Transit Interferometery data analysis and map reconstruction

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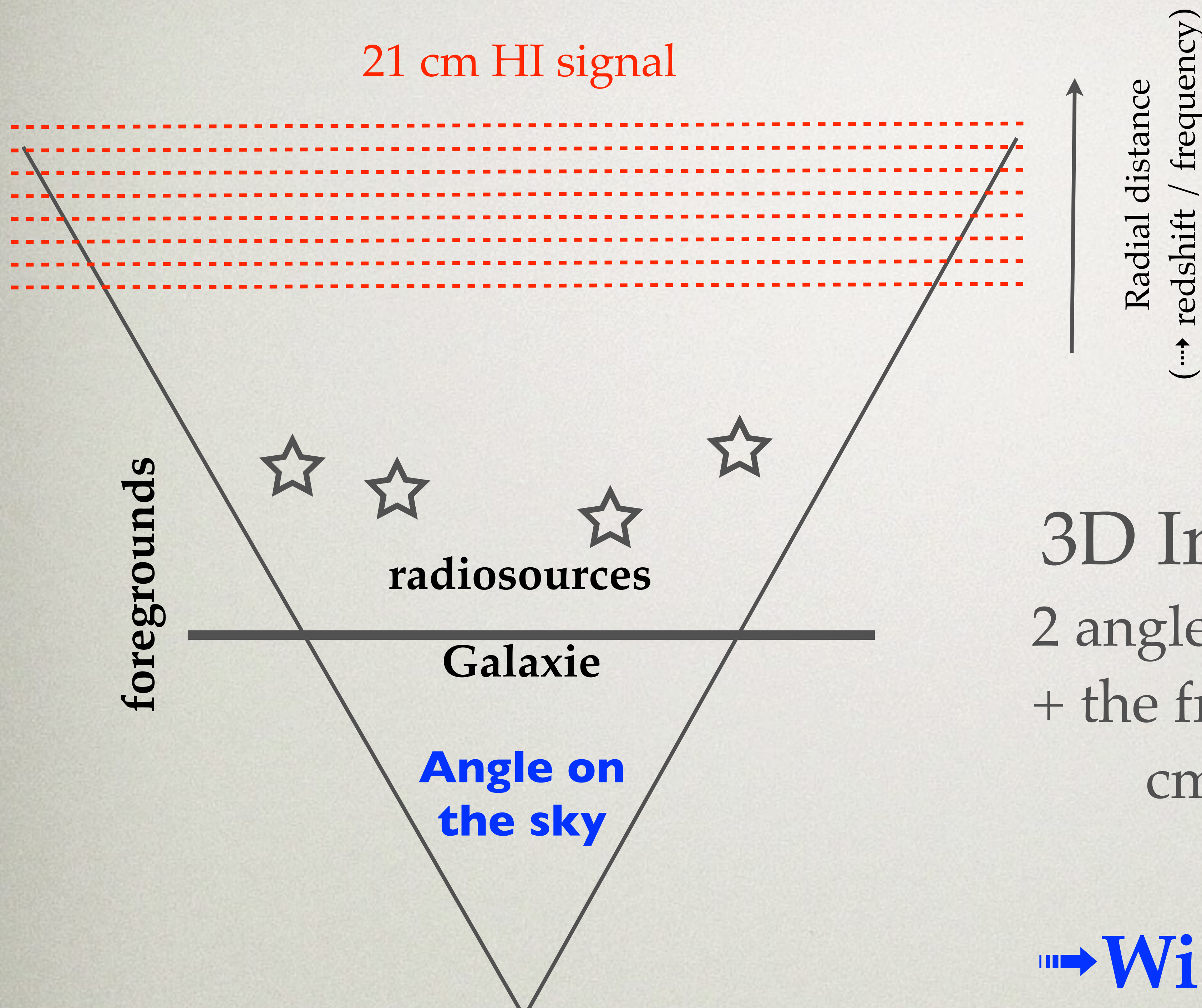
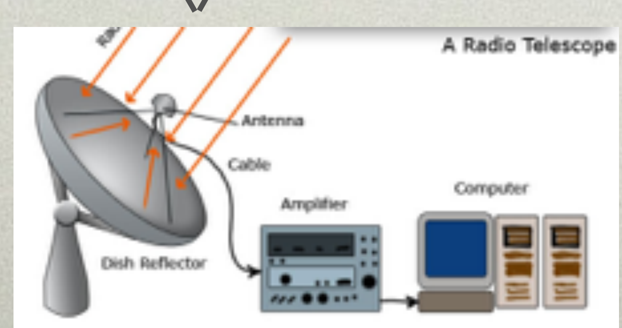
Tianlai Collaboration Meeting &
21cm Cosmology Workshop
Balikun, Xinjiang (China)
September 2015

- 3D Intensity mapping
- Transit interferometers: data processing overview
- Map making , mode mixing
- Calibration
- Application to PAON-4

3D Intensity mapping





➟**Wide band**

L-band ,
Resolution ~ 10 arc.min
for cosmology

3D Intensity mapping
2 angles (direction on the sky)
+ the frequency (redshifted 21 cm signal) → I(α,δ,ν)

➟**Wide field**

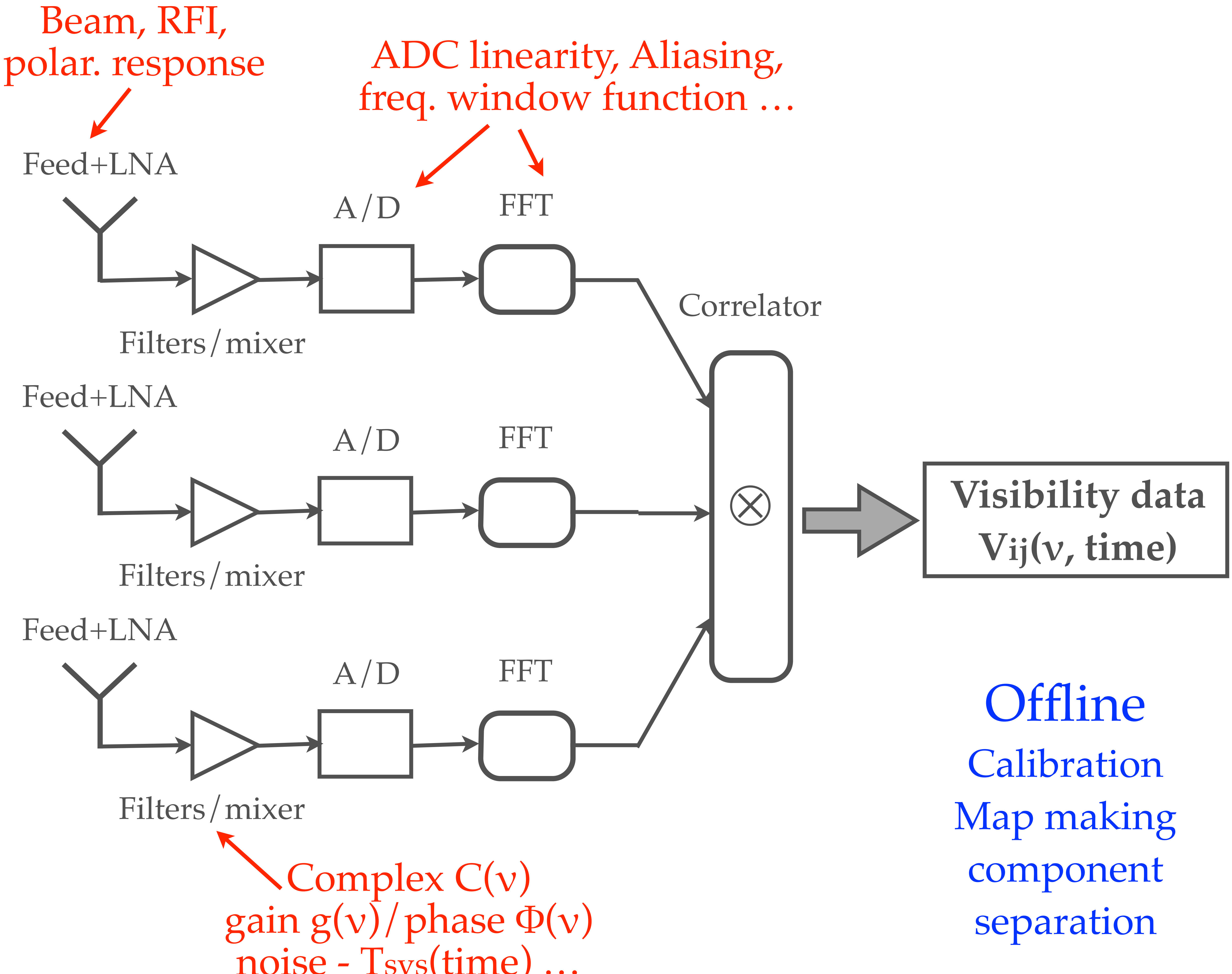
Single dish - Multi-feed / Phased array
or Interferometer array

