Beams and correlators

Aard Keimpema

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JIVE
Joint Institute for VLBI
ERIC

SFXC

- MPI application written in C++
- Runs on generic linux based computing clusters
- Used for all correlation at JIVE
- Has a rich set of features, including:
  - Mixed bandwidth correlation
  - Tsys extraction
  - Pulsar binning / gating
  - Coherent dedispersion
  - Multiple simultaneous phase centers
  - Phased array mode

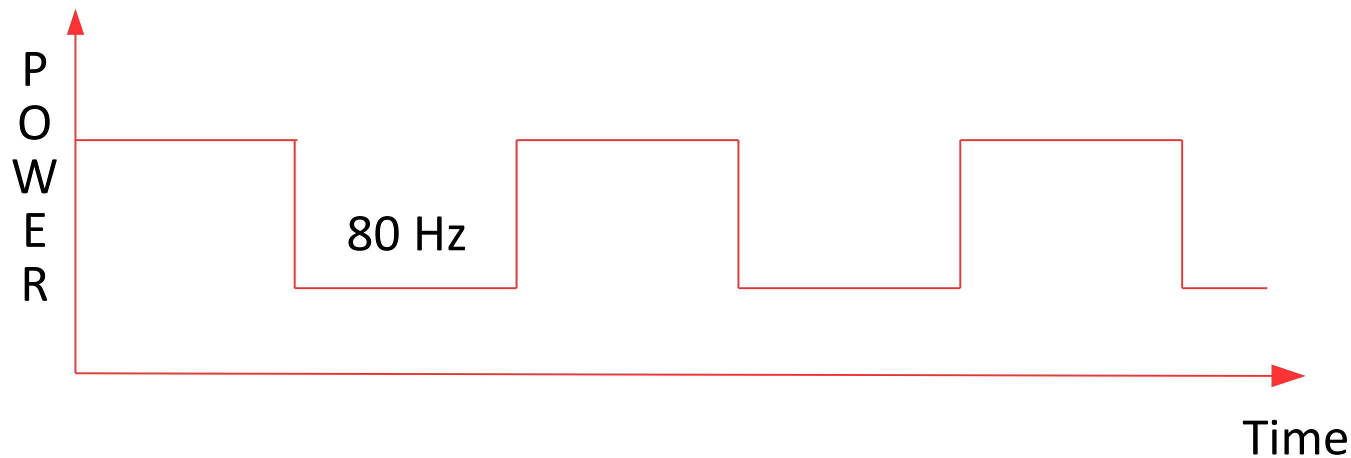
Obtaining SFXC

- Nightly mirror of development repo: https://svn.astron.nl/sfxc
- Installation instructions http://www.jive.nl/jivewiki/doku.php?id=sfxc
- Tools for conversion to MeasurementSet and FITS-IDI: http://www.jive.nl/~kettenis/sfxc/tools
- SFXC is Open Source software available under GPL version 2 or later

Keimpema, Kettenis, Pogrebenko, et al., Experimental Astronomy, ***39****, 259 (2015).*

- 41 nodes (+ 2 FlexBuff and 23 Mark5 units)
- 396 cores (E5520, E6520, E5-2670, E5-2630 v2)
- QDR Infiniband + 8 nodes with 10 GbE
- 14 stations @1024 Mbit/s real-time

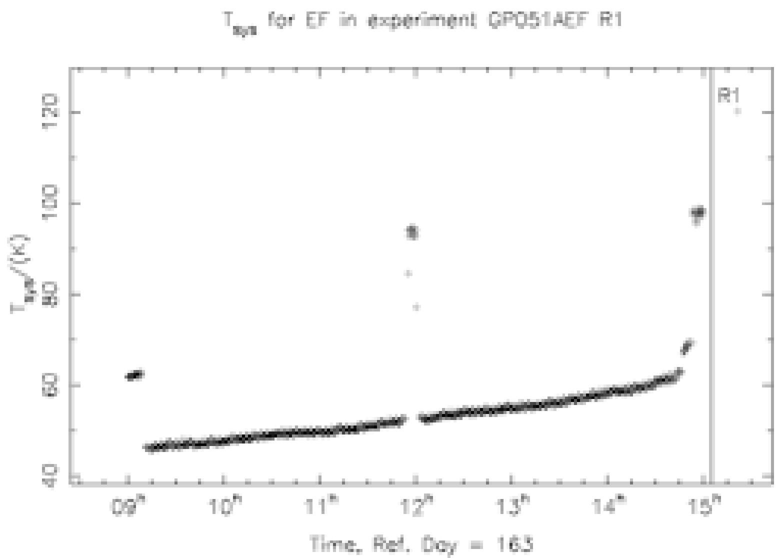
T_{sys} Measurments in SFXC

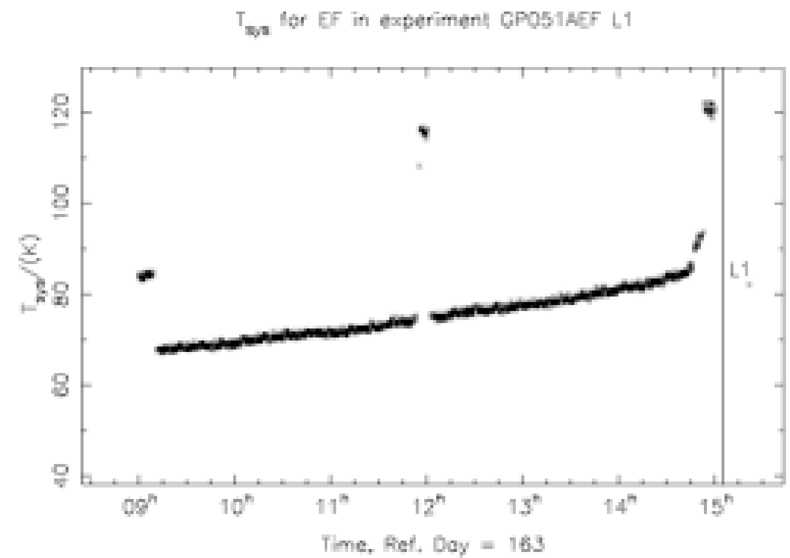


- 80 Hz switched power signal is injected into data stream
- Ratio between between on-off power is computed from samples statistics
- Very small overhead; all samples used
- See VLBA Sensitivity Upgrade Memo 34 (Brisken)

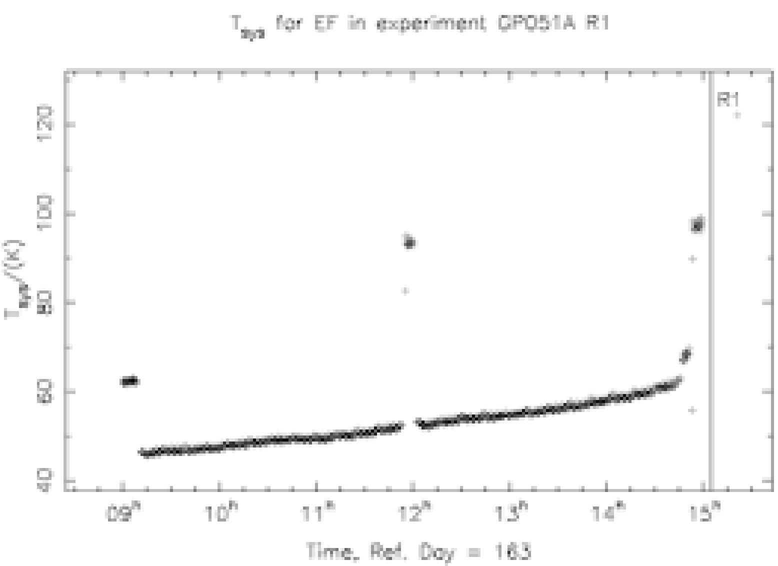
T_{sys} Measurements in SFXC

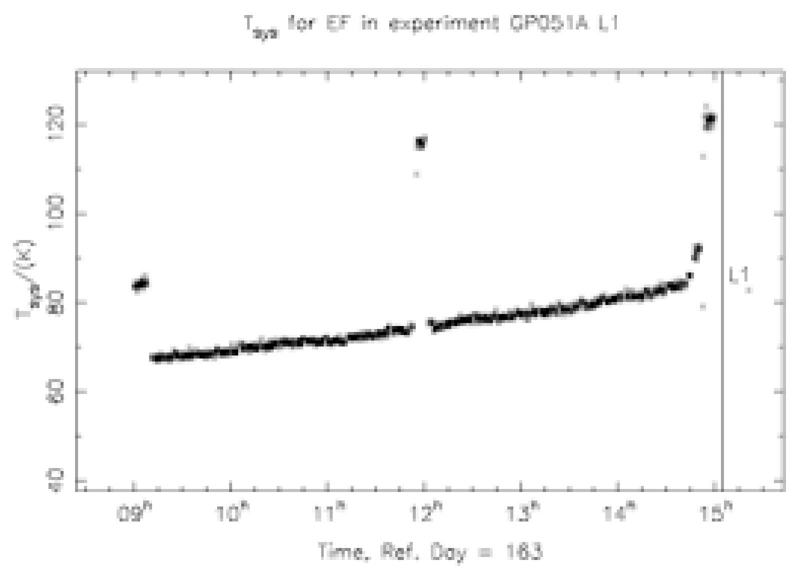
DBBC



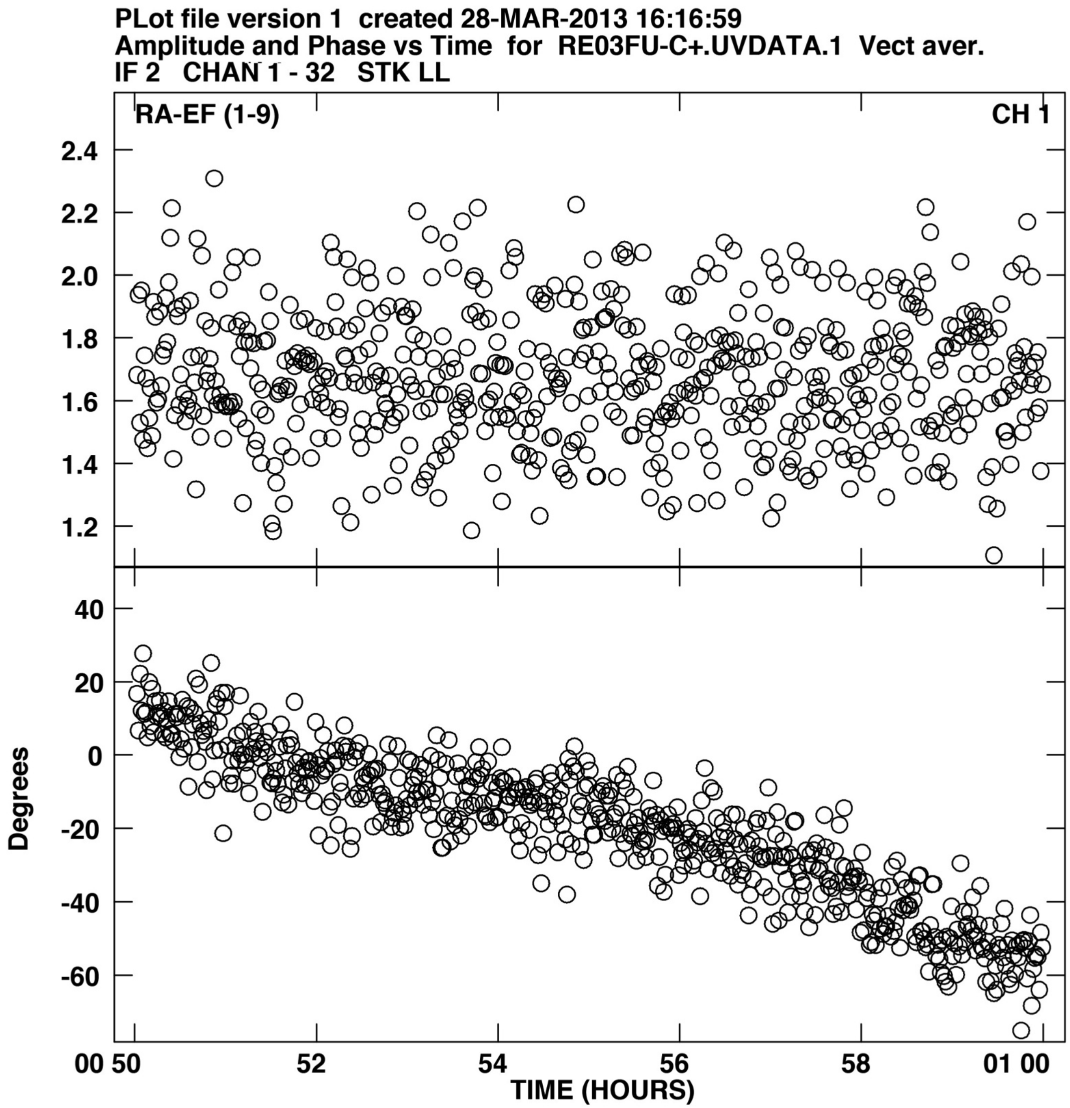


SFXC





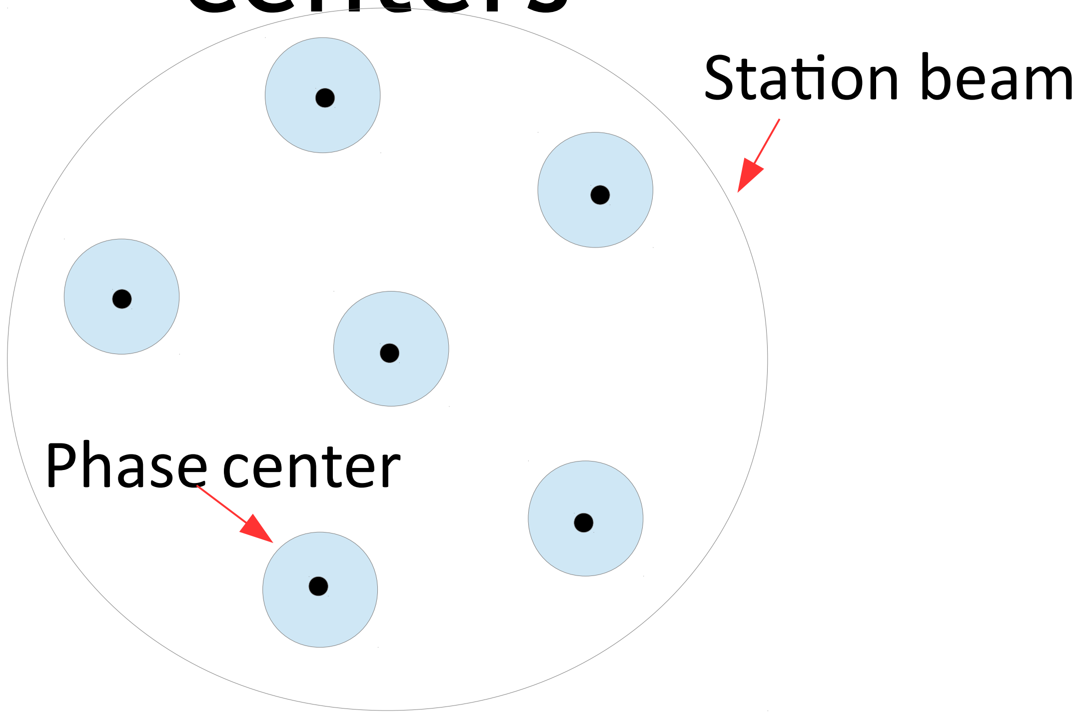
Radio Astron



Fringe amplitude (top, arbitrary units, uncalibrated) and phases (bottom, degrees) at 5 GHz, baseline Ra-Ef, integration 1s per point.

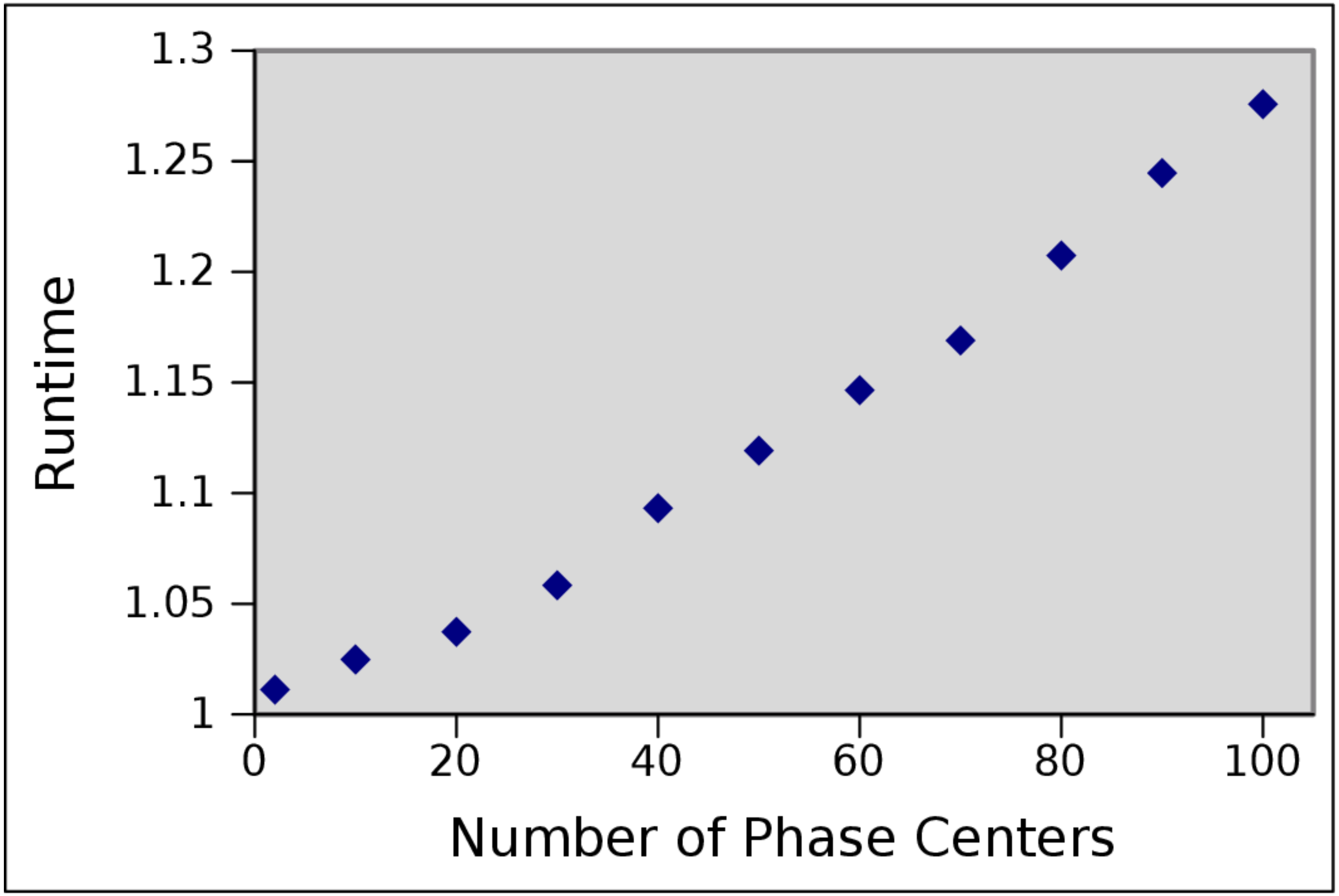
- Correlated using delay model by Duev et al., A&A **573**, 99 (2015)

