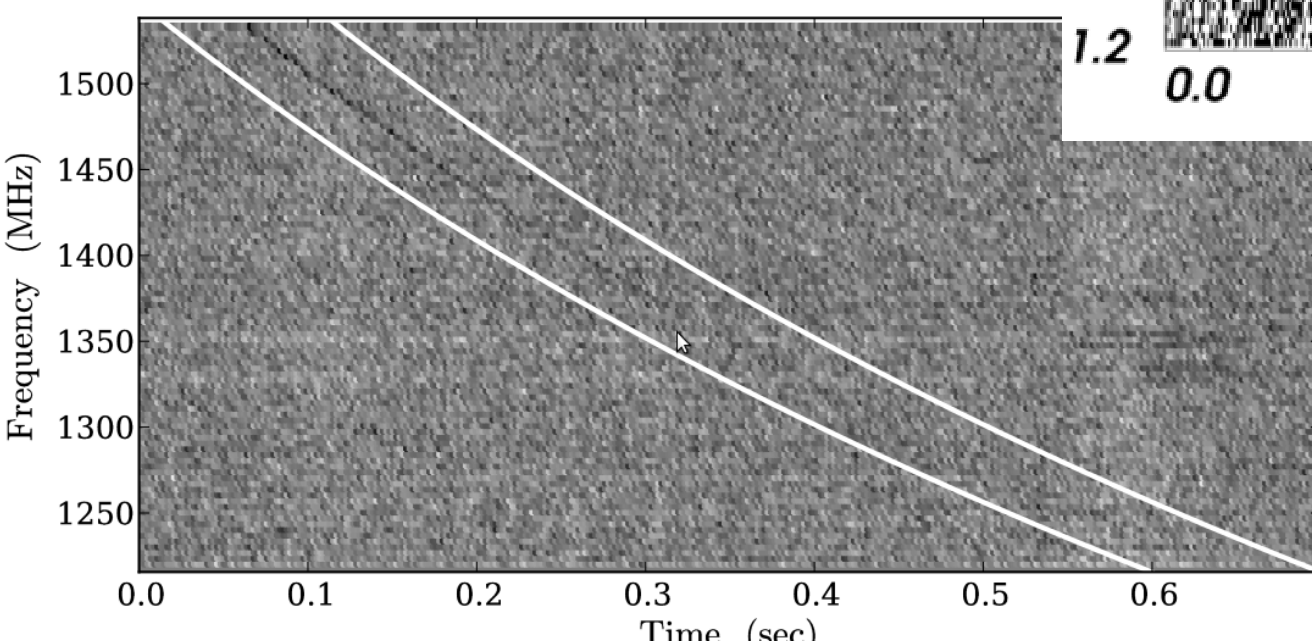

- Voltage data has very high data rate
- For known pulsars data rate can be reduced by folding pulsar inside the correlator (*planned feature*)
- Impractical for finding new pulsars

# 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*