Transit Interferometers

- Usual radio interferometry : observe a given patch of the sky ($\lesssim$ 1 deg) , the telescope tracking compensates for the earth rotation - Aim : achieve high resolution through long baselines

- Dense transit interferometric arrays for IM : Fixed (non tracking) reflector/feeds, observing in the meridian plane - the sky moving in front of the array due to earth rotation (E-W or right ascension direction) - Aim: achieve large FOV (multi-beam) and high sensitivity.

- Wide band ($>$ 100 MHz in L-band) mandatory for 3D HI Intensity Mapping


Beam, RFI,
polar. response
ADC linearity, Aliasing,
freq. window function …
Feed+LNA
A/D
FFT
Filters/mixer
Correlator
Feed+LNA
A/D
FFT
Visibility data
Vij(ν, time)
Filters/mixer
Feed+LNA
A/D
FFT
Offline
Calibration
Map making
component
separation
Filters/mixer
Complex C(ν)
gain g(ν)/phase Φ(ν)
noise - Tsys(time) …

Processing & bandwidth requirements for the correlator

	A	B	C
NFeed	32	256	1024
BandWidth	100 MHz	200 MHz	400 MHz
1→2→3	6.4 GBytes/sec	100 GBytes/sec	800 GBytes/sec
M	8	64	256
3/M→	0.8 GBytes/sec	1.6 GBytes/sec	3.2 GBytes/sec
NVis	528	32896	526336
@4 TFlops	~ 1	~ 100	~ 3200
4→ / M	5 MBytes/sec	50 MBytes/sec	400 MBytes/sec

Easy … *Challenging* … *??*

Level 0 (**L0**)

Visibility data, computed on-site ,
using dedicated hardware (correlator), or
by software
ancillary / housekeeping data

Level 1 (**L1**)

Raw visibility data
[Vij (ν)]

(L0 output)

→

- First stage RFI cleaning,
- data quality monitoring
- data compression, mainly through time averaging
- transfer to TAC

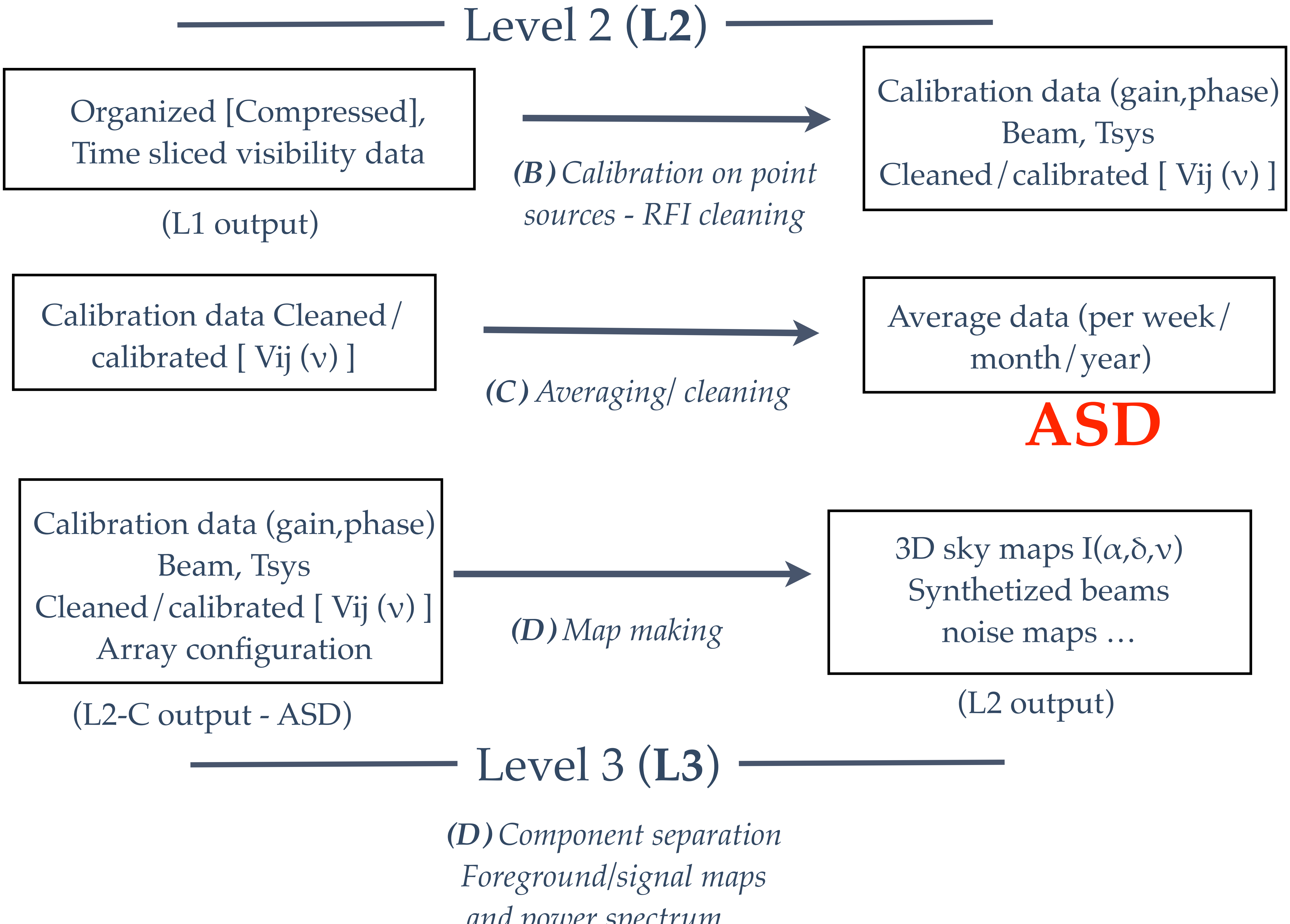
Organized [Compressed], Time sliced visibility data

(L1 output)

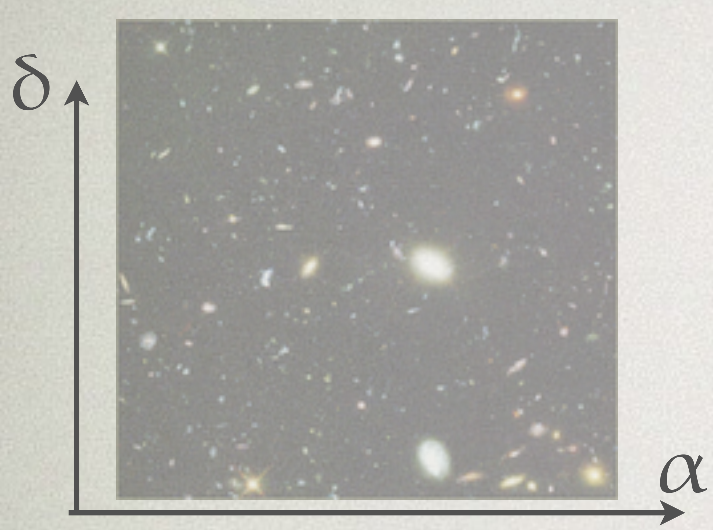
TOD

L1 output data :