Multiple simultaneous phase centers



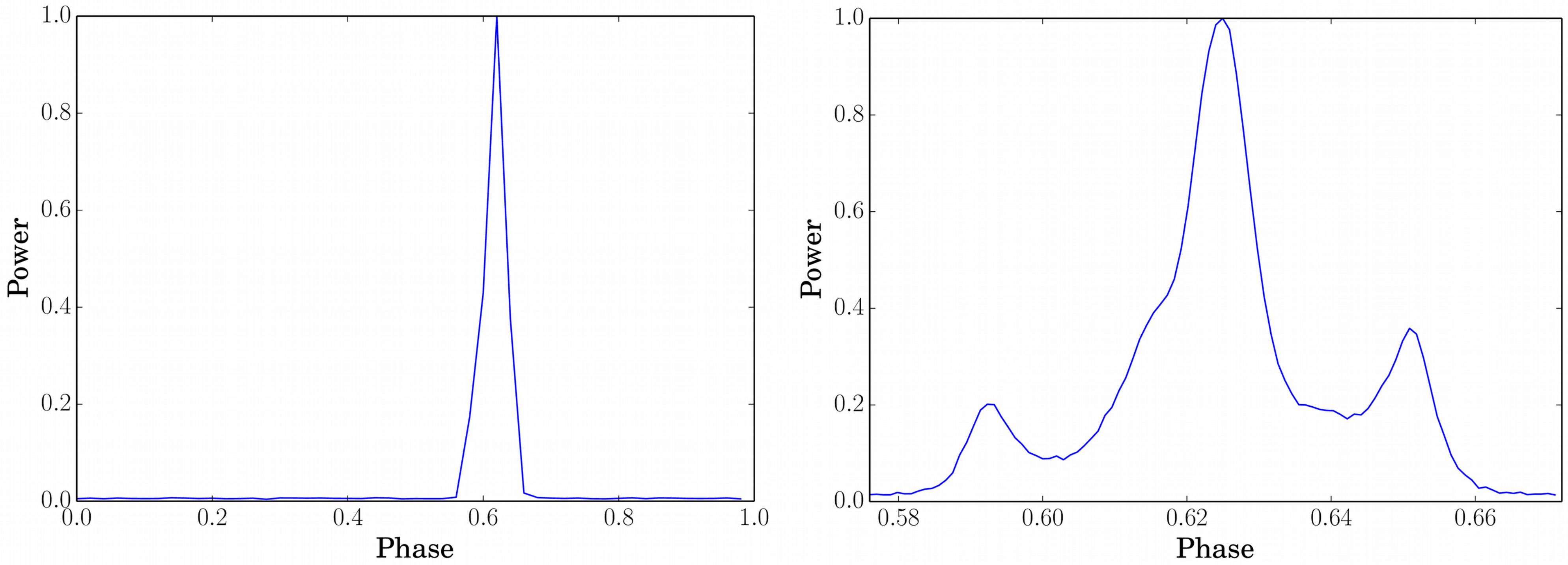
- Internally correlate at high temporal / spectral resolution
- Output a narrow field data set for each source in the beam
- On average 30-50% slowdown but each additional phase center comes at very little additional cost
- Requires an addition primary beam correction

Multiple simultaneous phase centers



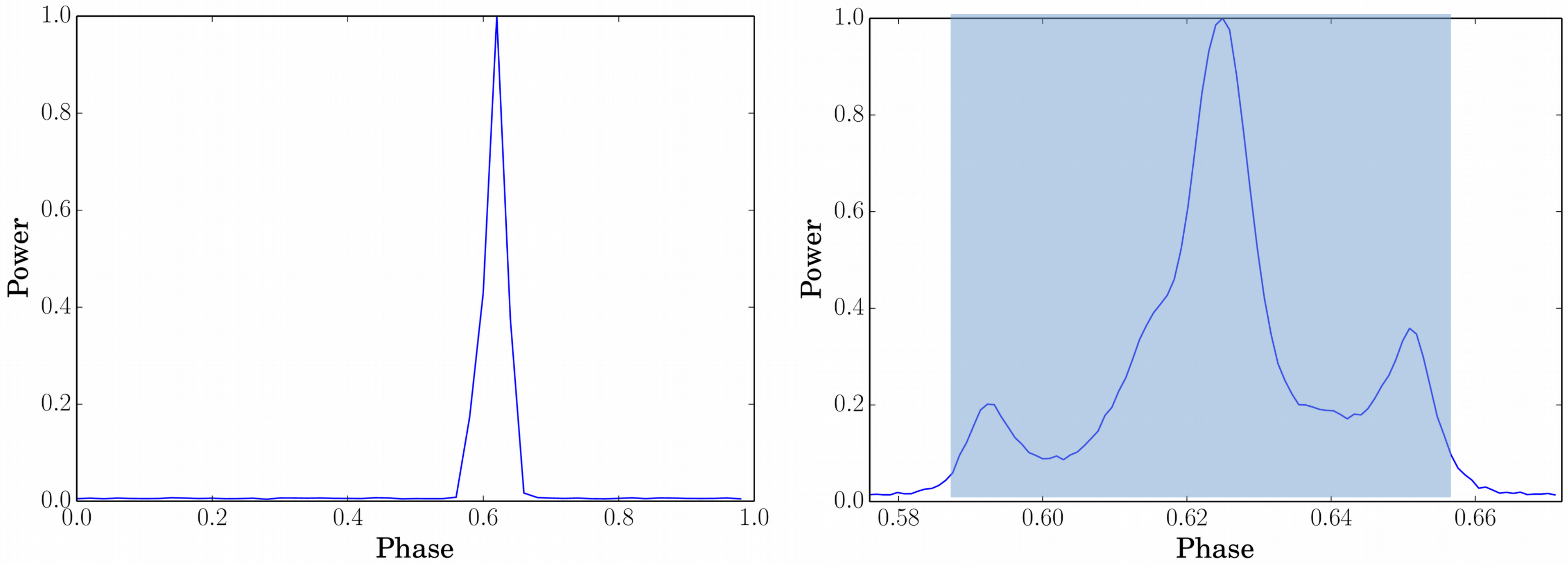
Going from 2 to 100 sources requires only 30% more correlation time!

Pulsar gating



- Increase SNR by only accumulating when the pulsar is on
- Improvement in SNR typically factor 3-5
- Requires TEMPO polyco model of the pulsar

Pulsar gating



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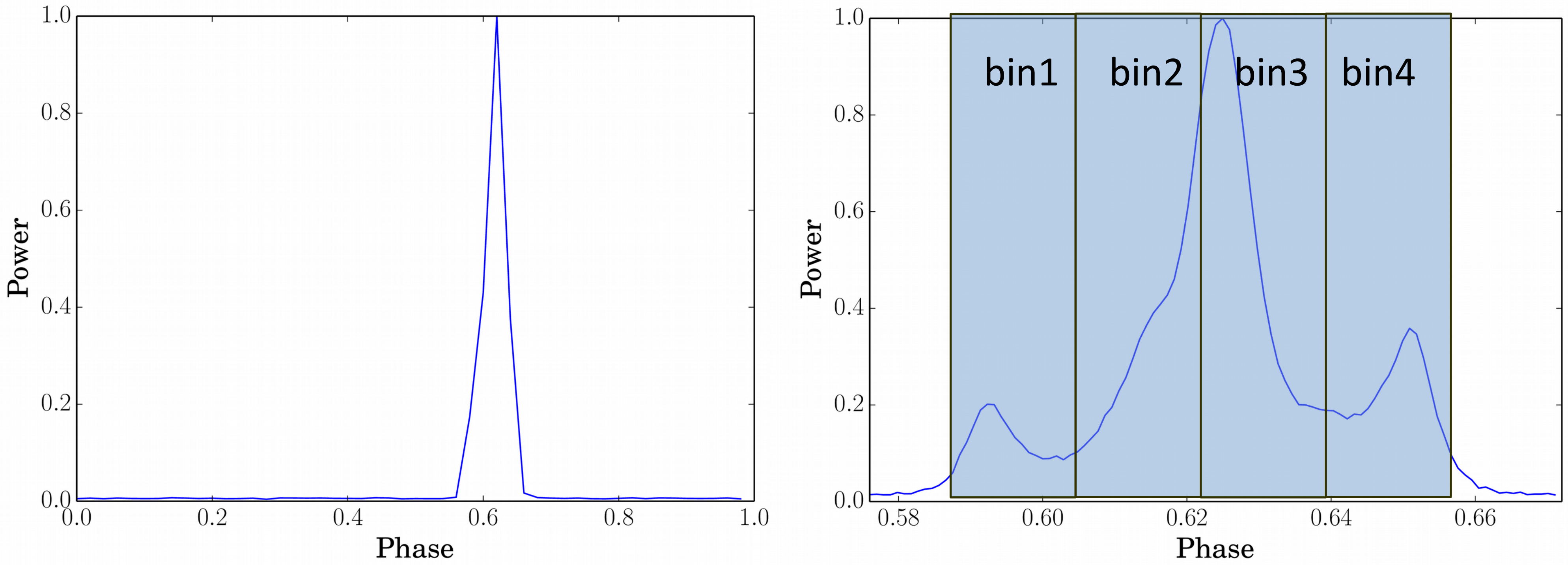
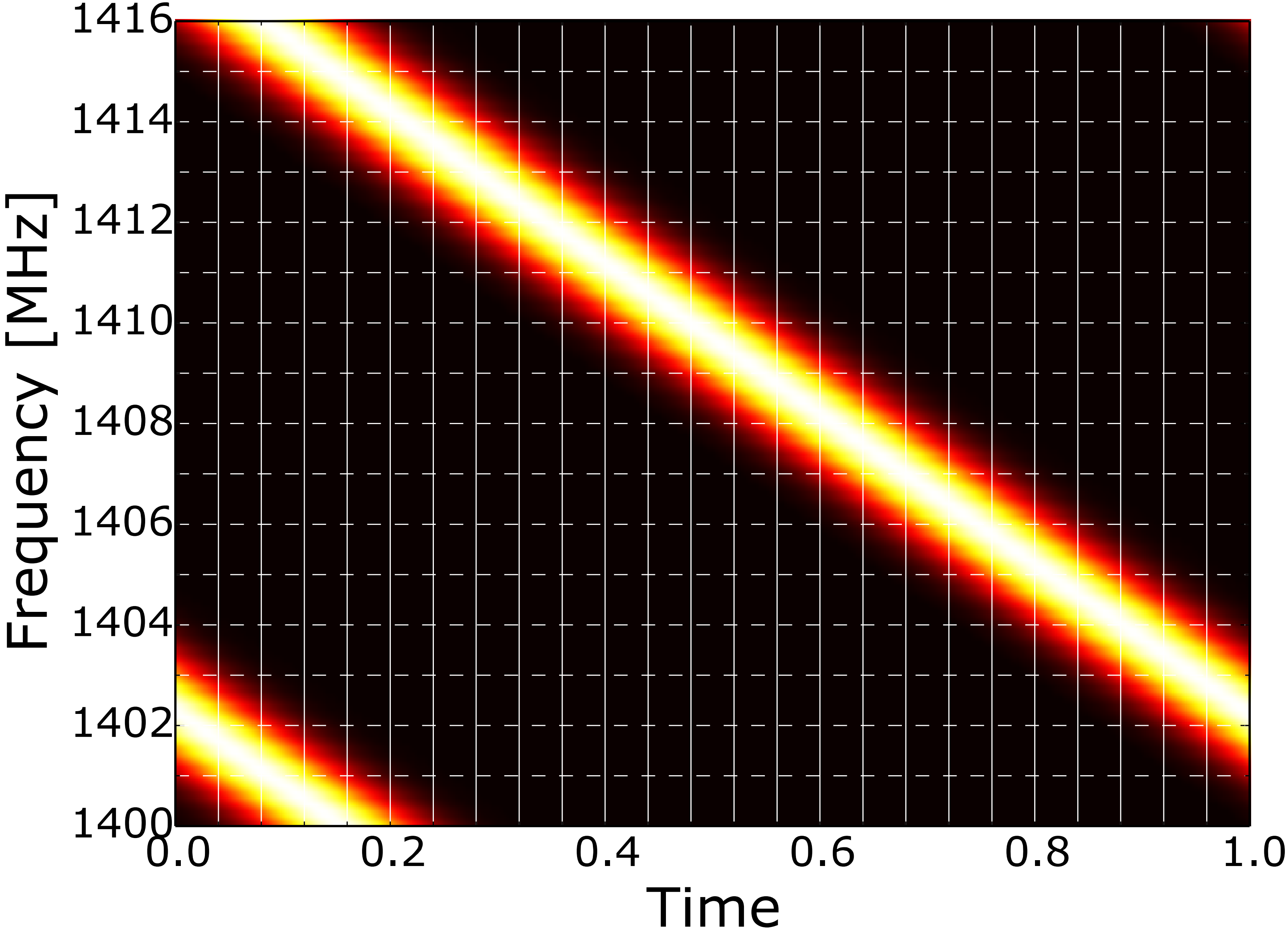
Pulsar binning



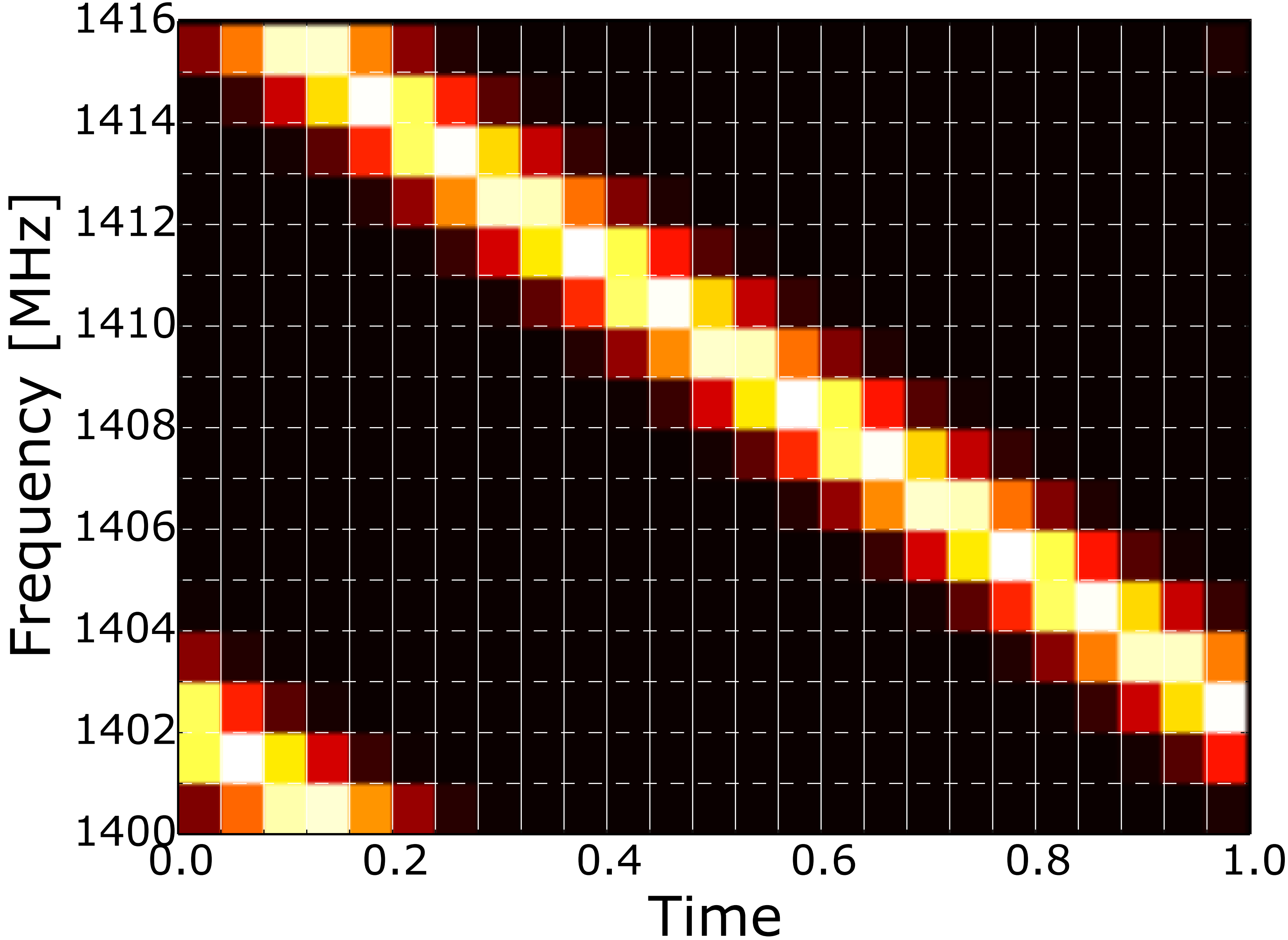
- Divide the pulse into multiple bins and accumulate the correlation function for each bin seperately.
- Each bin is output to a separate file

Dispersion



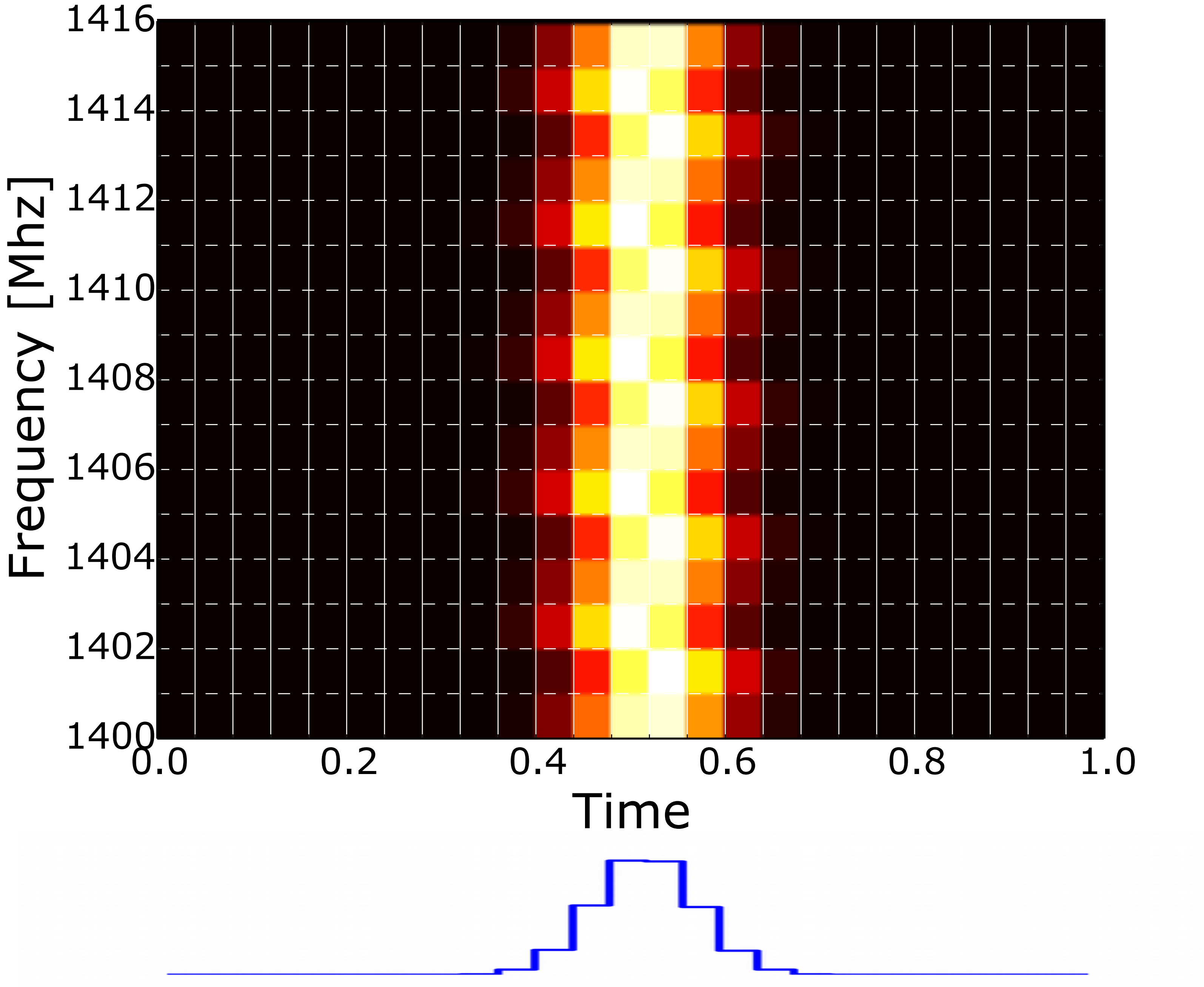
Dispersive delay : $\Delta t \approx 4.15 \times 10^{6} \times DM \times (\nu_1^{-2} - \nu_2^{-2}) [ms]$