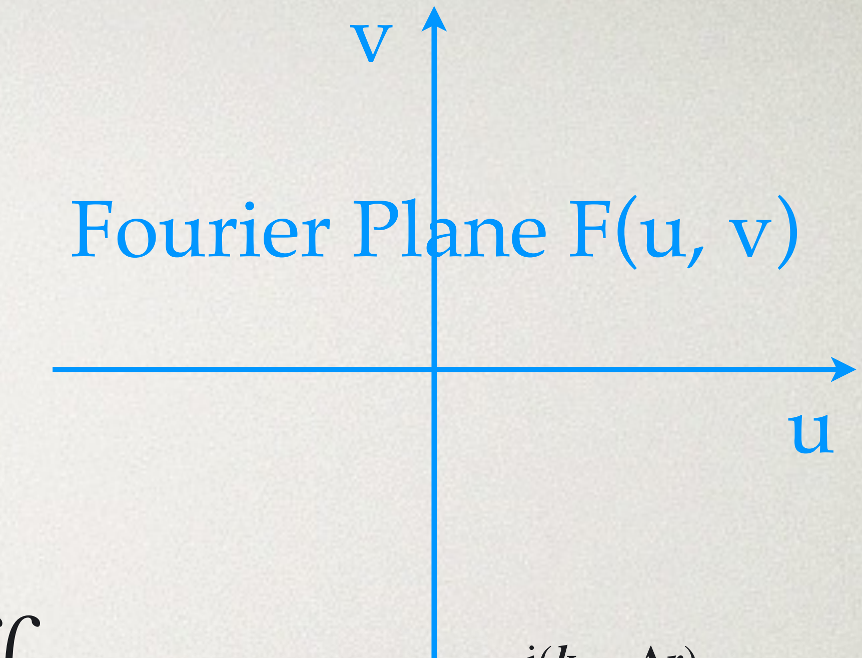
- T-16DA : ~35-70 GB / day , ~1000 files / day , ~100 TB / year
- T-3Cyl: ~500 GB / day , ~10000 files / day , ~1000 TB / year


Level 2 (L2)
Organized [Compressed], Time sliced visibility data
(L1 output)
(B) Calibration on point sources - RFI cleaning
Calibration data (gain,phase) Beam, Tsys Cleaned / calibrated [Vij (ν)]
Calibration data Cleaned / calibrated [Vij (ν)]
(C) Averaging/ cleaning
Average data (per week / month / year)
ASD
Calibration data (gain,phase) Beam, Tsys Cleaned / calibrated [Vij (ν)] Array configuration
(L2-C output - ASD)
(D) Map making
3D sky maps I(α,δ,ν) Synthetized beams noise maps …
(L2 output)
Level 3 (L3)
(D) Component separation
Foreground/signal maps
and power spectrum …

Visibilities (u,v) plane, sky map reconstruction



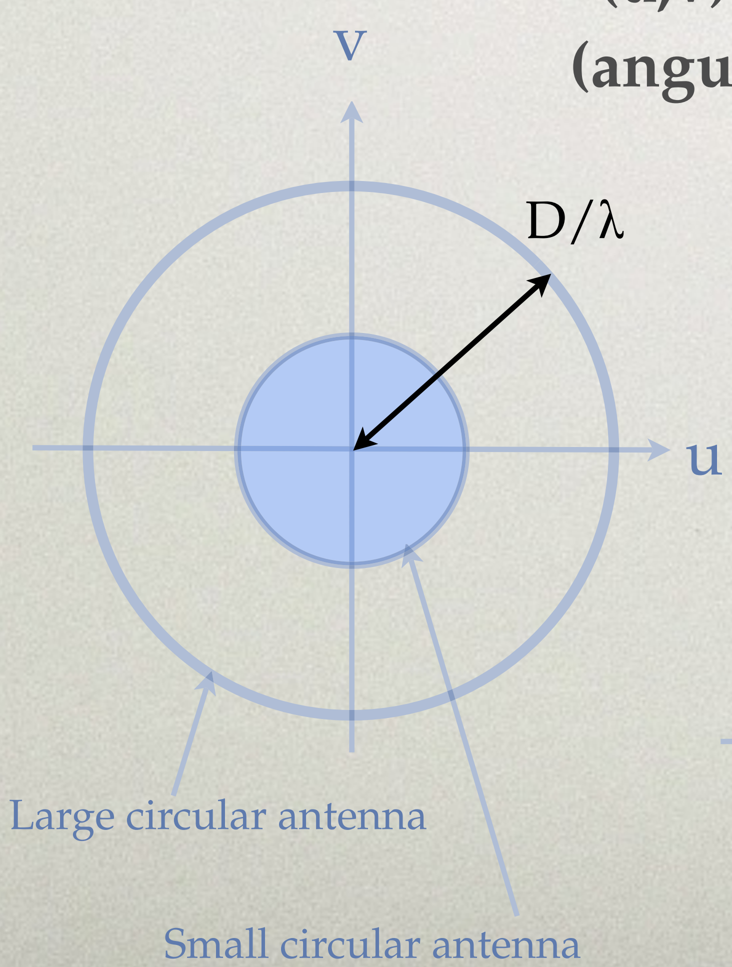
Sky plane I(α, δ)



Visibility

$$\mathcal{V}_{12}(\lambda) = \langle s_1(\lambda) s_2(\lambda)^* \rangle = \iint \mathrm{d}\boldsymbol{\Theta}\, I(\boldsymbol{\Theta}, \lambda) L(\boldsymbol{\Theta}, \lambda) \mathrm{e}^{\mathrm{i}(\boldsymbol{k}_{\mathrm{EM}}.\boldsymbol{\Delta r})}.$$

(u,v) plane coverage
(angular wave modes)



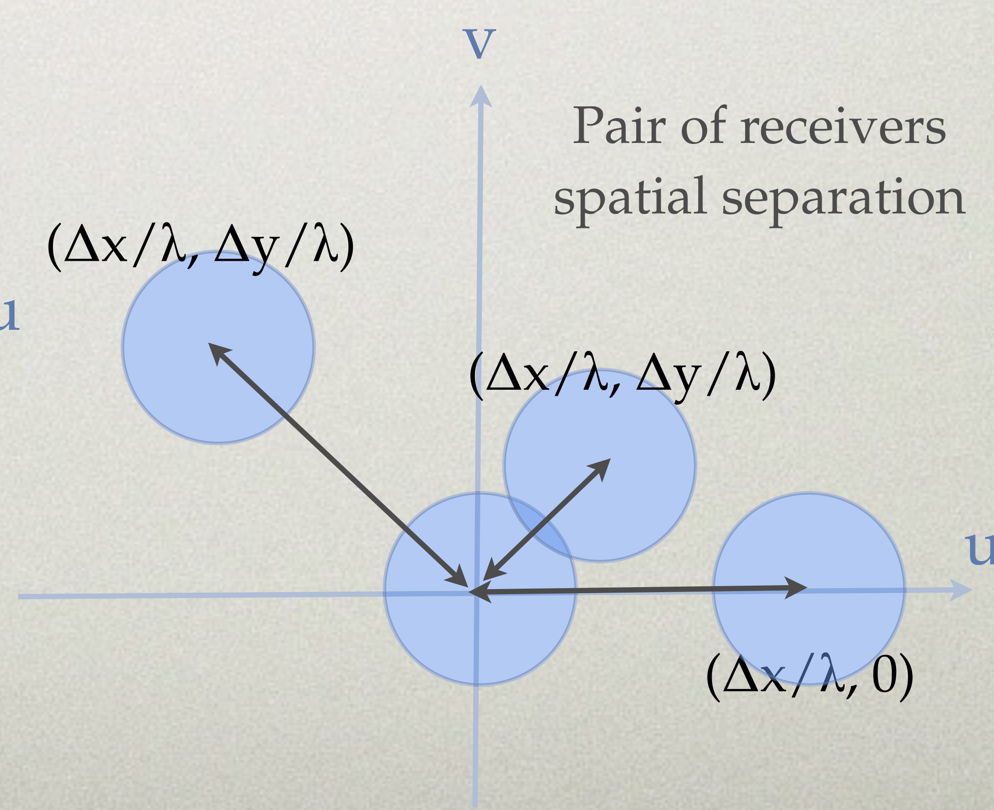
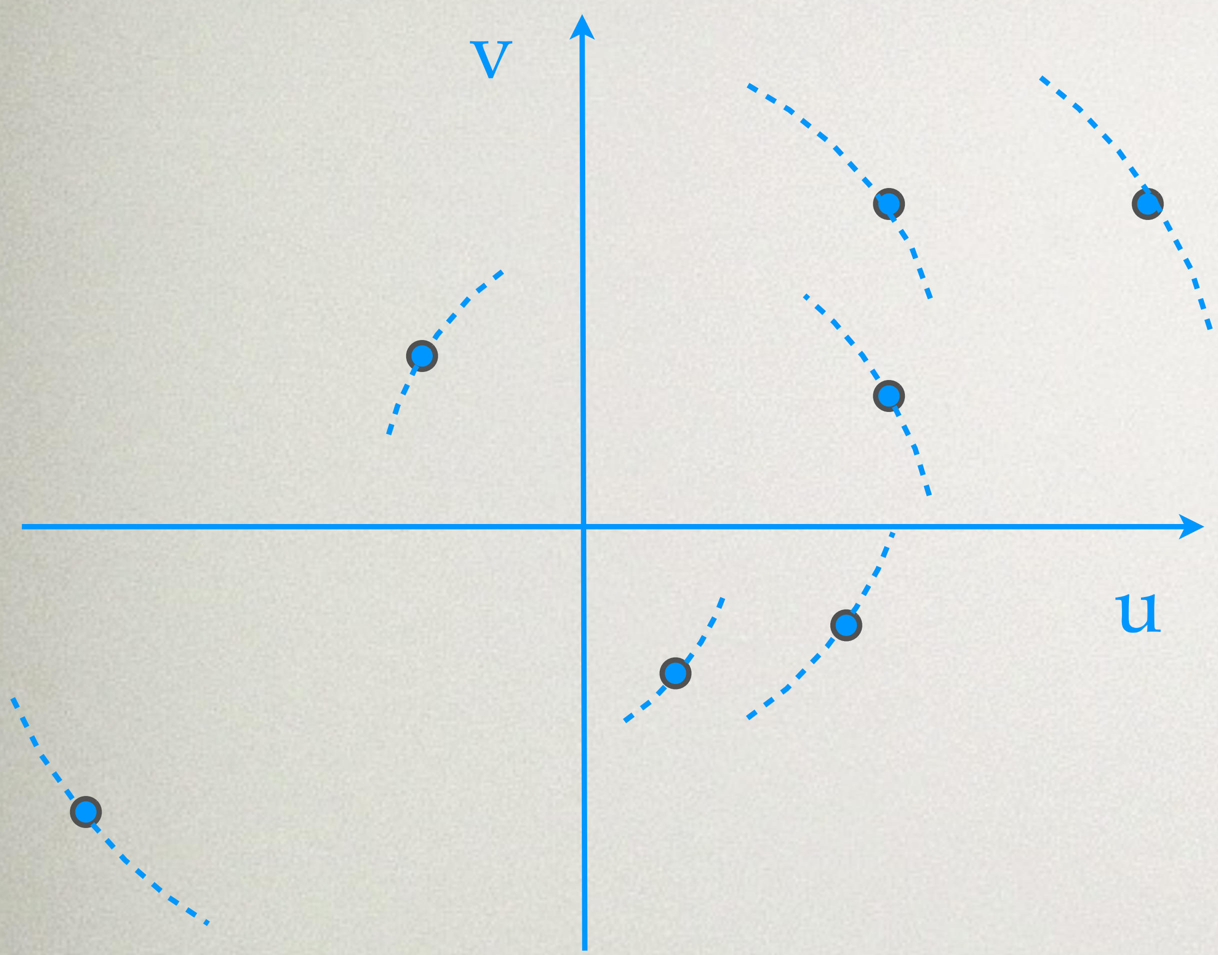


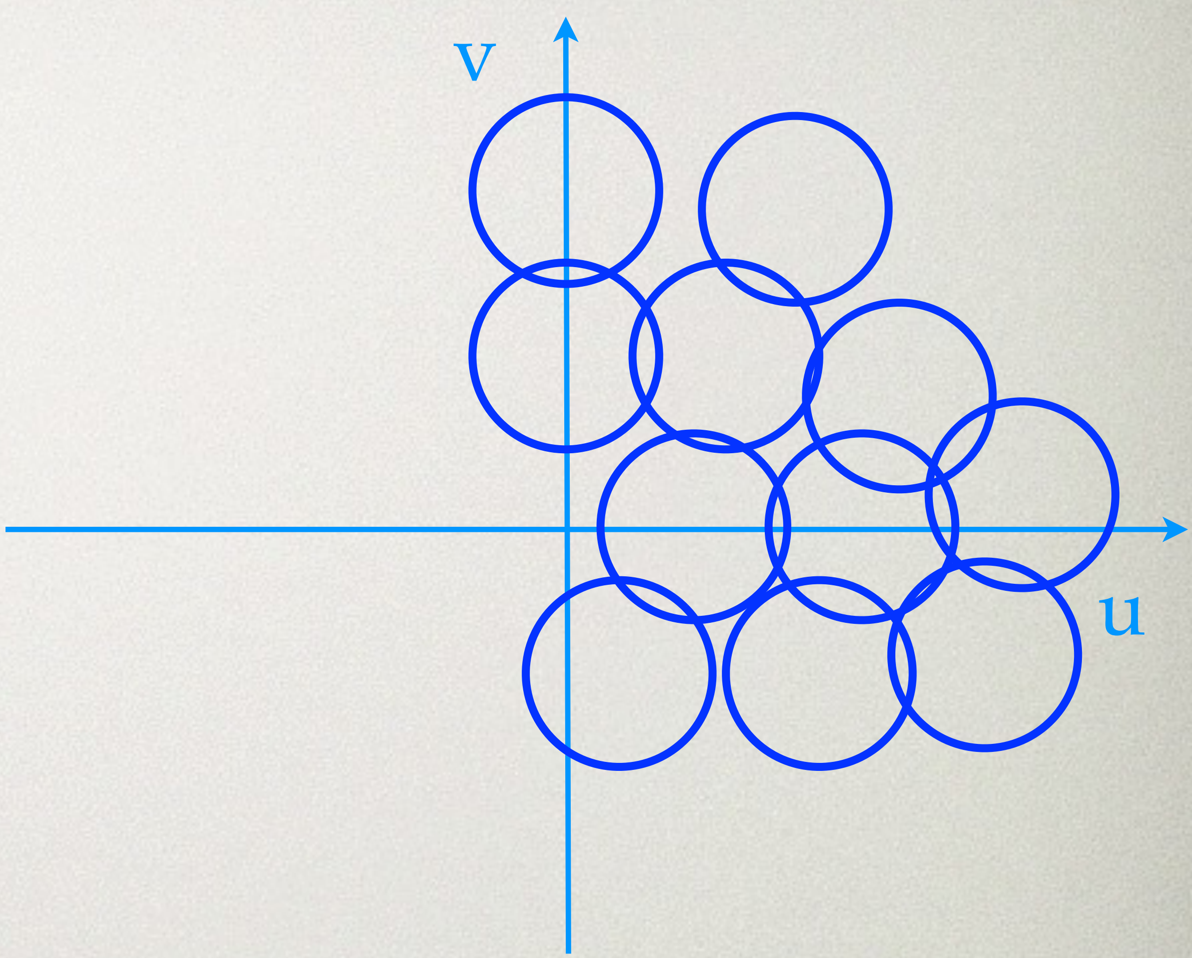
Fig. from Ansari et al (2012) , A&A 540

High resolution interferometry



Interferometry with long baselines
sparse sampling of the (u,v), even with rotation synthesis - (source tracking) -
dish-size ≪ baselines ⟹
Visibilities sample the (u,v) plane
F(u,v) × Beam(u,v)

Dense arrays



Interferometry with dense arrays
in transit mode
dish-size ~ baselines ⟹
near complete coverage of the (u,v)
we need to resolve modes averaged
in a single visibility measurement

Assuming the instrument response is known (beam, gain, stationary noise …)