Dispersion

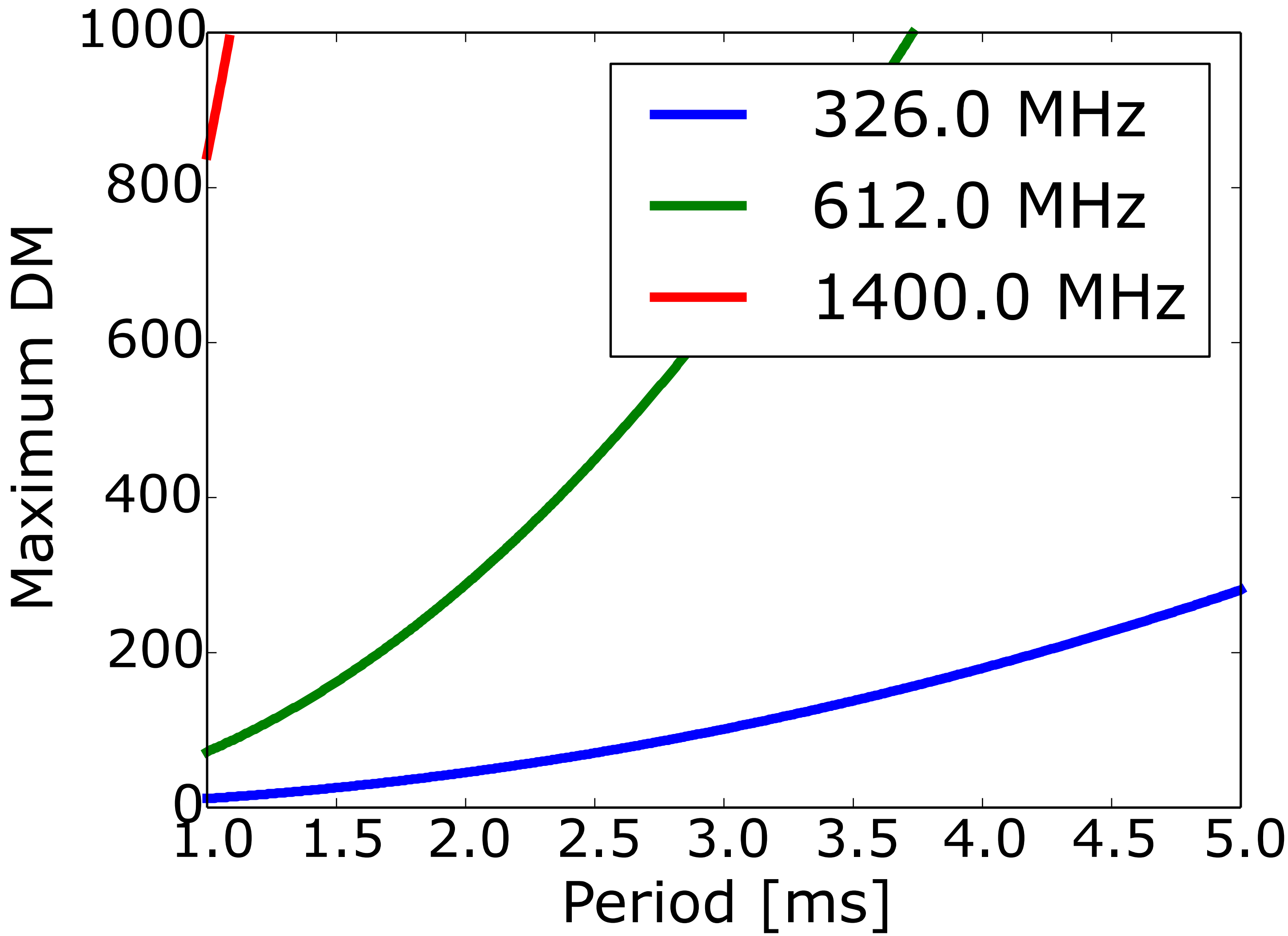


Dispersive delay : $\Delta t \approx 4.15 \times 10^6 \times DM \times \left(\nu_1^{-2} - \nu_2^{-2}\right)[ms]$

Incoherent de-dispersion



Limits to incoherent dedispersion



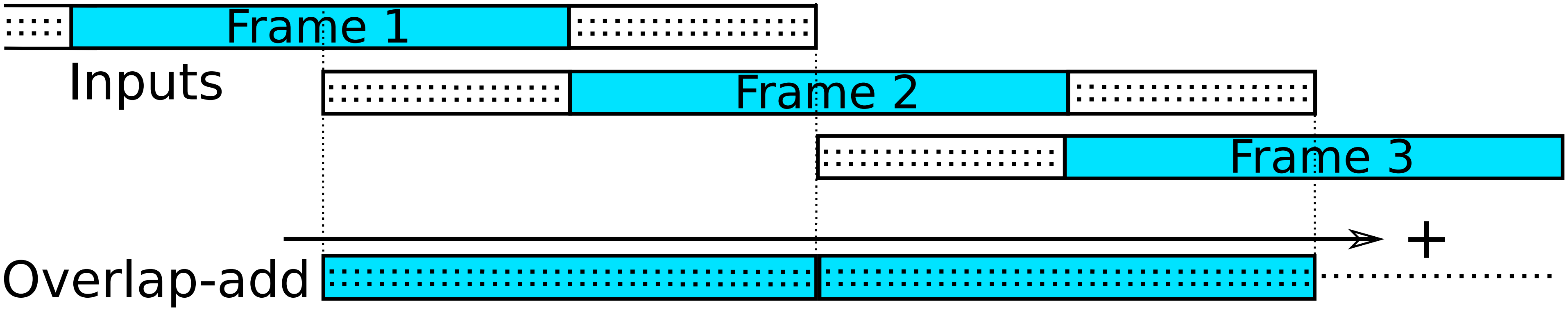
- Maximum dispersion measure for which dispersive delay and FFT length are within half a pulse width.
- Pulse width is 5% of pulse period

Coherent de-dispersion

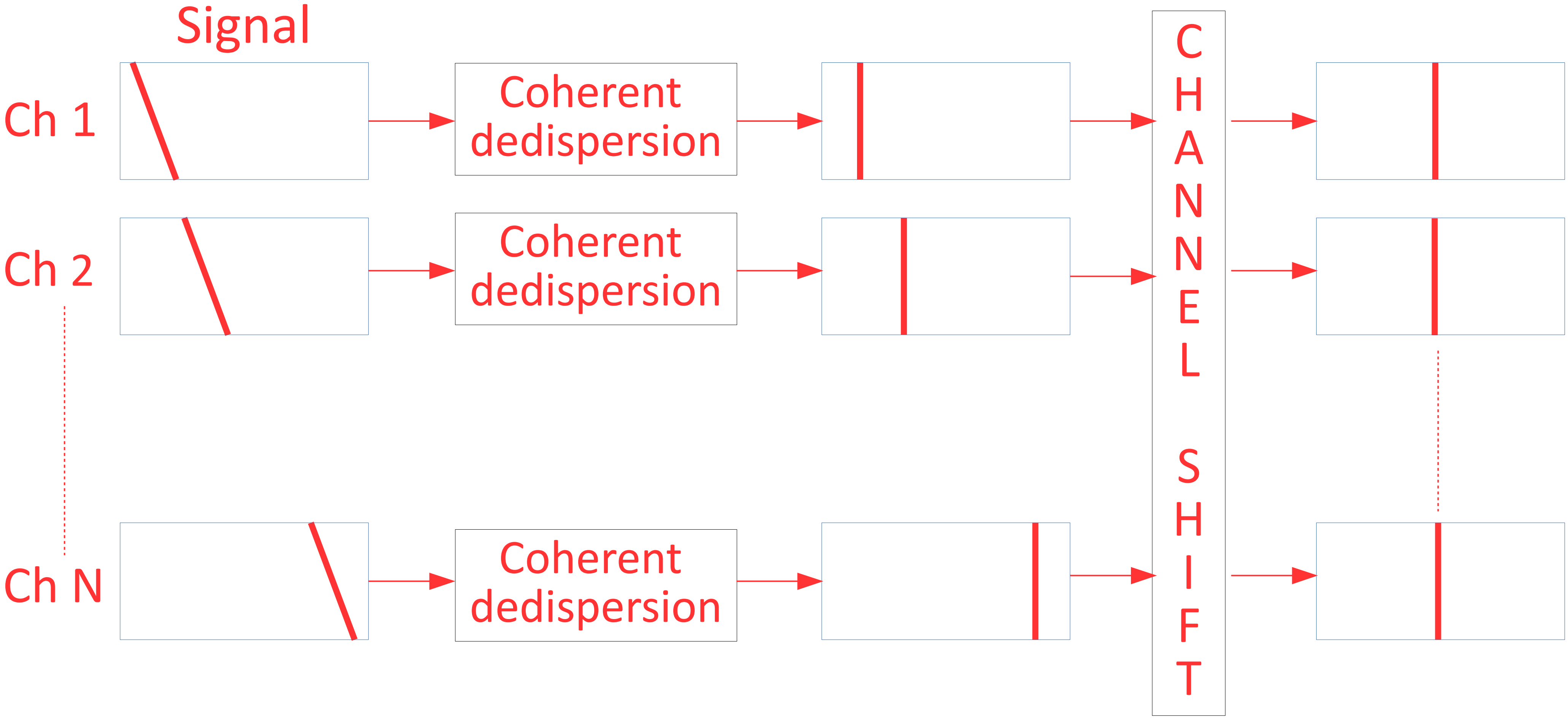
- Dispersive delay can be exactly removed by applying a filter H(υ) with transfer function

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

- Filter is applied in overlap – add structure

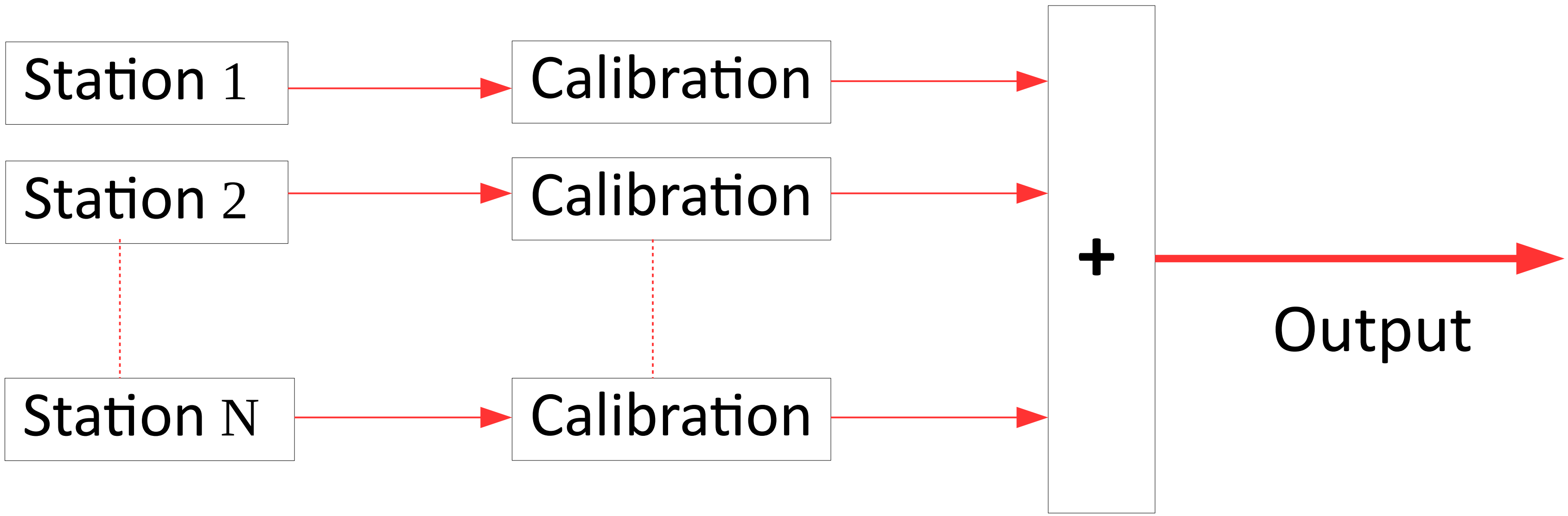


Coherent filterbank



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

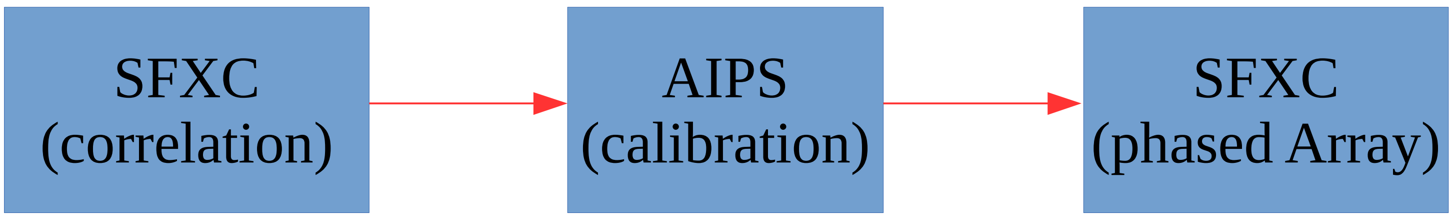
Phased Array Mode



- 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

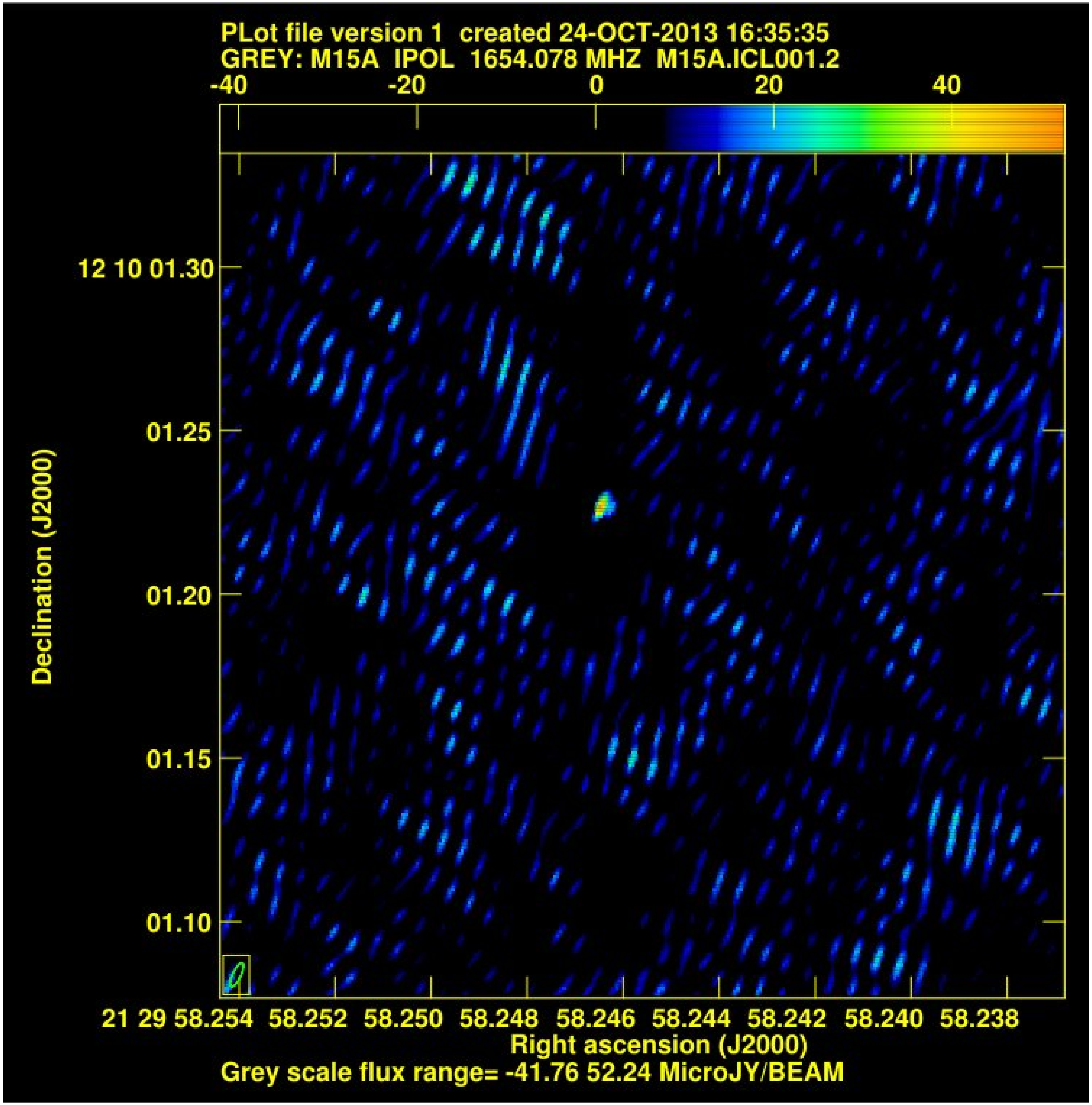
Calibration

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

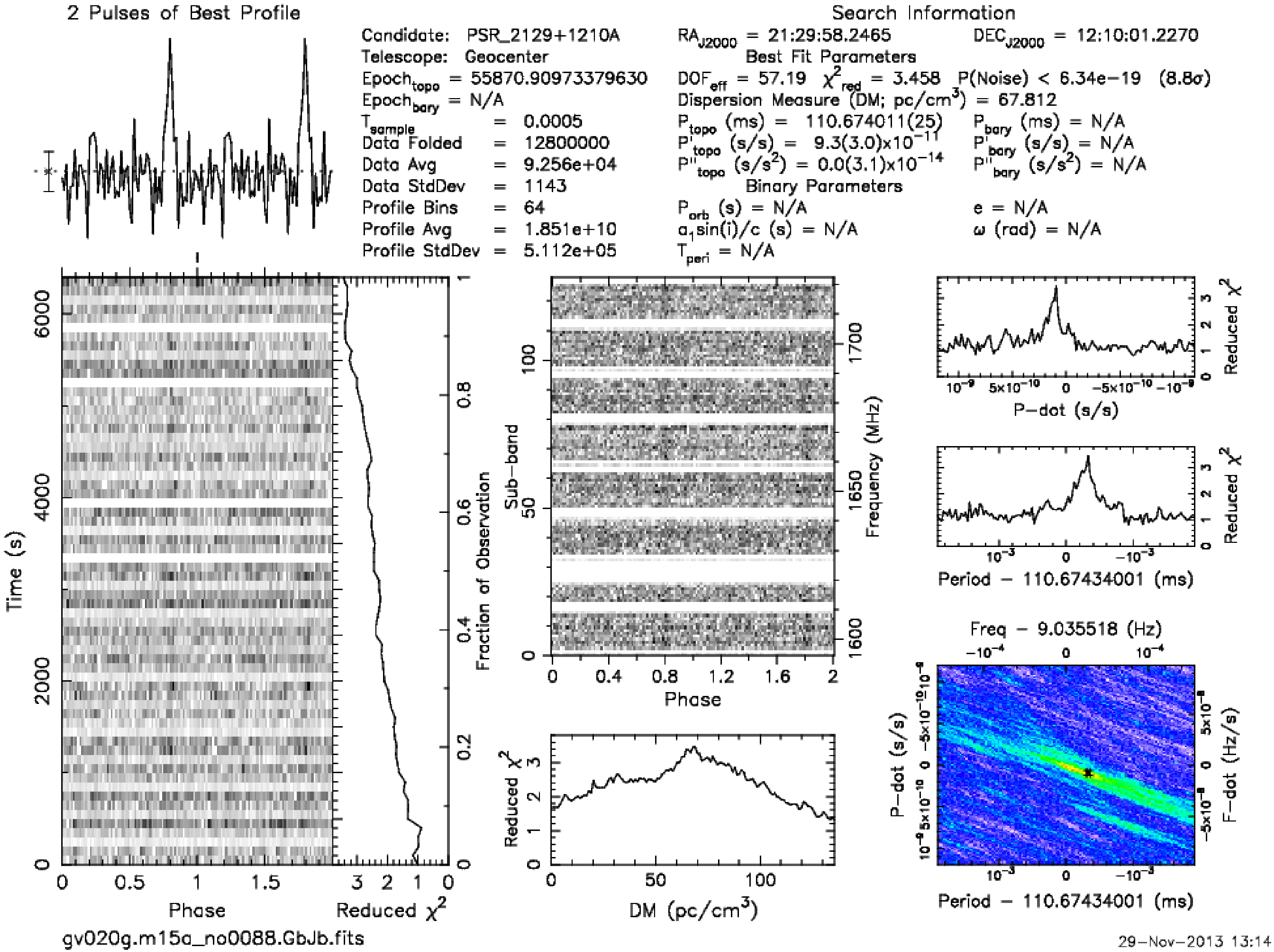


- Two pass process, data is first correlated like a regular VLBI experiment and the usual data reduction steps are performed in AIPS.
- Calibration (CL) and bandpass (BP) tables from AIPS are exported back to the correlator.
- Bad frequency channels are masked in BP table
- Calibration tables are then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