We can write the measurement process as a linear system

For each frequency slice

$$[\, V_{ij}(\text{time}) \,] = [[\, \mathbf{A} \,]] \times [\, I(\alpha,\delta) \,] + [\, n \,] \quad (\nu)$$

Set of visibilities (vector)

Matrix encoding instrument response, scan/tracking …

Vector representing the sky brightness

noise (vector)

$$[\, V_{ij}(\text{time}) \,] = [[\, \mathbf{A'} \,]] \times [\, F(u,v) \,] + [\, n \,] \quad (\nu)$$

or written in the Fourier plane

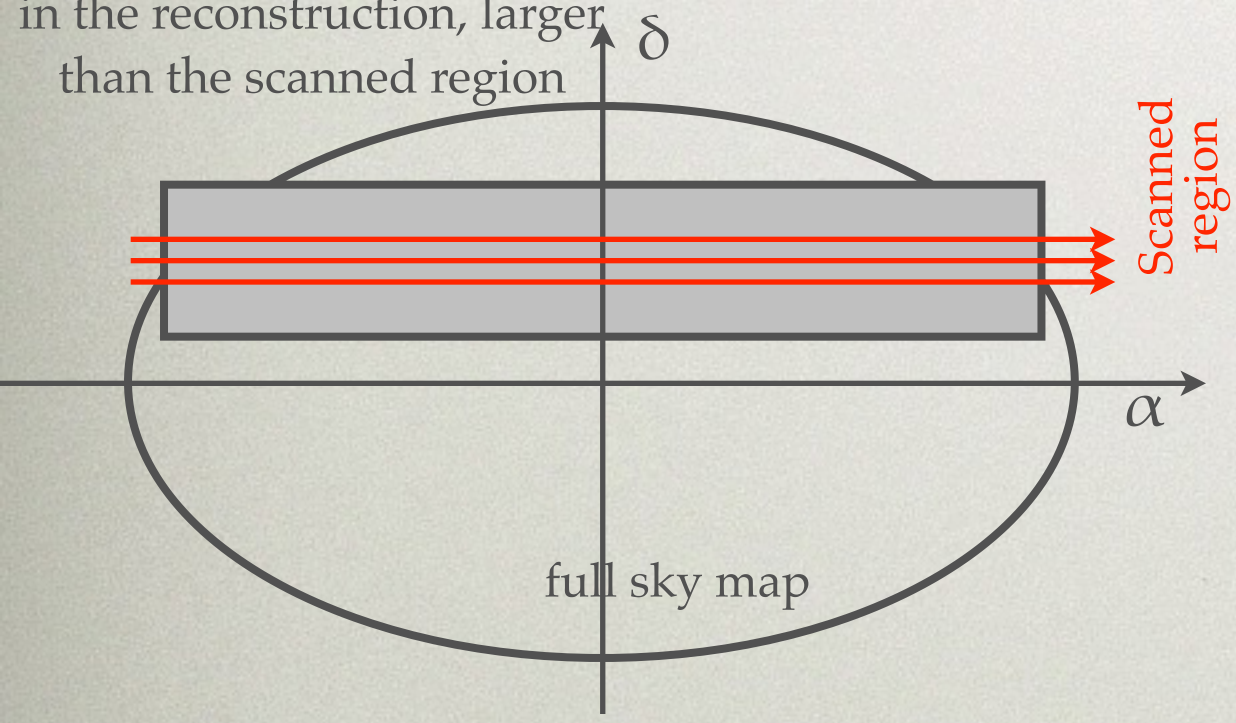
Transit interferometer: map making

$$\begin{aligned} \text{Sky} &: \alpha \ \ (\text{RA, East} - \text{West, EW}) \\ & \quad \delta \ \ (\text{DEC, North} - \text{South, NS}) \\ \text{Fourier} &: (\alpha, \delta) \longrightarrow (u, v) \\ \text{Sky} &: I(\alpha, \beta) \longrightarrow F(u, v) \\ \text{Visibilities} &: V_{ij}(\alpha) \rightarrow \tilde{V_{ij}}(u) \end{aligned}$$

Similar relations hold in spherical geometry, where the Fourier transform is replaced by spherical harmonic transforms → F(l,m)

See Jiao Zhang presentation

Rectangular geometry used in the reconstruction, larger than the scanned region



$$\begin{aligned} \left(\tilde{V_{ij}}(u)\right) &= [A_u] \times (F_u(v)) + (n) \\ \left(\hat{F}_u(v)\right) &= [B_u] \times \left(\tilde{V_{ij}}(u)\right) \\ \left\{\hat{F}_u(v)\right\} &\rightarrow \hat{F}(u, v) \\ \hat{F}(u, v) &\rightarrow \hat{F}_W(u, v) = \hat{F}(u, v) \times W(u, v) \\ \hat{F}_W(u, v) &\longrightarrow \hat{I}(\alpha, \delta) \qquad (\text{FFT}) \end{aligned}$$

Note: The method is applicable to reconstruct polarisation maps I,Q,U,V (but needs computation of correlation between the two polarisations

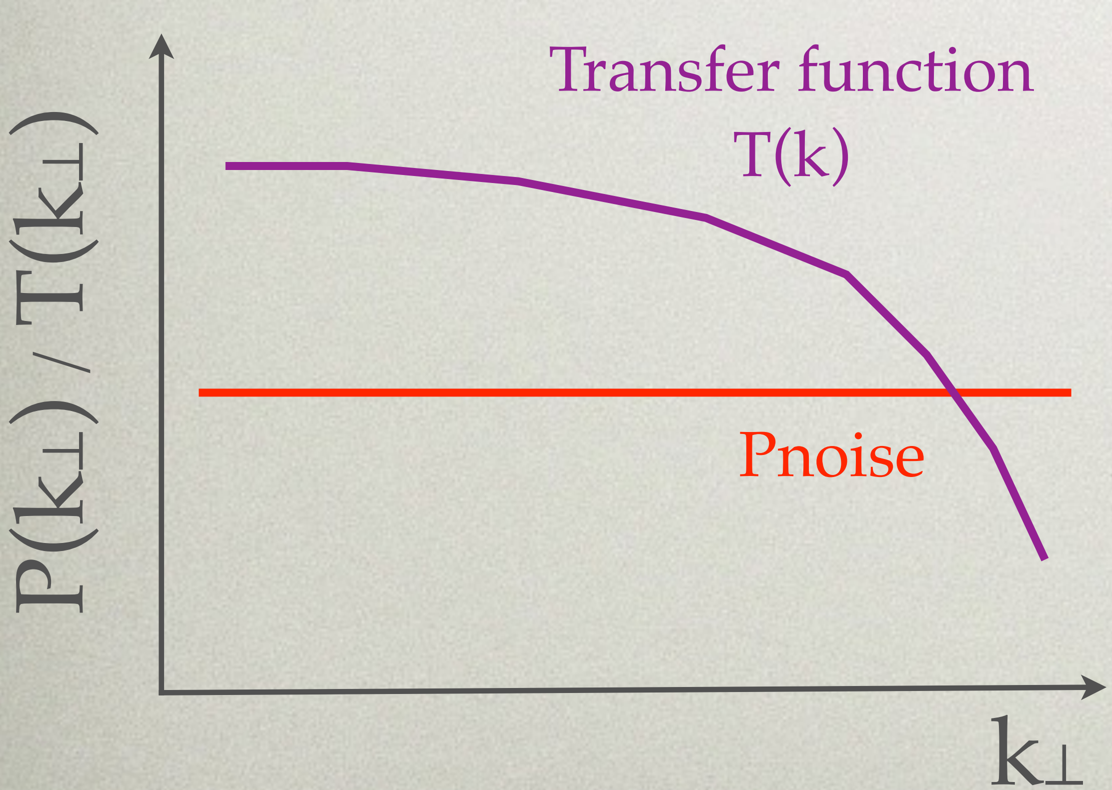
Estimate the sky Fourier amplitude (or Sph. Harmon. coeff) by solving (inverting) the linear system

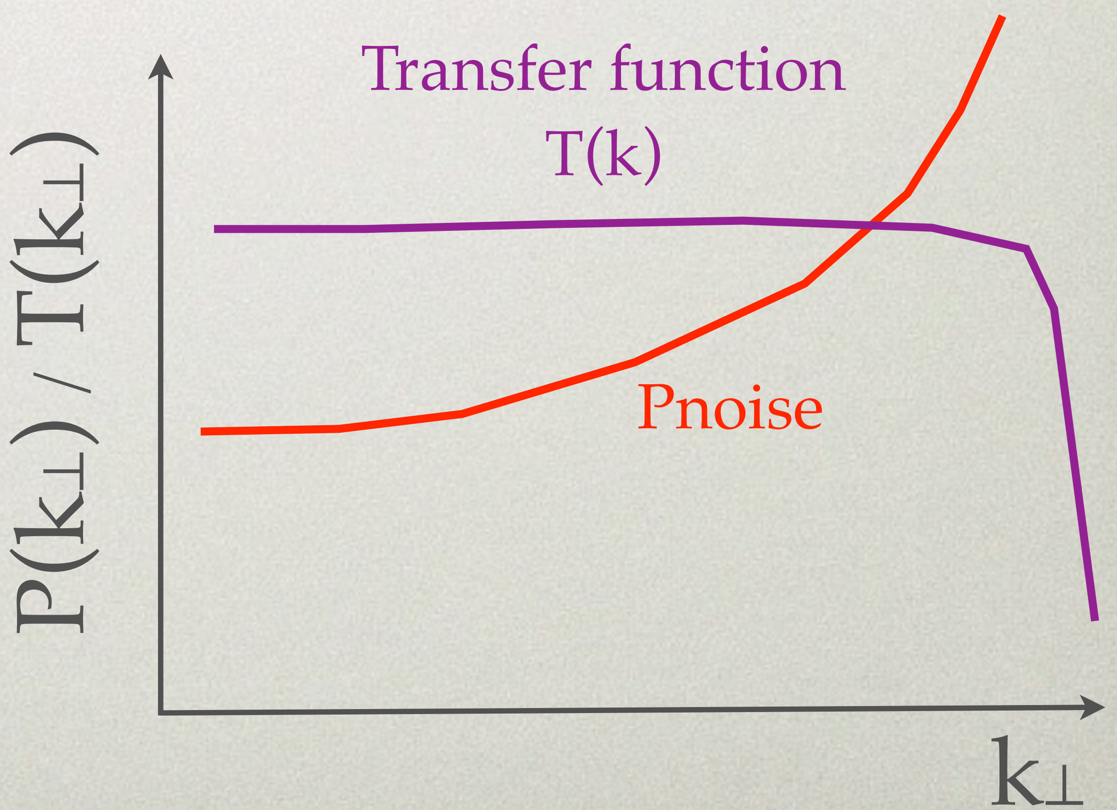
$$[\ V_{ij}\ (\text{time})\ ] = [[\ \mathbf{A'}\ ]] \times [\ F(u,v)\ ] + [\ n\ ]$$

for each frequency slice (ν)

Different maps can be made depending on the acceptable noise level

Estimated F(u,v) or F(l,m) have different uncertainties for each mode and are correlated

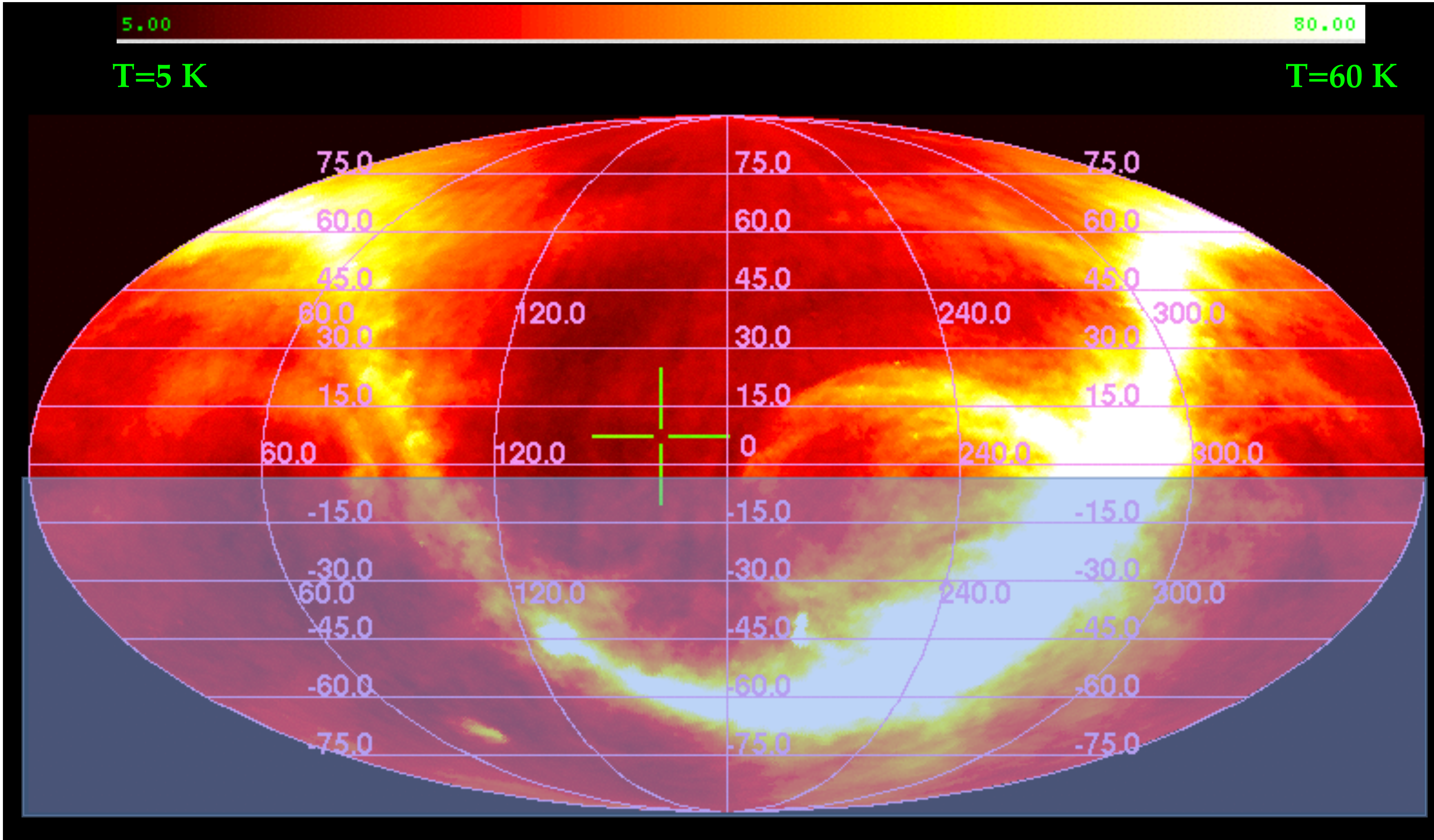




Weight function can be applied to the reconstructed F(u,v) or F(l,m) to control the noise level and mode mixing