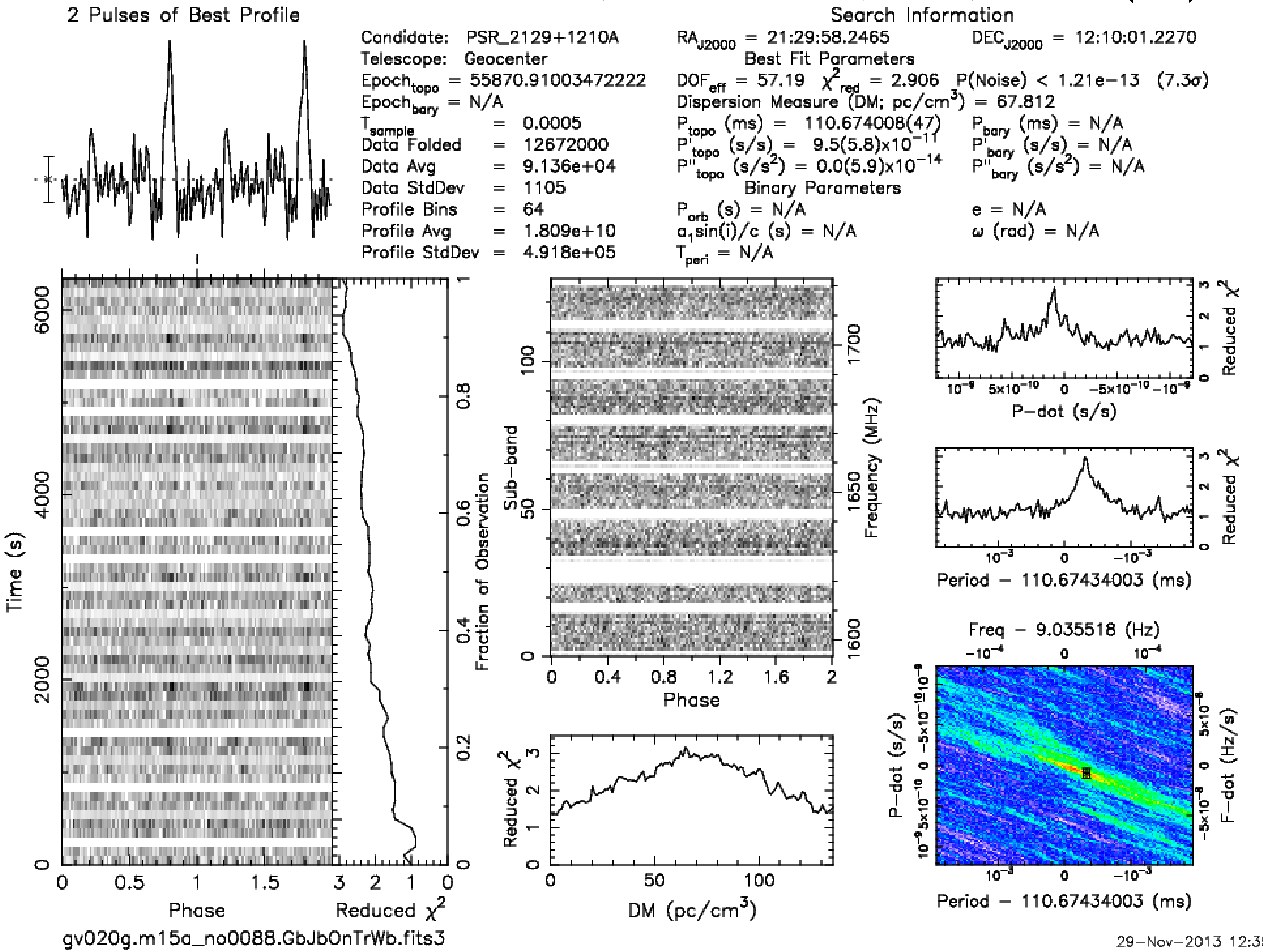
M15A (Kirsten, Vlemmings, et al.)



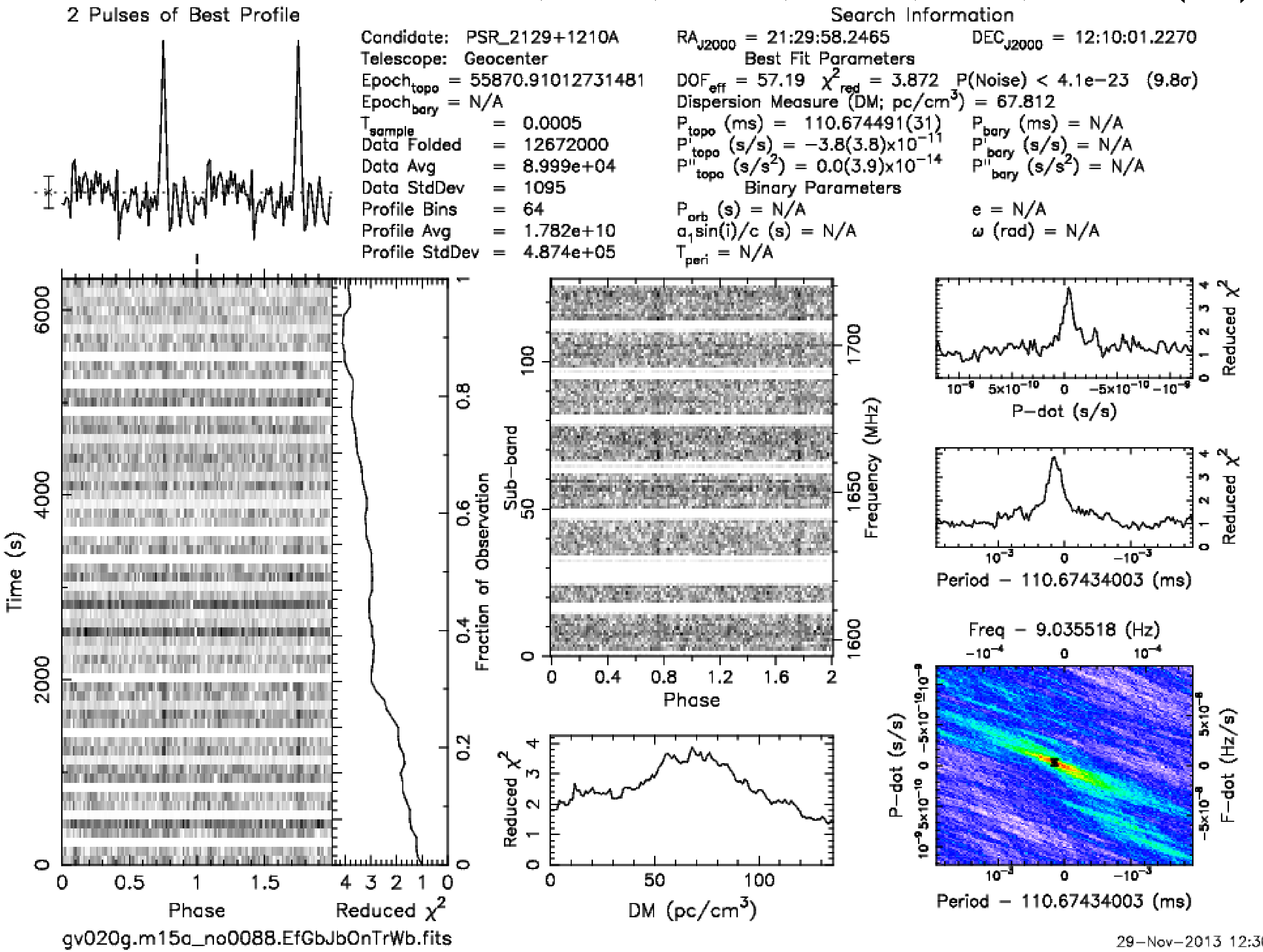
Stations = Jb,Gb



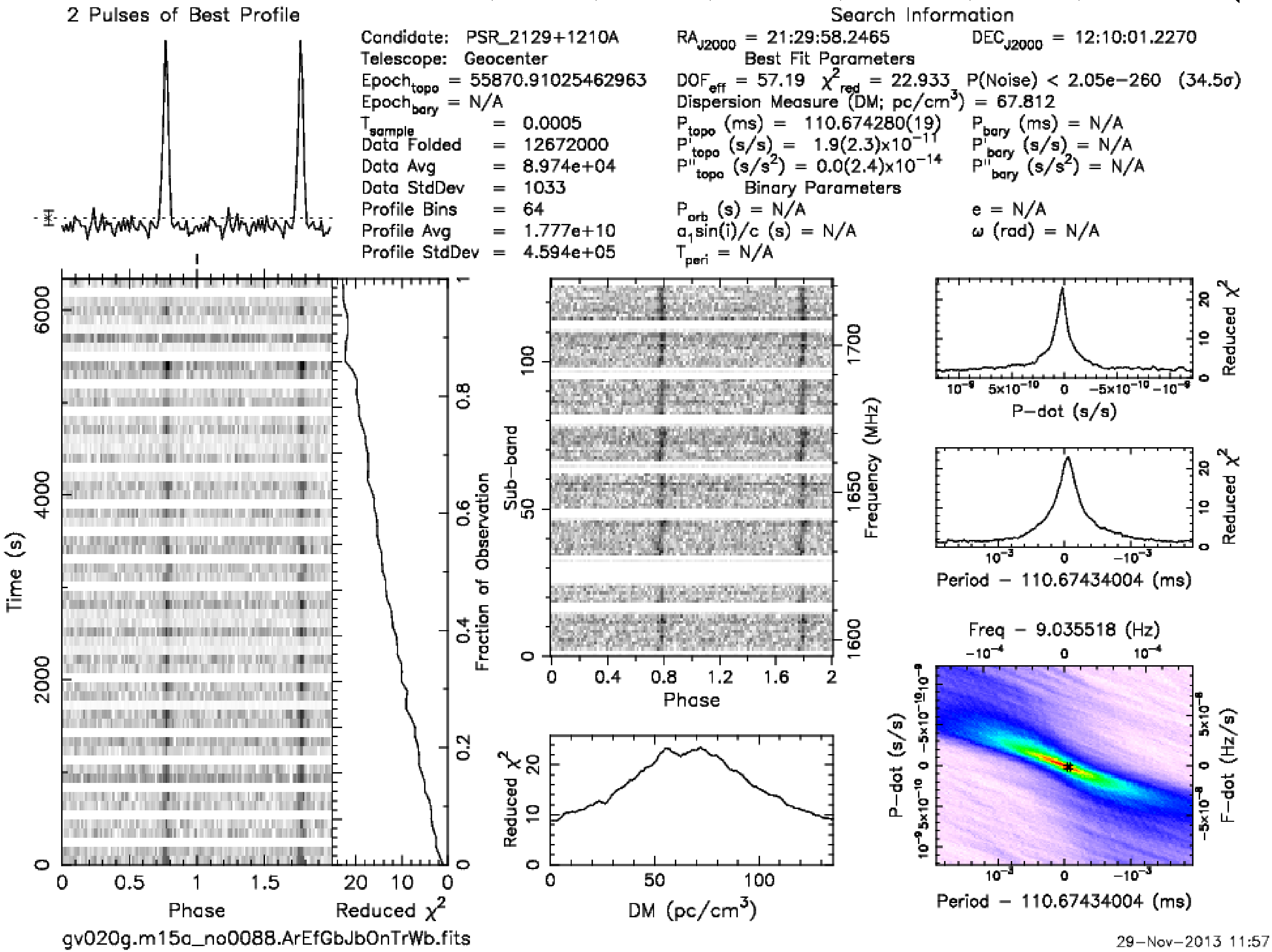
Stations = Jb,Gb,On,Tr,Wb(1)

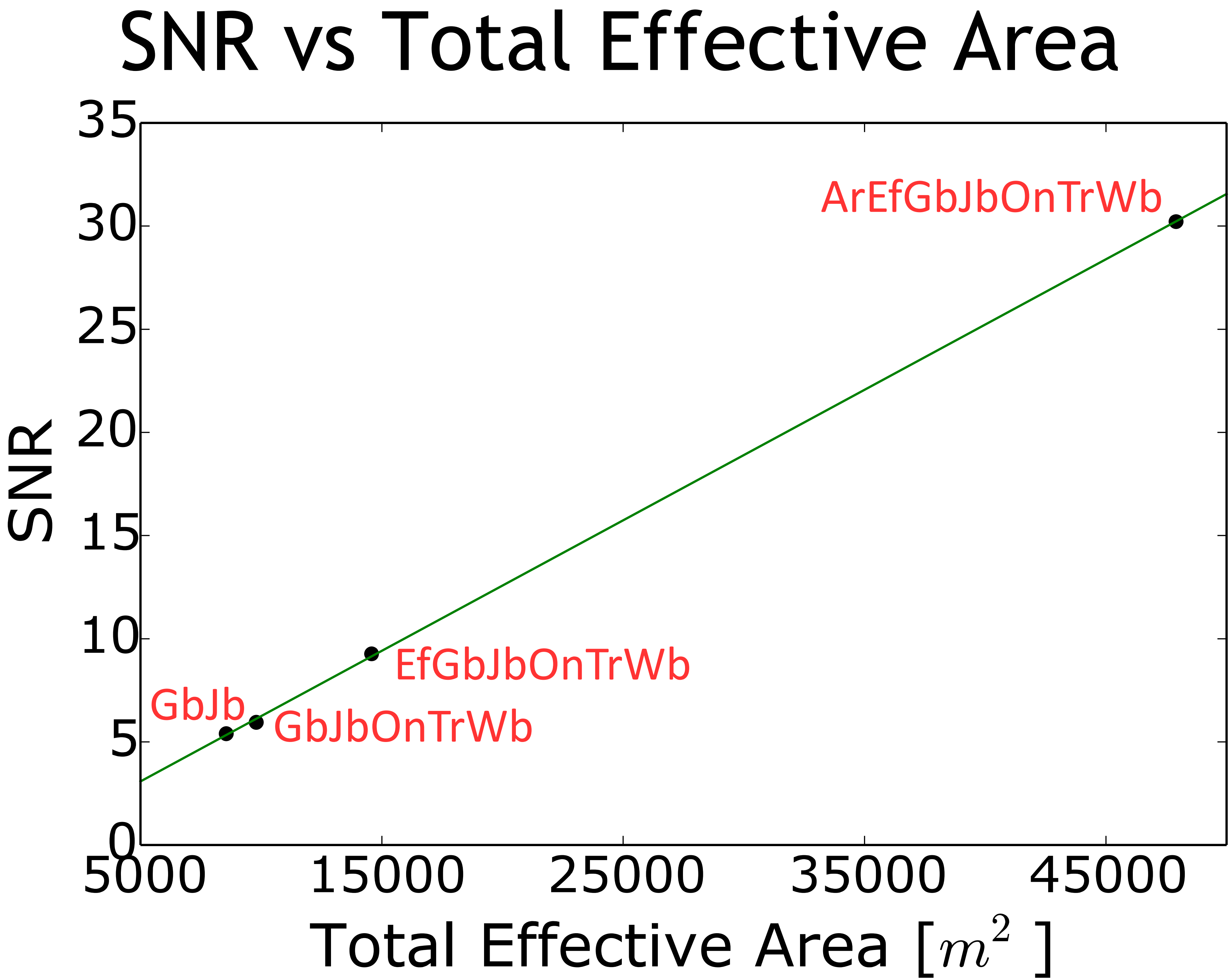


Stations = Ef,Jb,Gb,On,Tr,Wb(1)



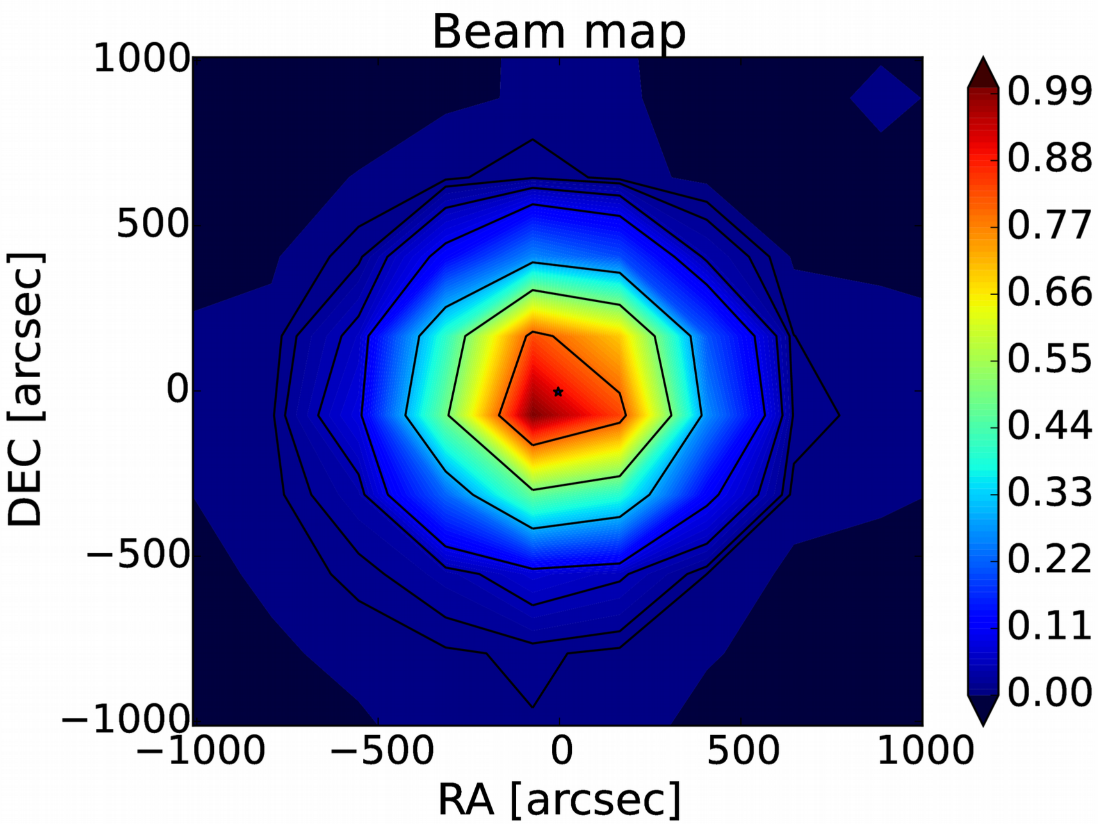
Stations = Ar,Ef,Jb,Gb,On,Tr,Wb(1)

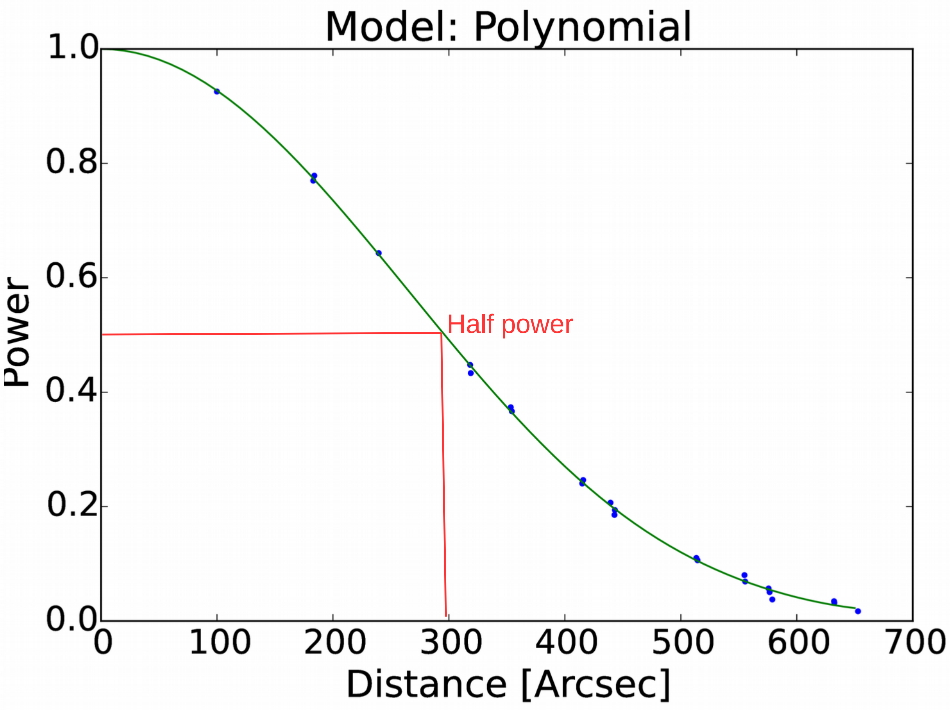



SNR vs Total Effective Area
SNR
0
5
10
15
20
25
30
35
5000
15000
25000
35000
45000
Total Effective Area [m^2]
ArEfGbJbOnTrWb
EfGbJbOnTrWb
GbJb
GbJbOnTrWb

Beam maps

Effelsberg @21 cm, target 3C286





- Series of deliberate mispointings around a point source

Model fitting beam shapes

- Least square fit beam model to beam map
- Written in python
- Supported data formats: FITS, ASCII table
- Example ASCII data:

RA offset	DEC offset	LCP	RCP
-0.196584	-0.154995	0.118596	0.147875
-0.171007	-0.155042	0.246834	0.120844
-0.142839	-0.154967	0.039953	0.127841
-0.114712	-0.154985	0.119025	0.097853

- Supported beam models : Airy, Gaussian, Polynomial

Airy Disk Beam Model

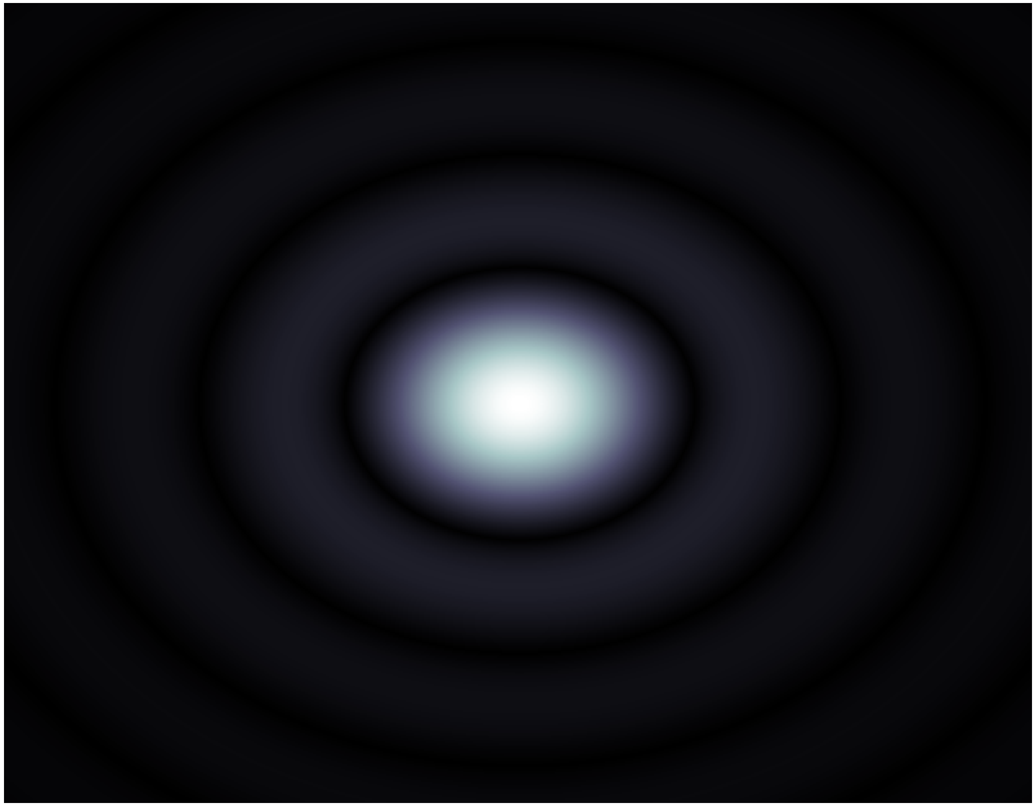
First order model : Uniformly illuminated circular aperture (Airy Disk)

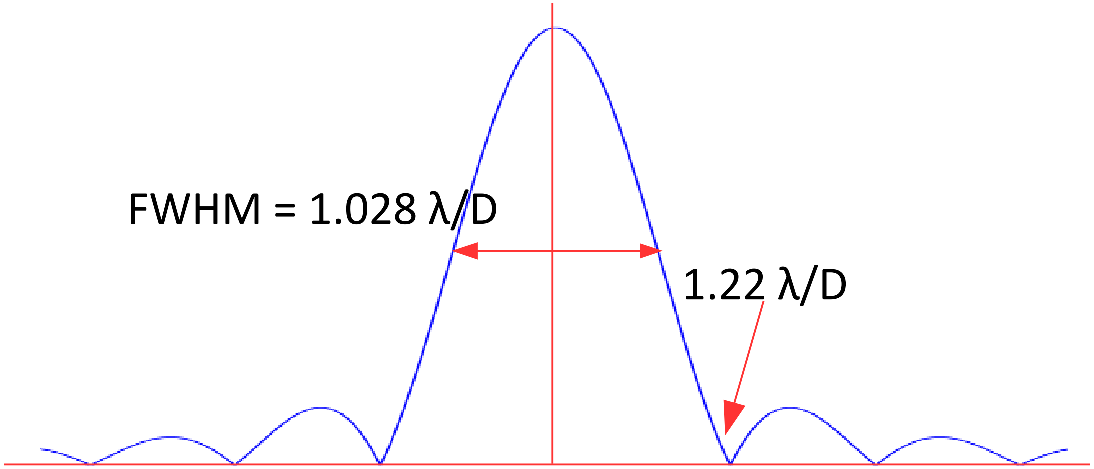
$$I(\theta)=\left|\frac{2J_1(z)}{z}\right|^2, z=\frac{\pi D}{\lambda}\sin(\theta)$$

D = Dish diameter,

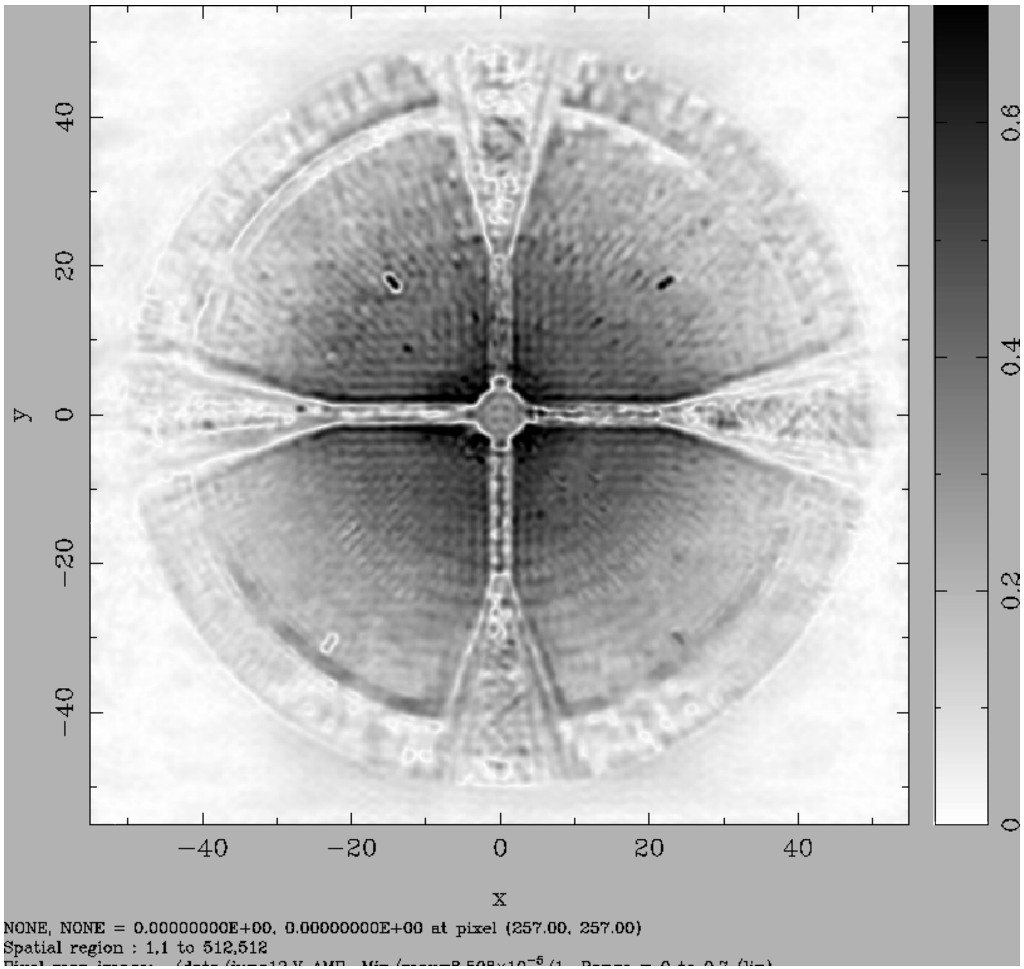
λ = wavelength

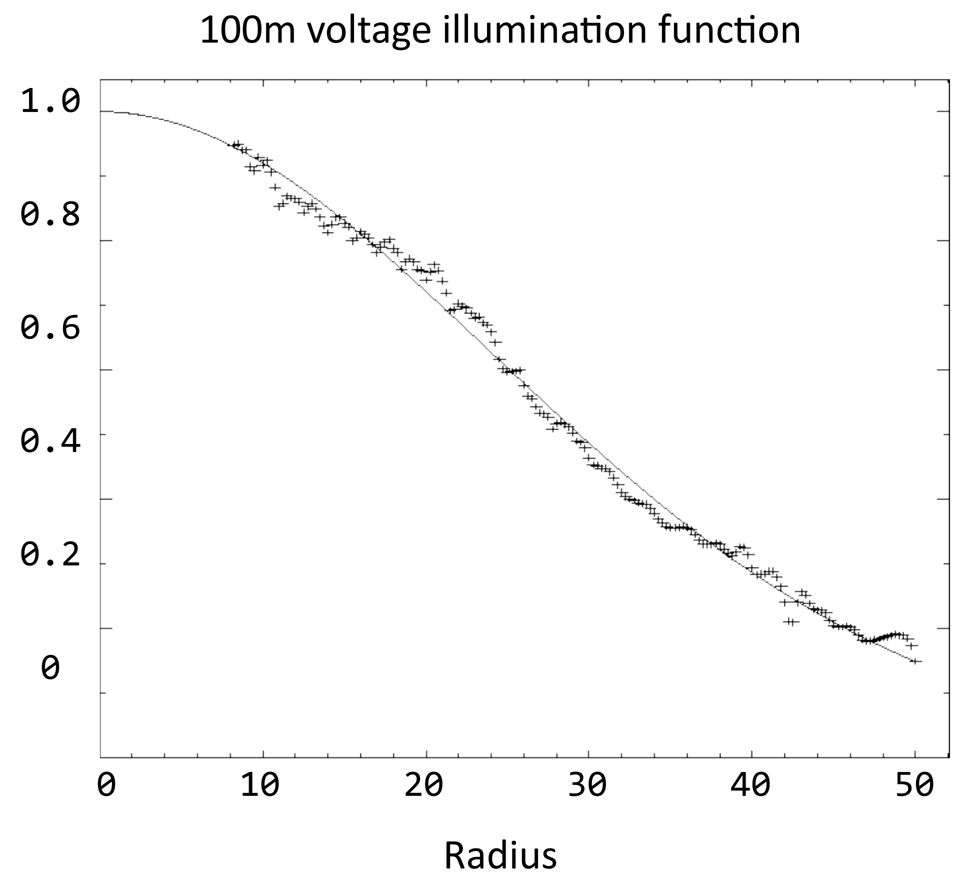
$J_1(z)$ = Bessel function of the first kind





Effelsberg illumination pattern @11.7 Ghz





The Effelsberg Holography Campaign - 2001

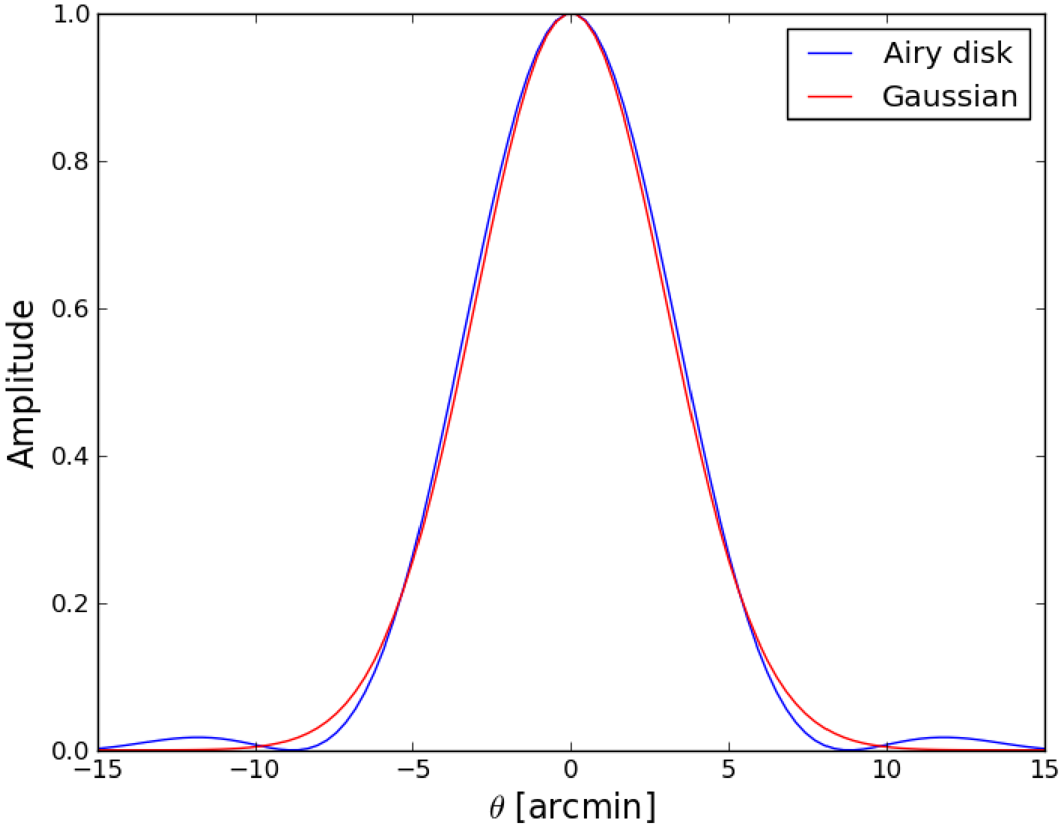
M.Kesteven, D.Graham, E.Fürst, O.Lochner & J.Neidhöfer

Gaussian model

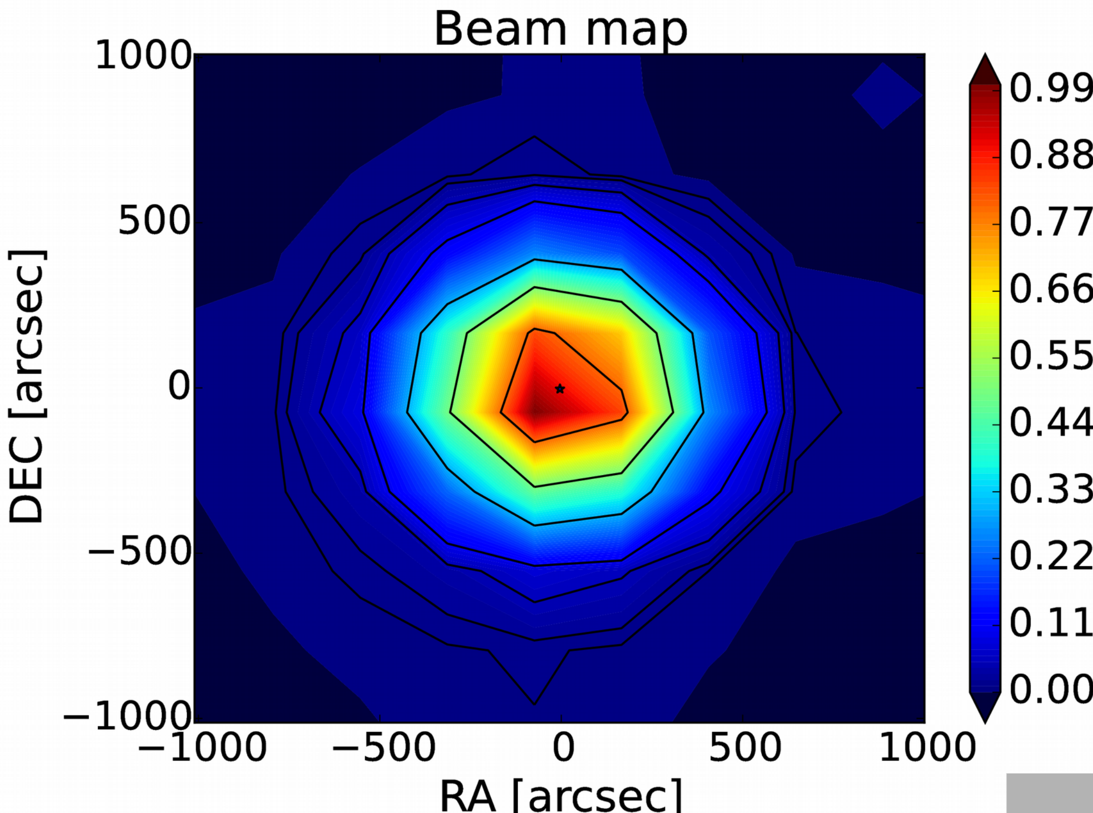
- The Airy disk model can very closely be approximated by a Gaussian model

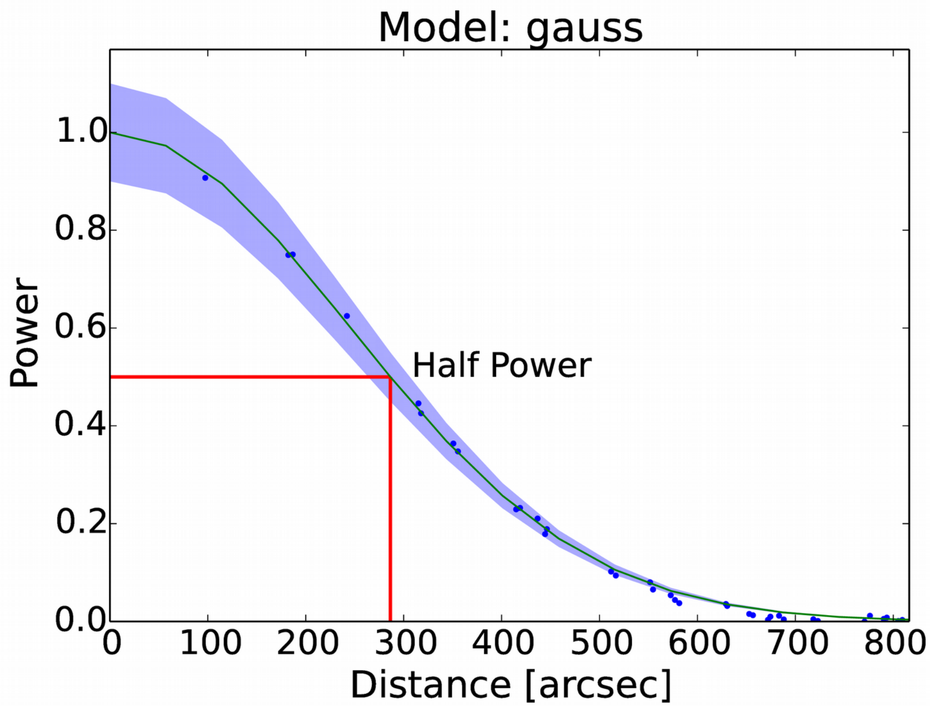
$$I(\theta) = A_0 e^{-\frac{\theta^2}{2\sigma^2}}$$