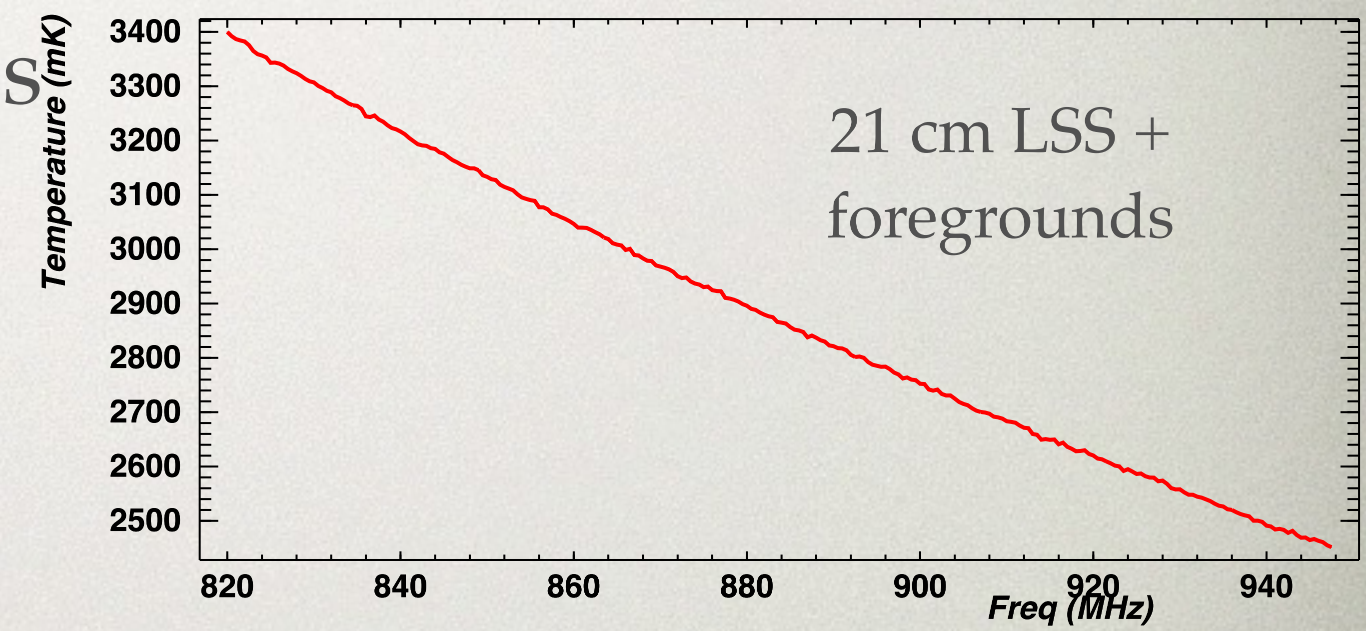
Foregrounds & mode mixing

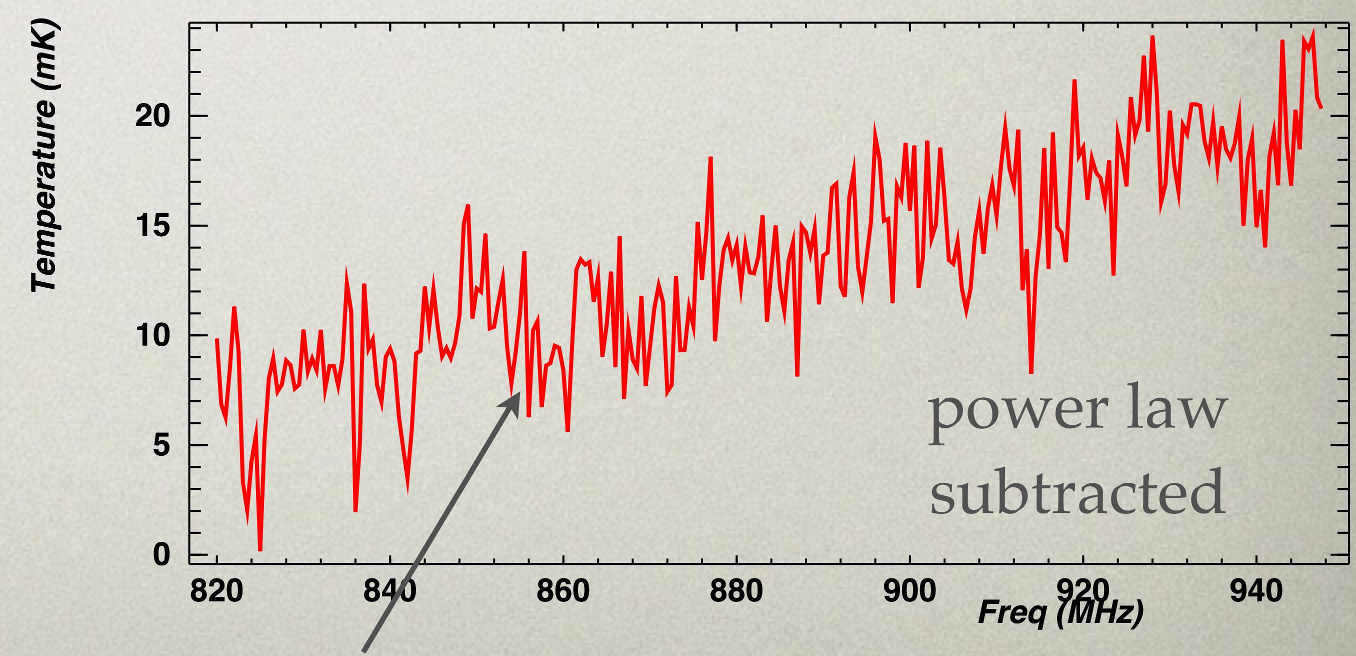
Synchrotron map @ 400 MHz - Eq. Coordinates (ra,dec)
(45 N ± 25 deg) → 20 < δ < 60 in Xinjiang (45 N)



Foreground removal

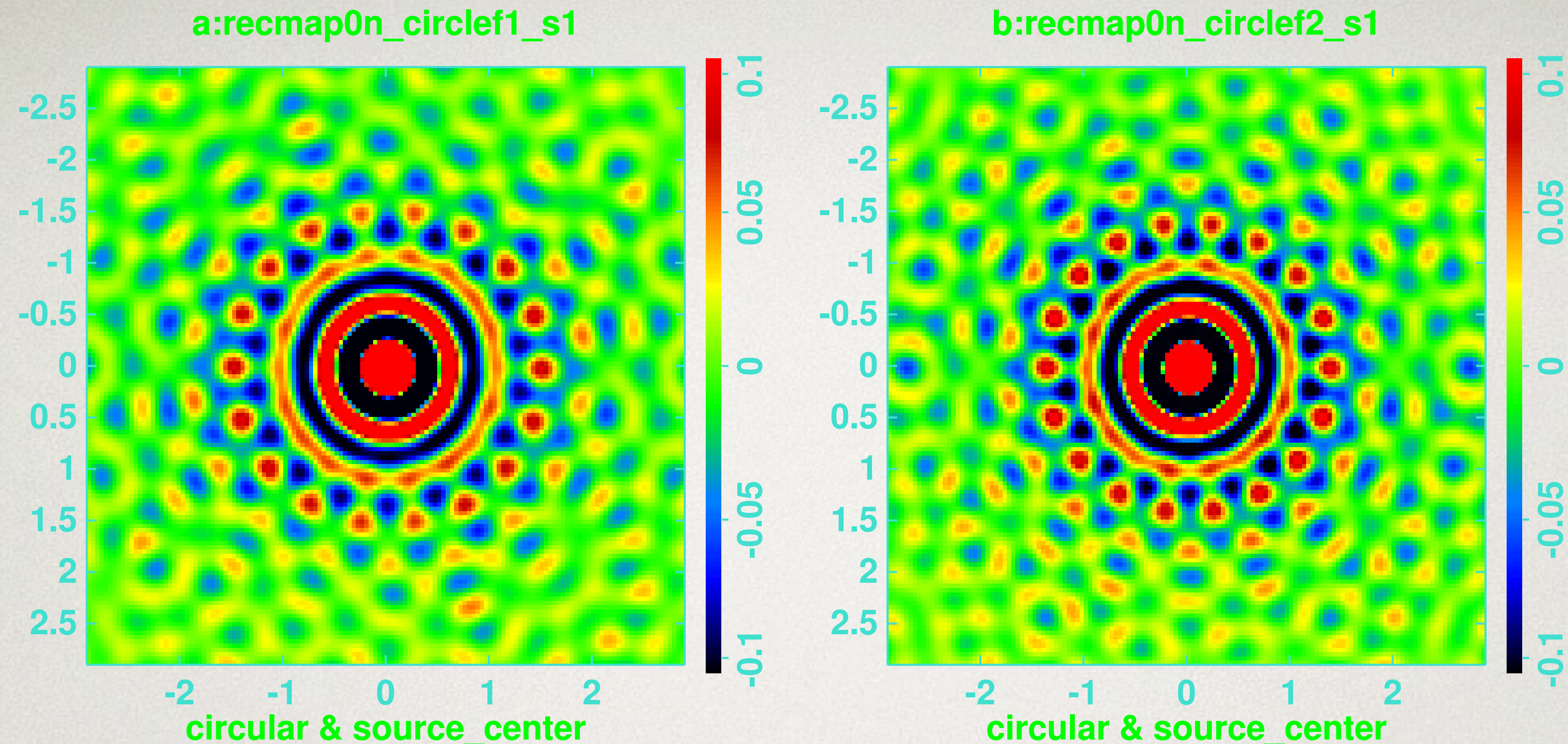
- Exploit frequency smoothness and power law ($\propto \nu^\beta$) behavior of foregrounds (synchrotron/radio sources)
- power law / polynomial / foreground model fit & subtraction
- Mode mixing, bias, error propagation …