- The optimum fit is σ = 0.42λ/D, for apperture of width D



Effelsberg @21CM, RCP





	RCP	LCP
X0	-6.88441”	-3.68020”
Y0	-3.42791”	-2.98701
Z	1151.51	1151.6
FWHM	572.9”	574.9”
D_{eff}	75.2 M	75.0 M

Model: $I(x,y)=e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2(z\lambda)^2}}$

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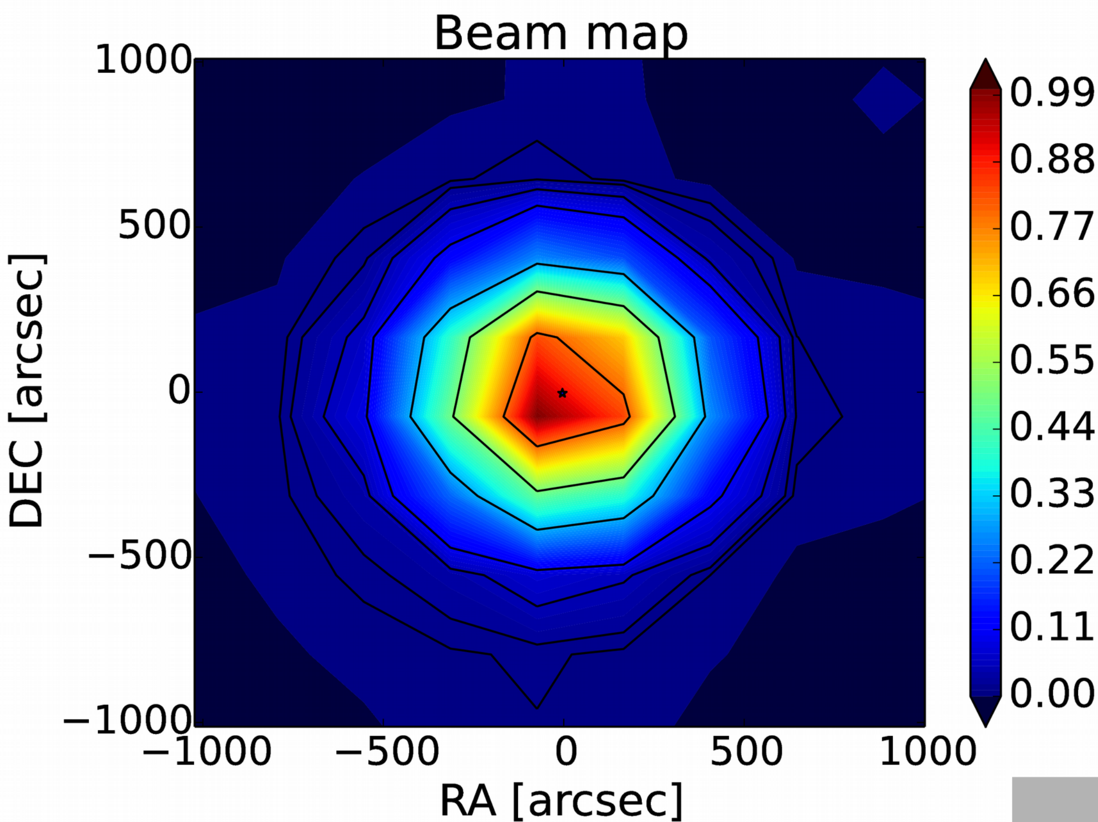

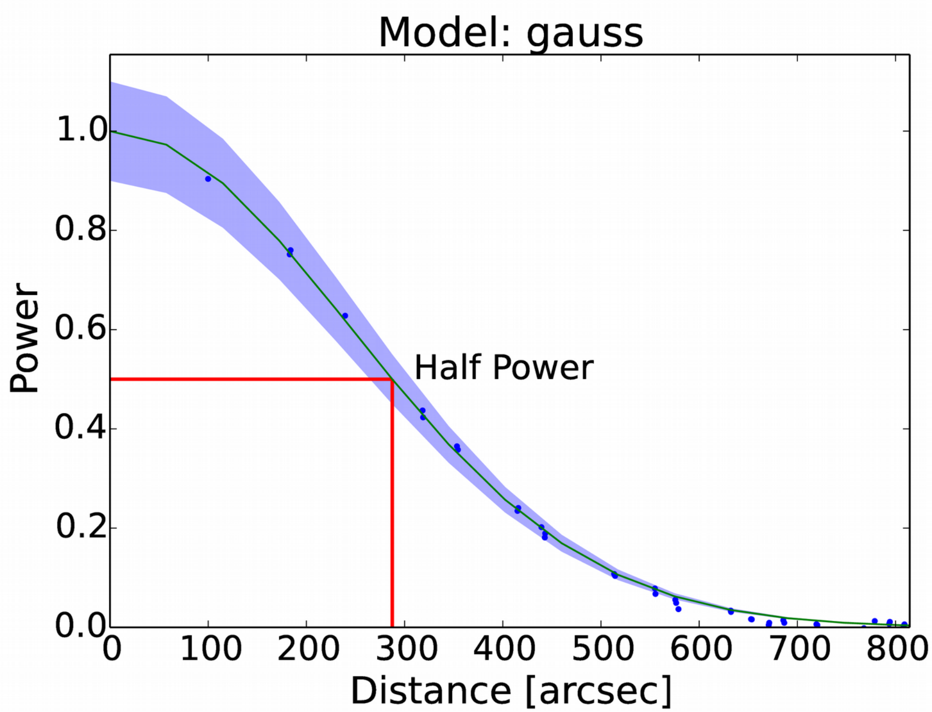

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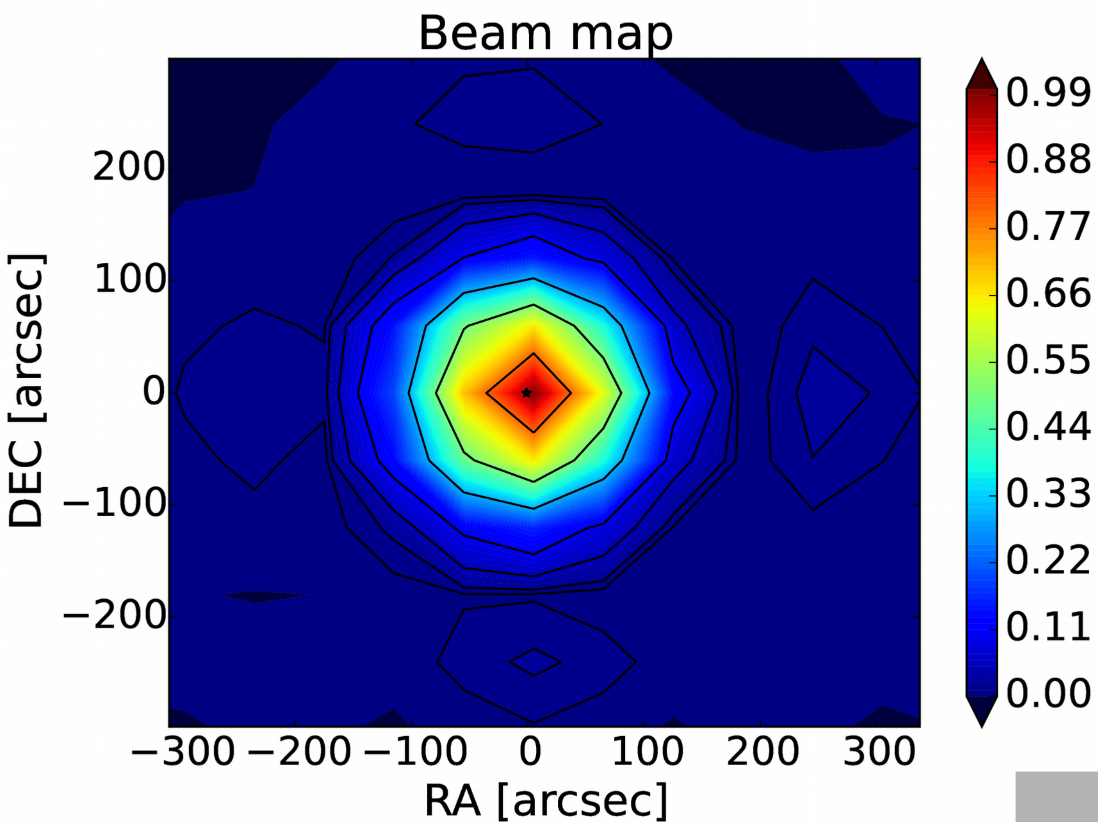
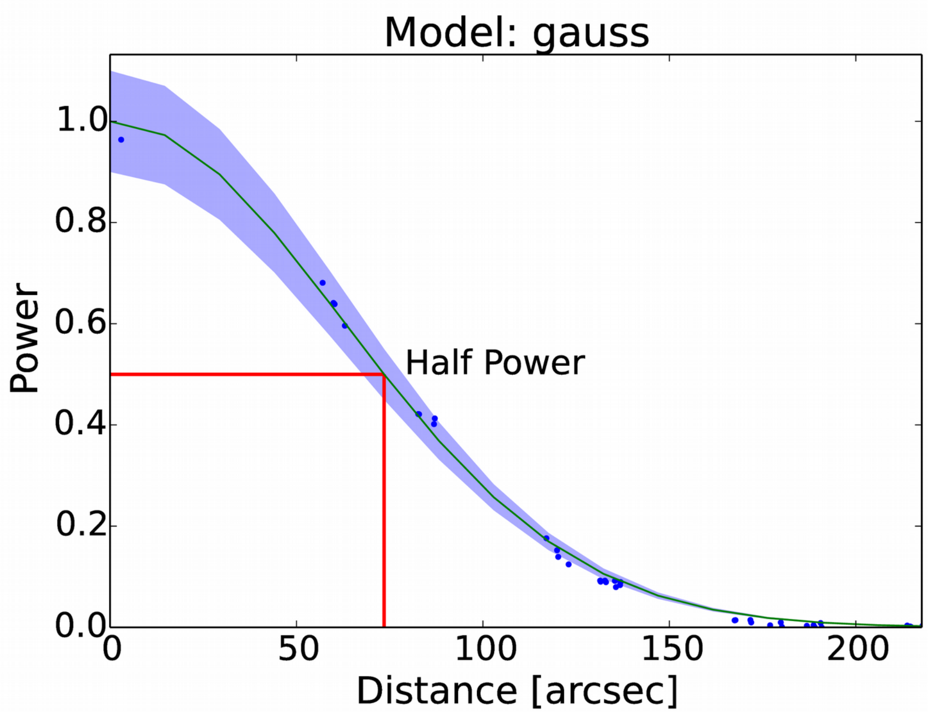
Effelsberg @6CM, RCP





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X0	7.985279"	-1.191061"
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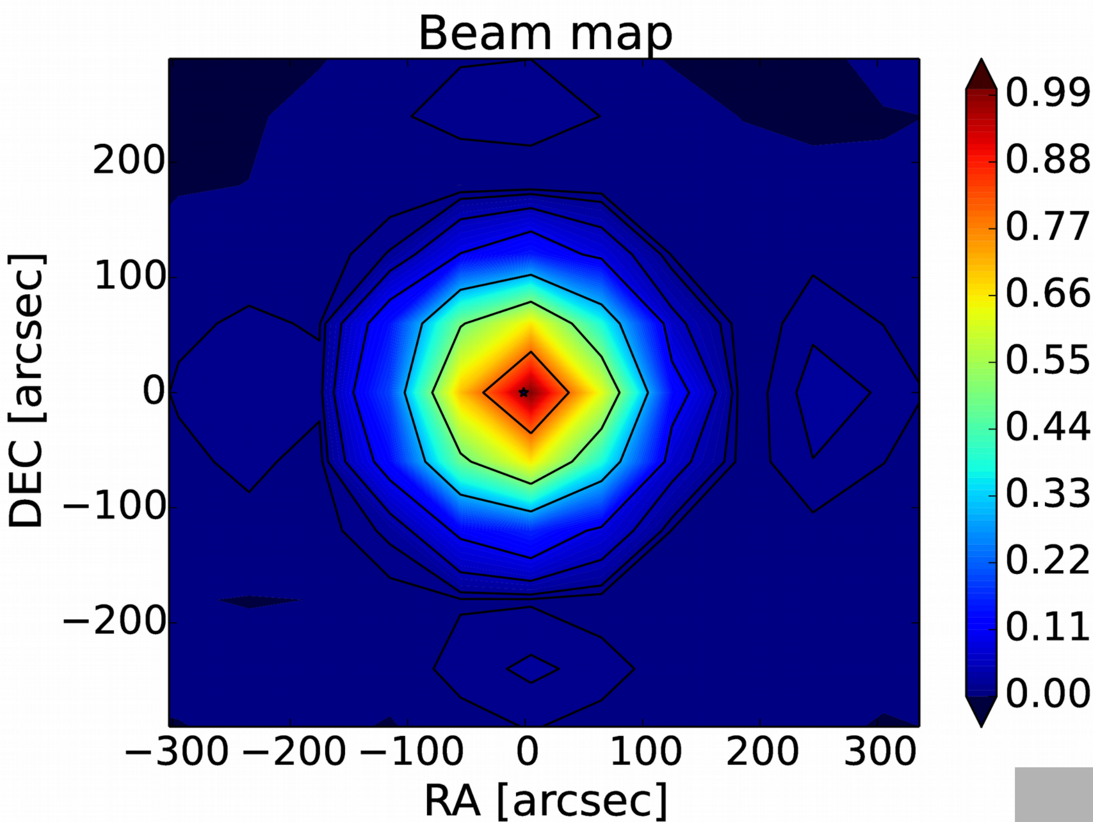

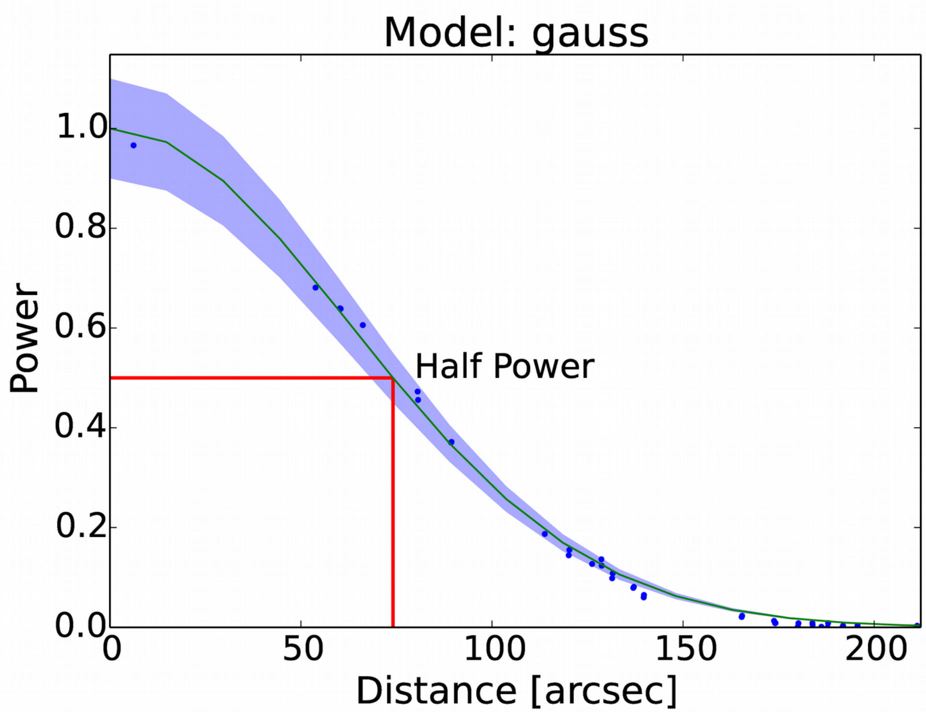

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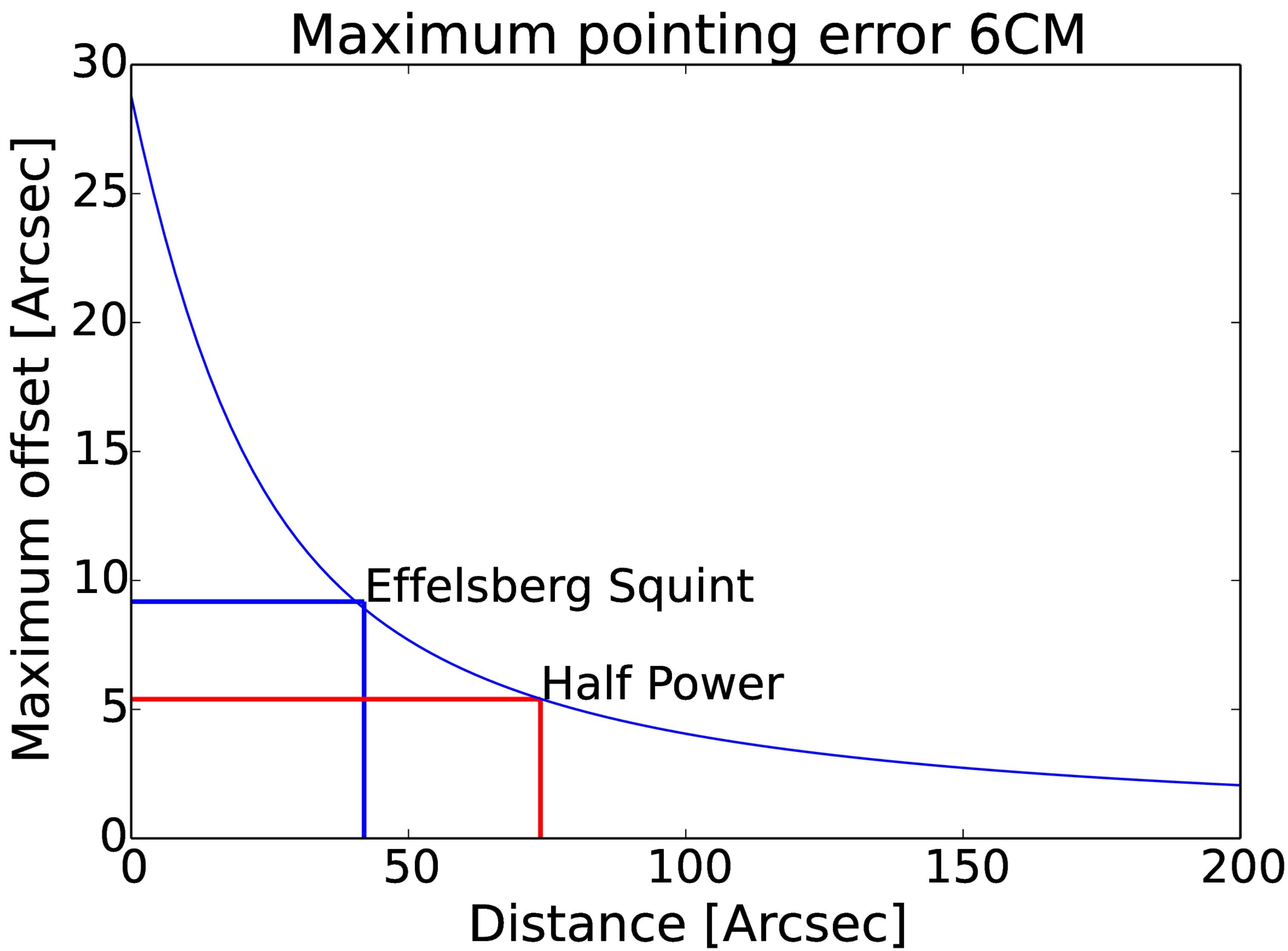
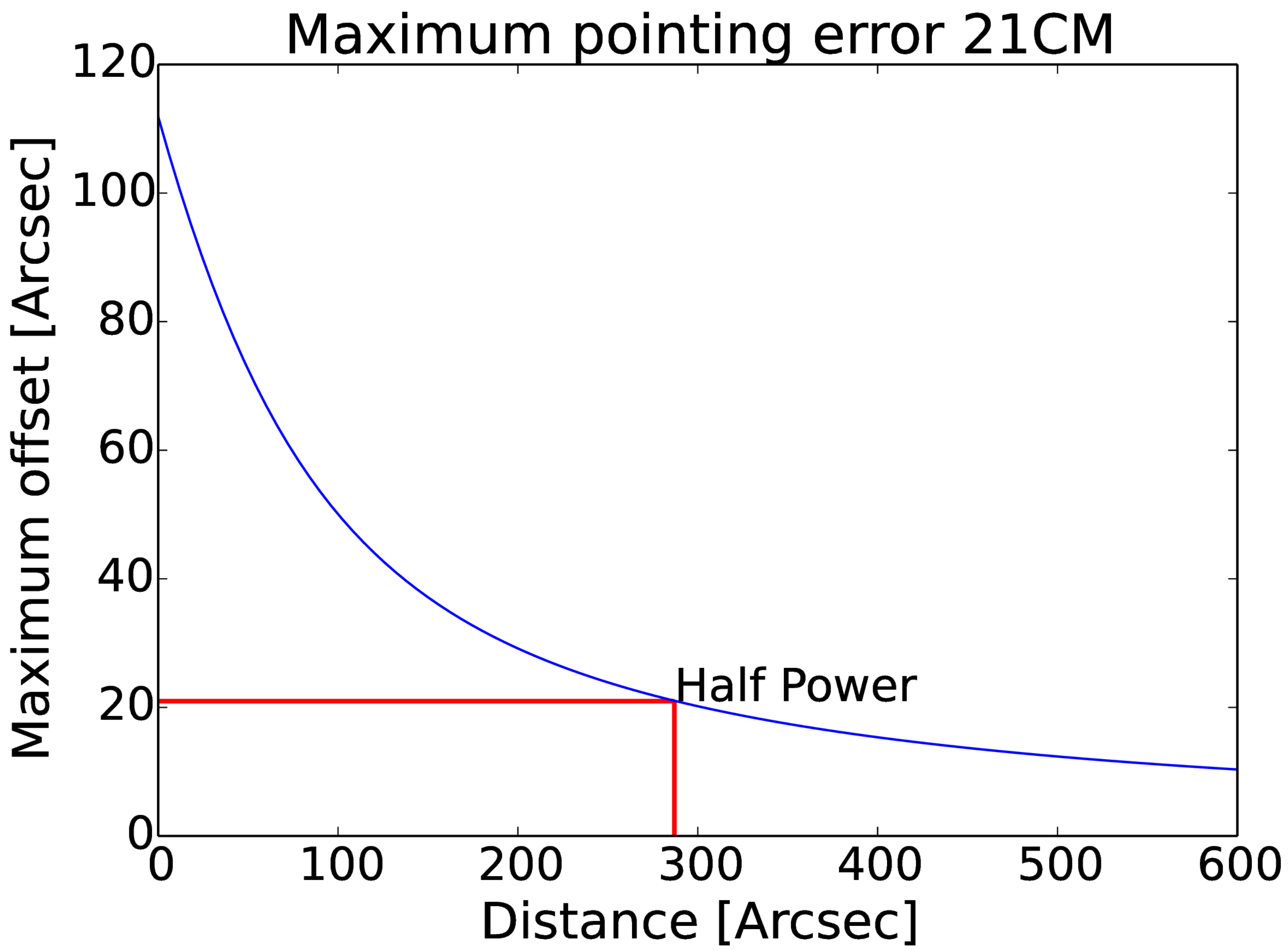
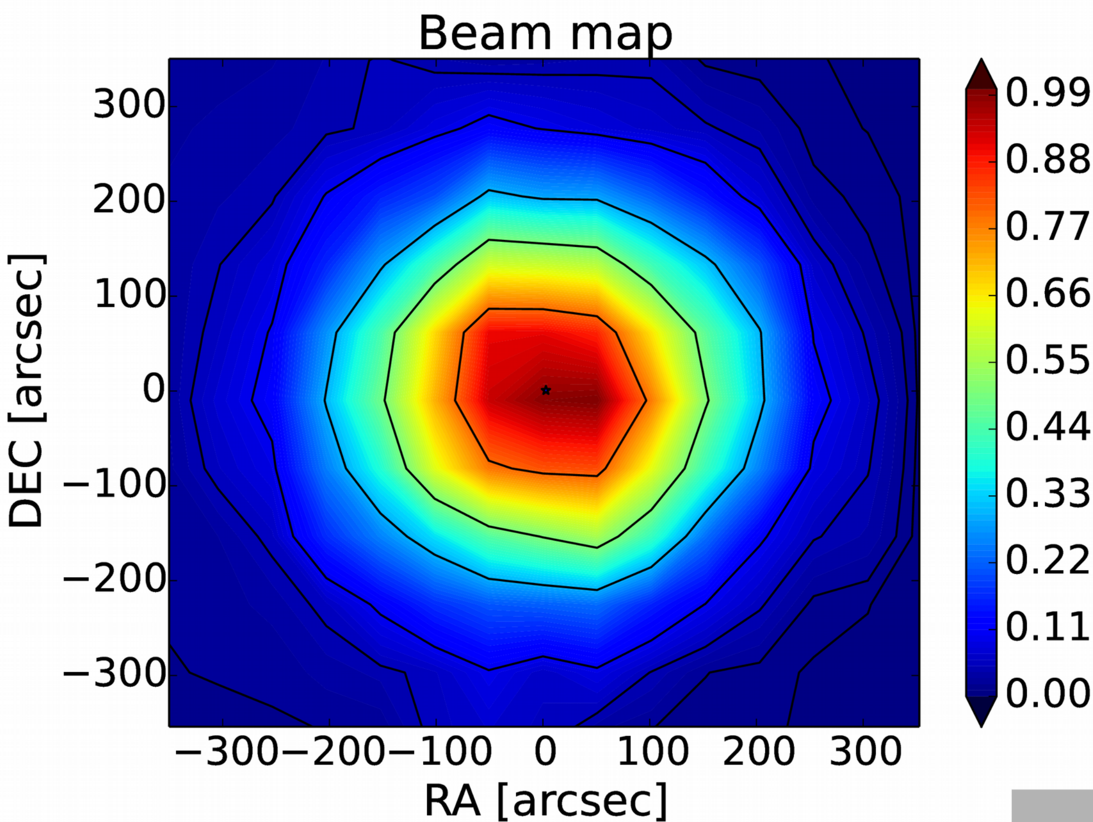


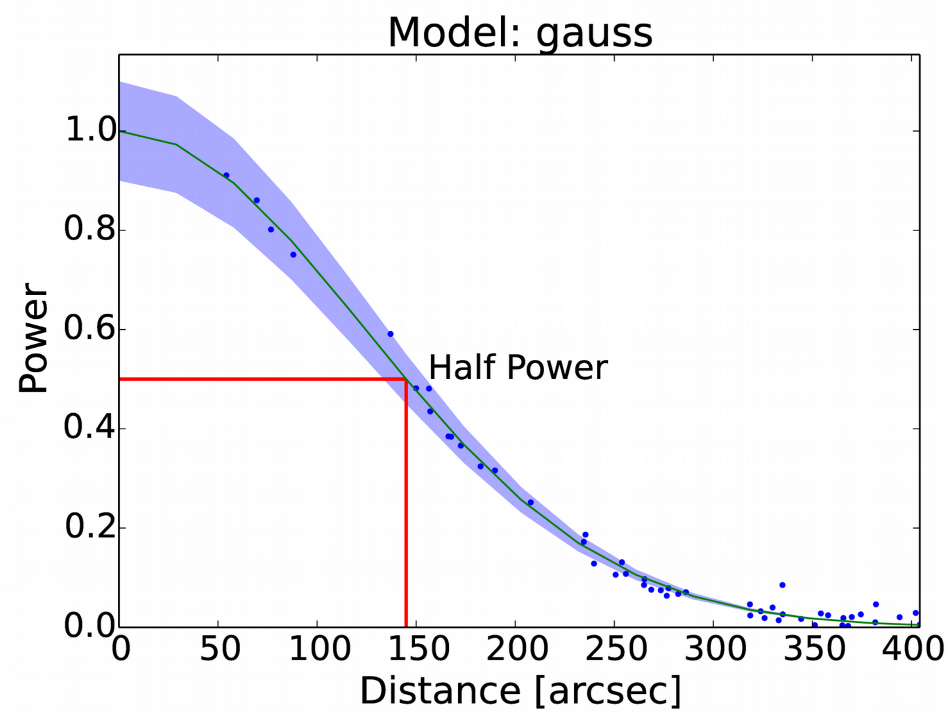
- Beam squint should be taken into account for C band
- Pointing errors?



- Less crucial for L band

Yebes @6CM, RCP





$$\text{Model}: I(x,y) = e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2(z\lambda)^2}}$$

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X0	2.807198”	-0.363737”
Y0	0.695973”	-4.880469”
Z	2052.1	2060.1
FWHM	289.9”	290.5”
D_{eff}	42.2 M	42.1 M

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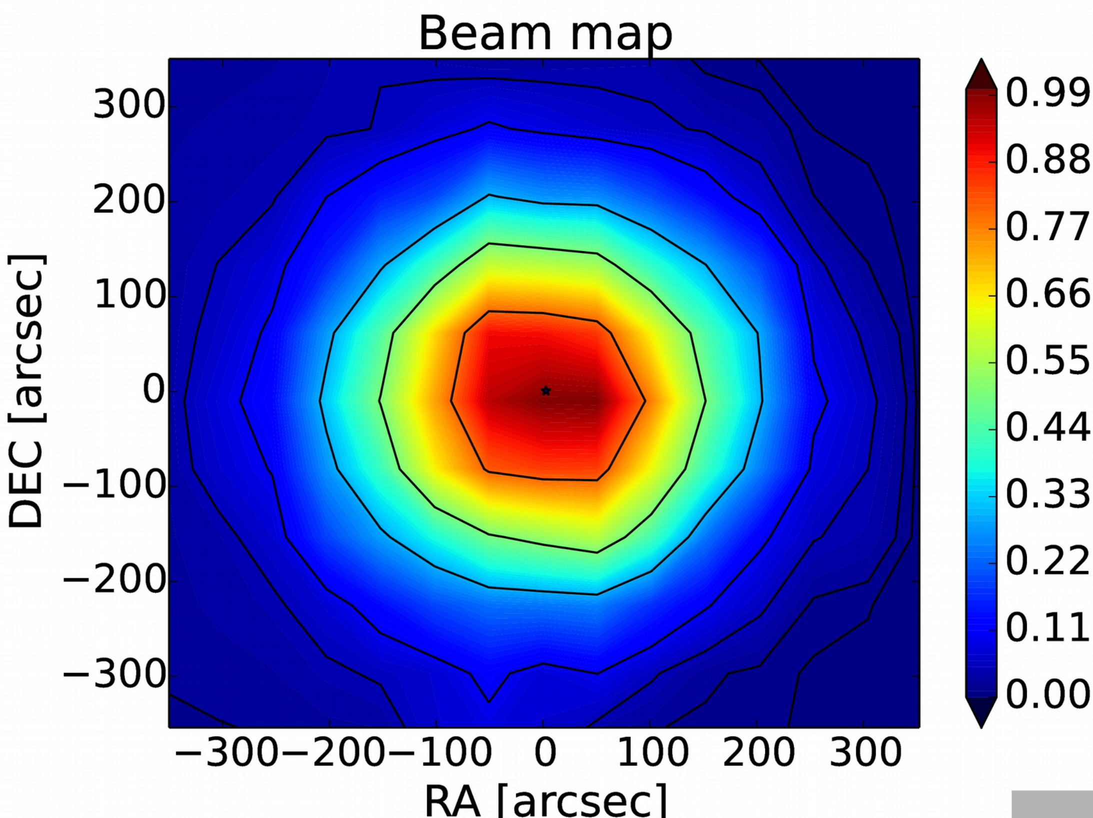

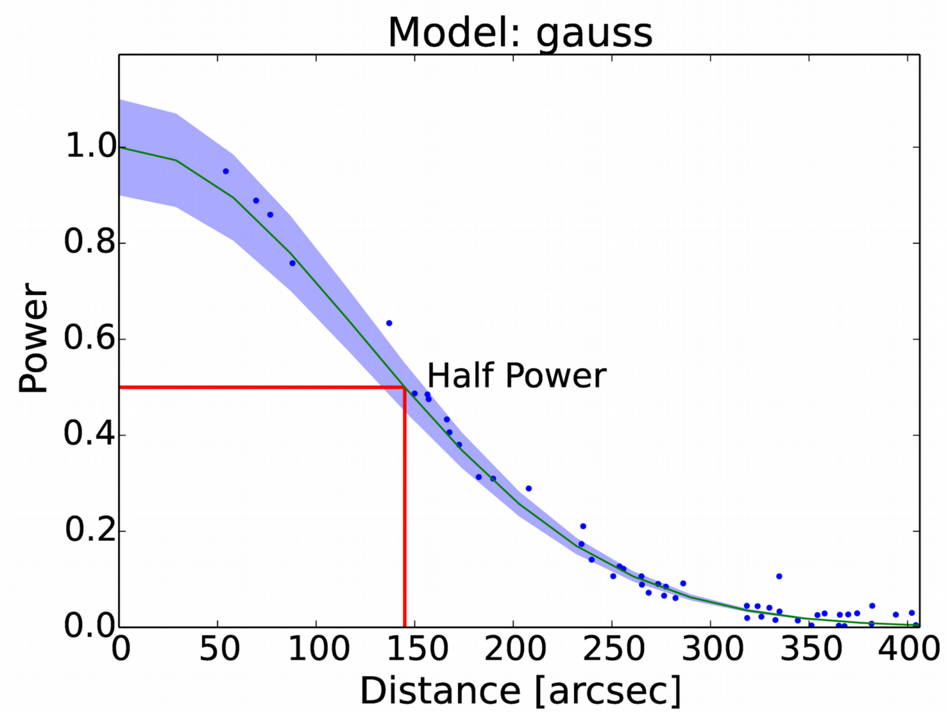

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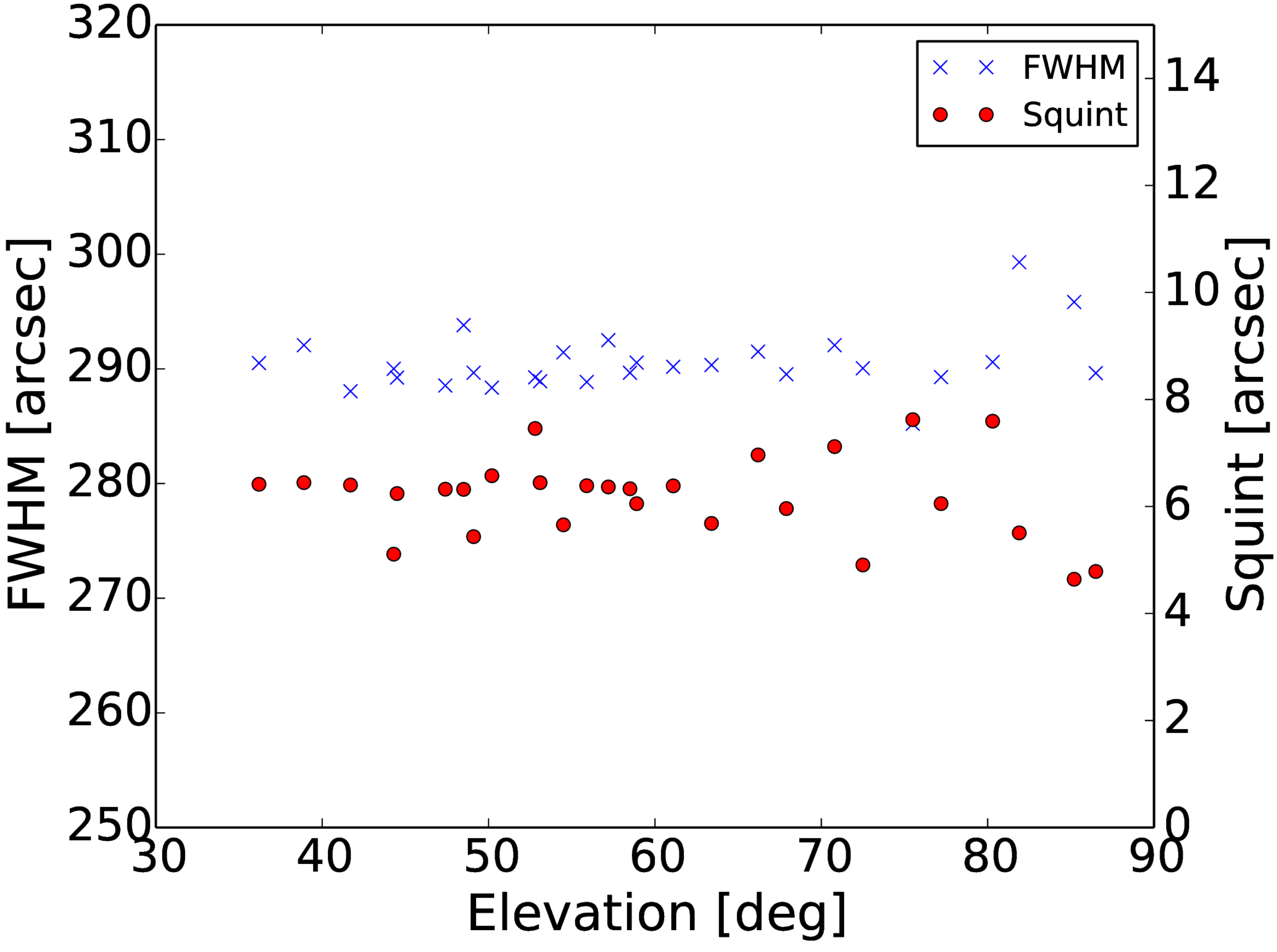
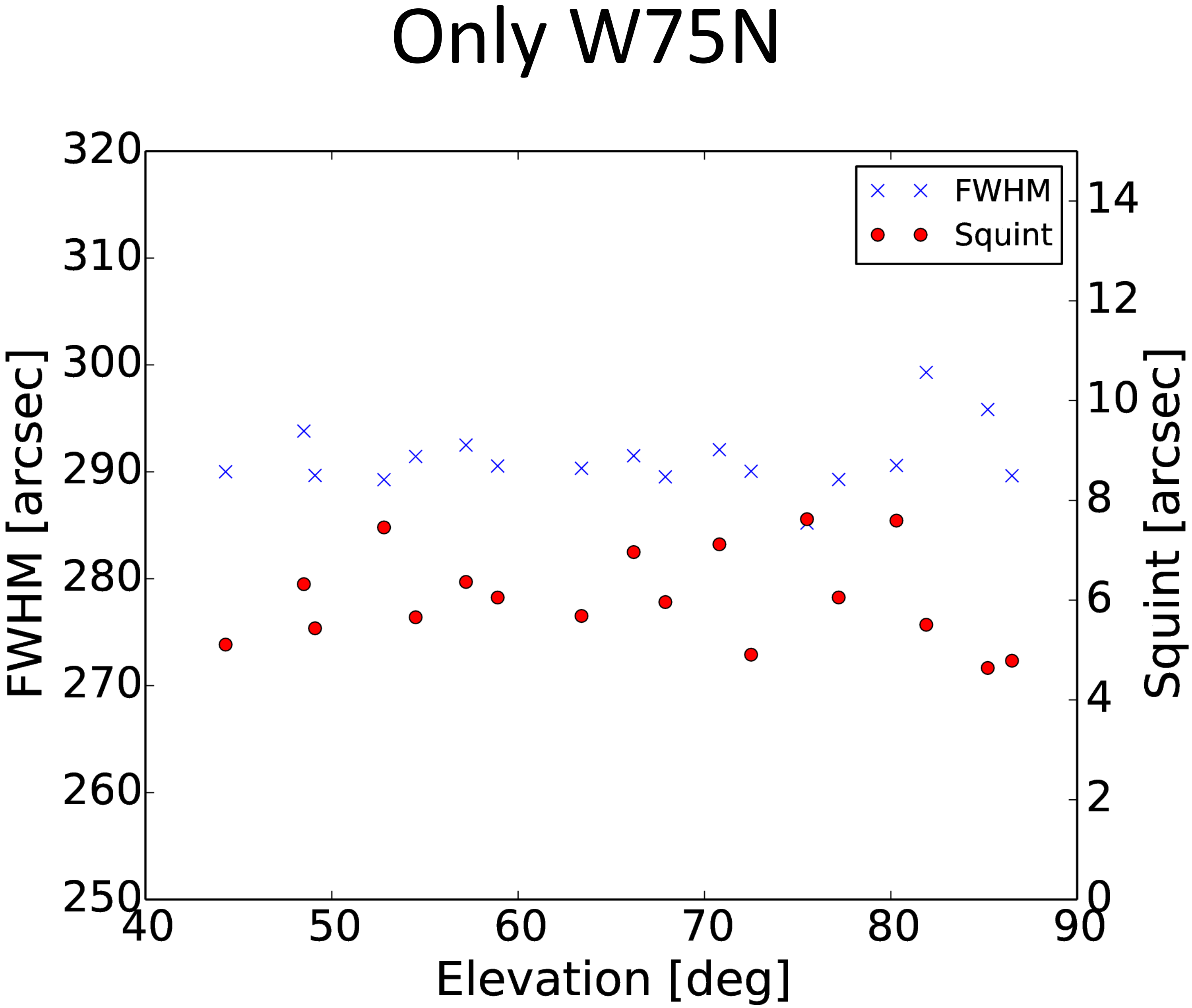
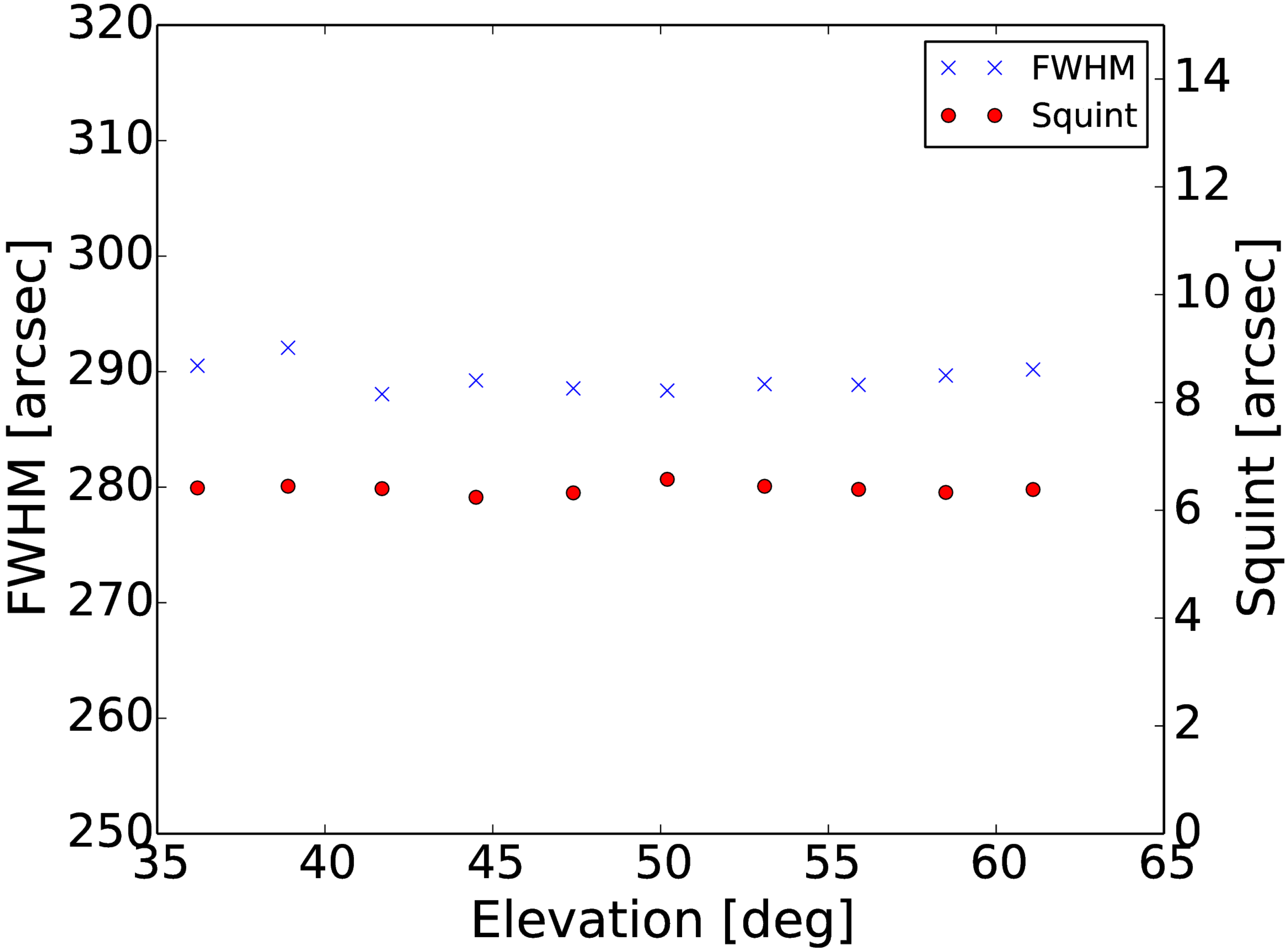


FWHM
Squint
FWHM [arcsec]
Squint [arcsec]
Elevation [deg]
320
310
300
290
280
270
260
250
30
40
50
60
70
80
90
14
12
10
8
6
4
2
0

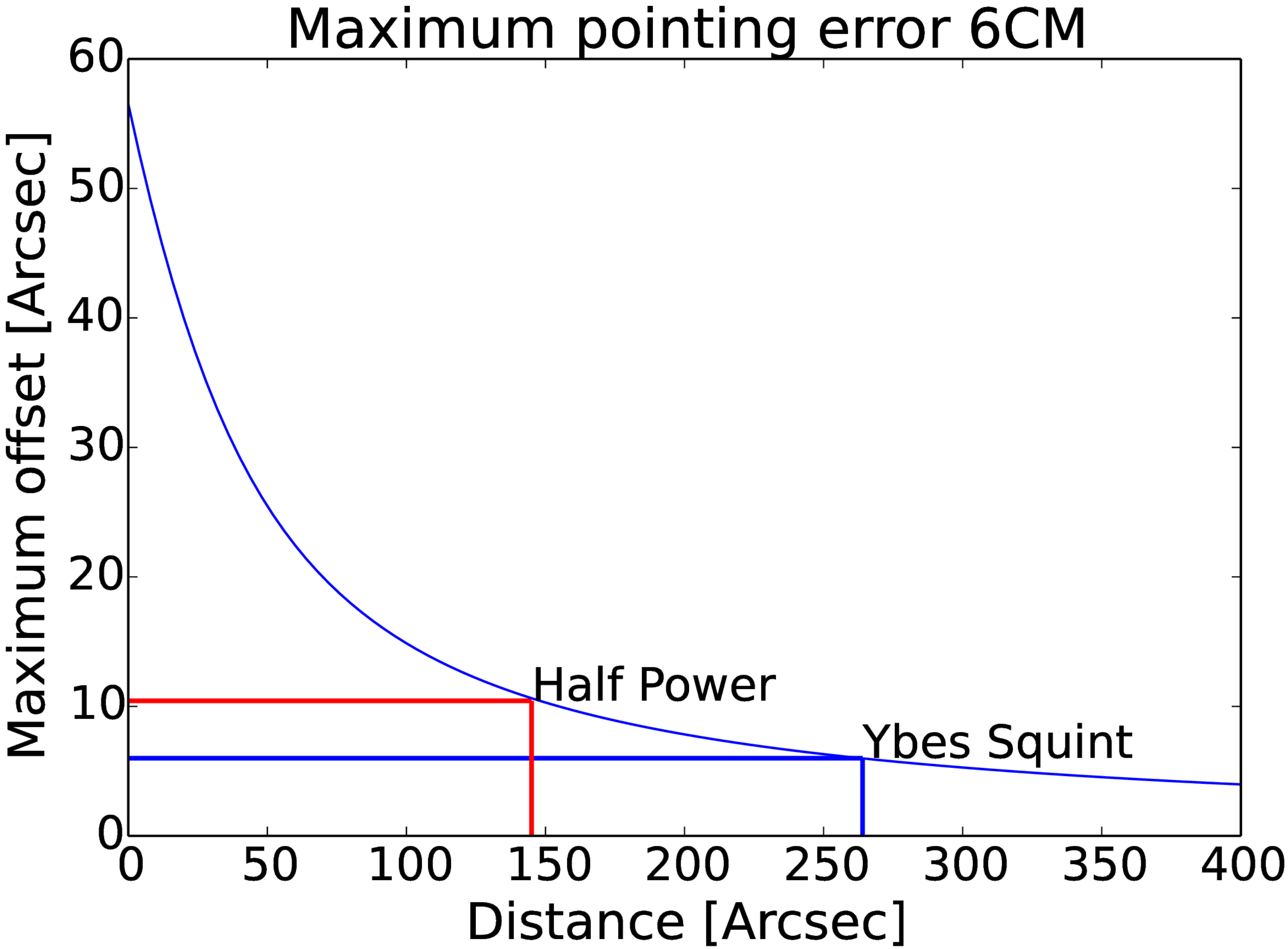


Only W75N
FWHM [arcsec]
Squint [arcsec]
Elevation [deg]
FWHM
Squint
320
310
300
290
280
270
260
250
40
50
60
70
80
90
14
12
10
8
6
4
2
0

Only W30H

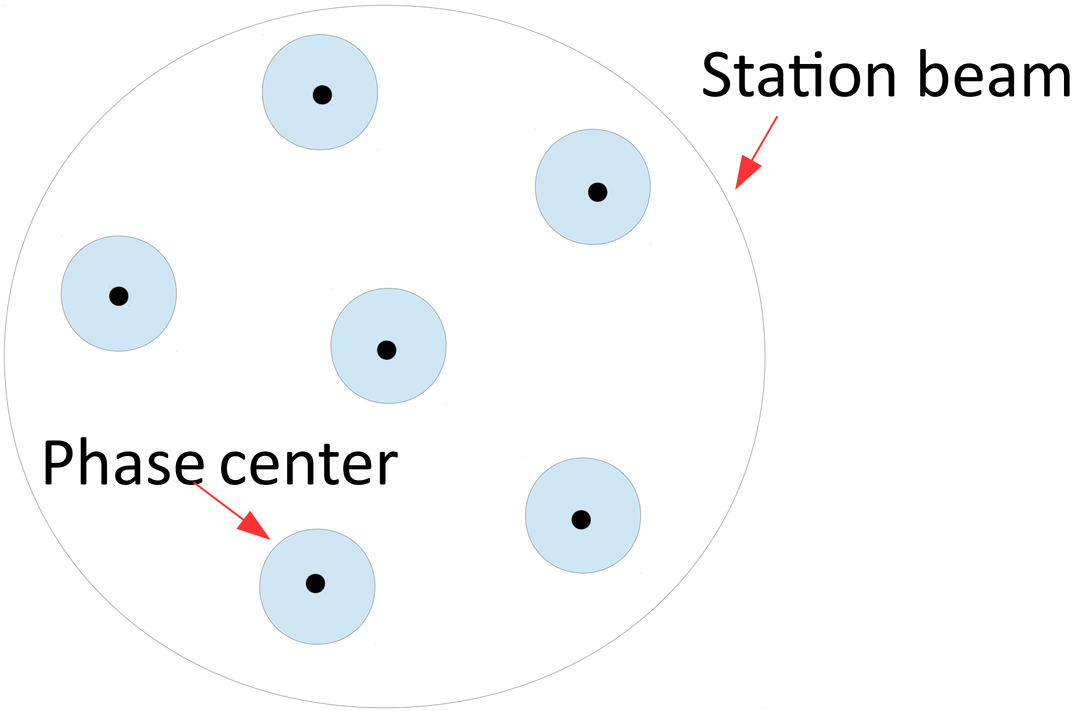


FWHM
Squint
FWHM [arcsec]
Squint [arcsec]
Elevation [deg]
320
310
300
290
280
270
260
250
14
12
10
8
6
4
2
0
35
40
45
50
55
60
65



Maximum pointing error 6CM
Maximum offset [Arcsec]
Distance [Arcsec]
Half Power
Ybes Squint
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350
400

Primary beam correction

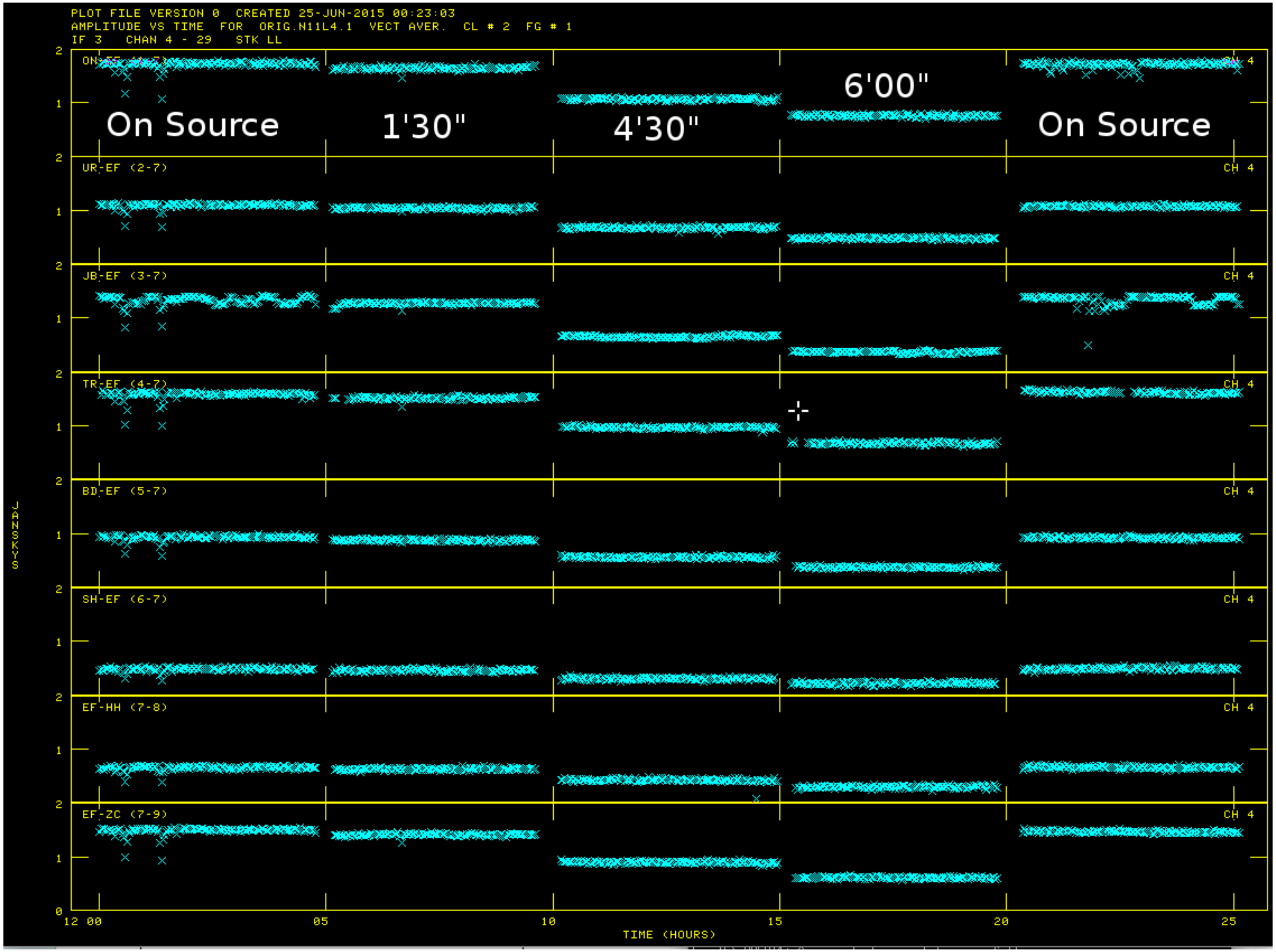


- Corrections are applied using a parseltongue script.
- Primary beam does not vary significantly over pencil beams.
- Correction factor is constant for each scan

N11L4 (18 cm)

- Test experiment to probe primary beam shapes
- A series of deliberate mis-pointings around 3C66A

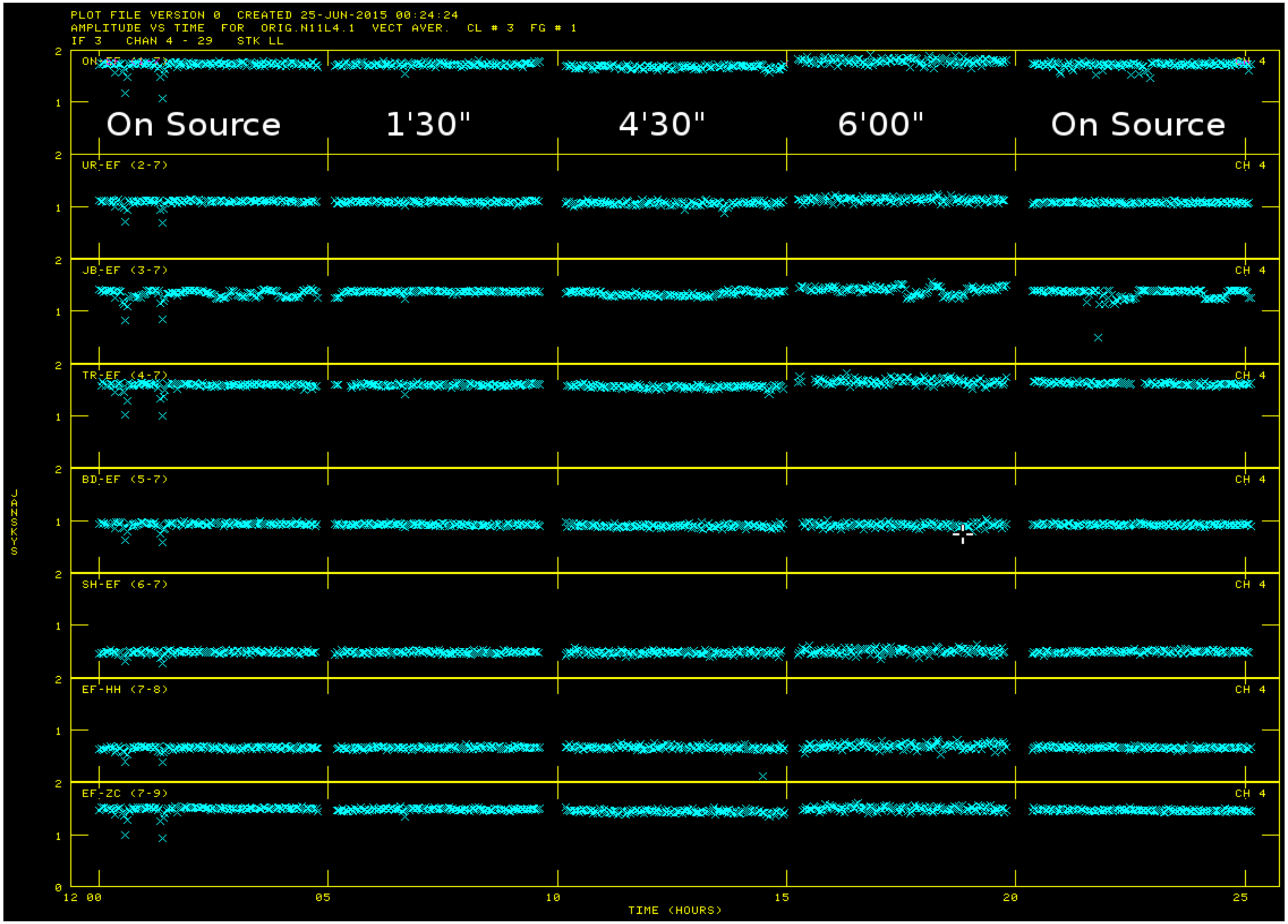
Before :



N11L4 (18 cm)

- Test experiment to probe primary beam shapes
- A series of deliberate mis-pointings around 3C66A

After :

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Questions?
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