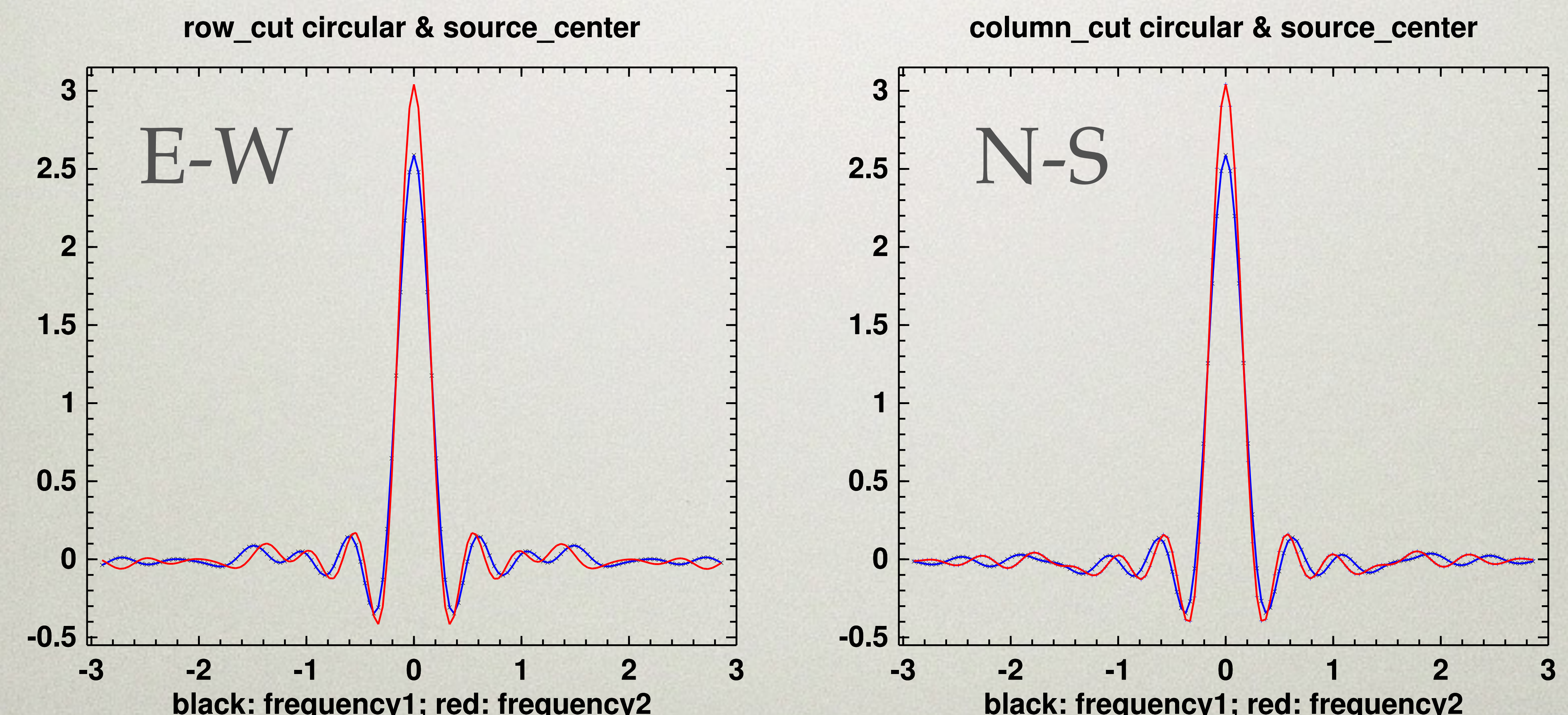




1200 MHz

1300 MHz



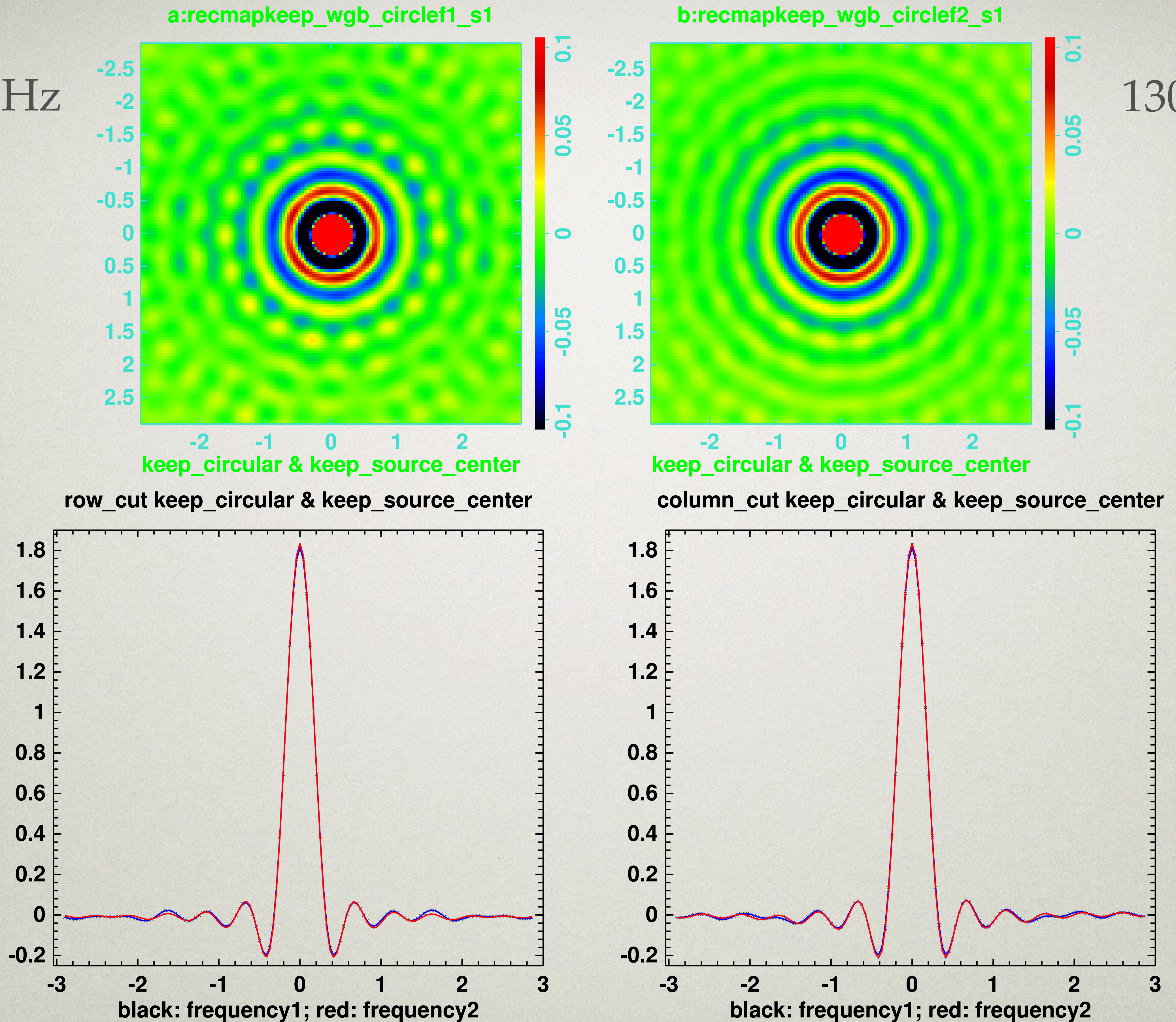


Computation by Jiao Zhang

Beam frequency dependency - circular configuration (b) - 1200 MHz, 1300 MHz

1200 MHz

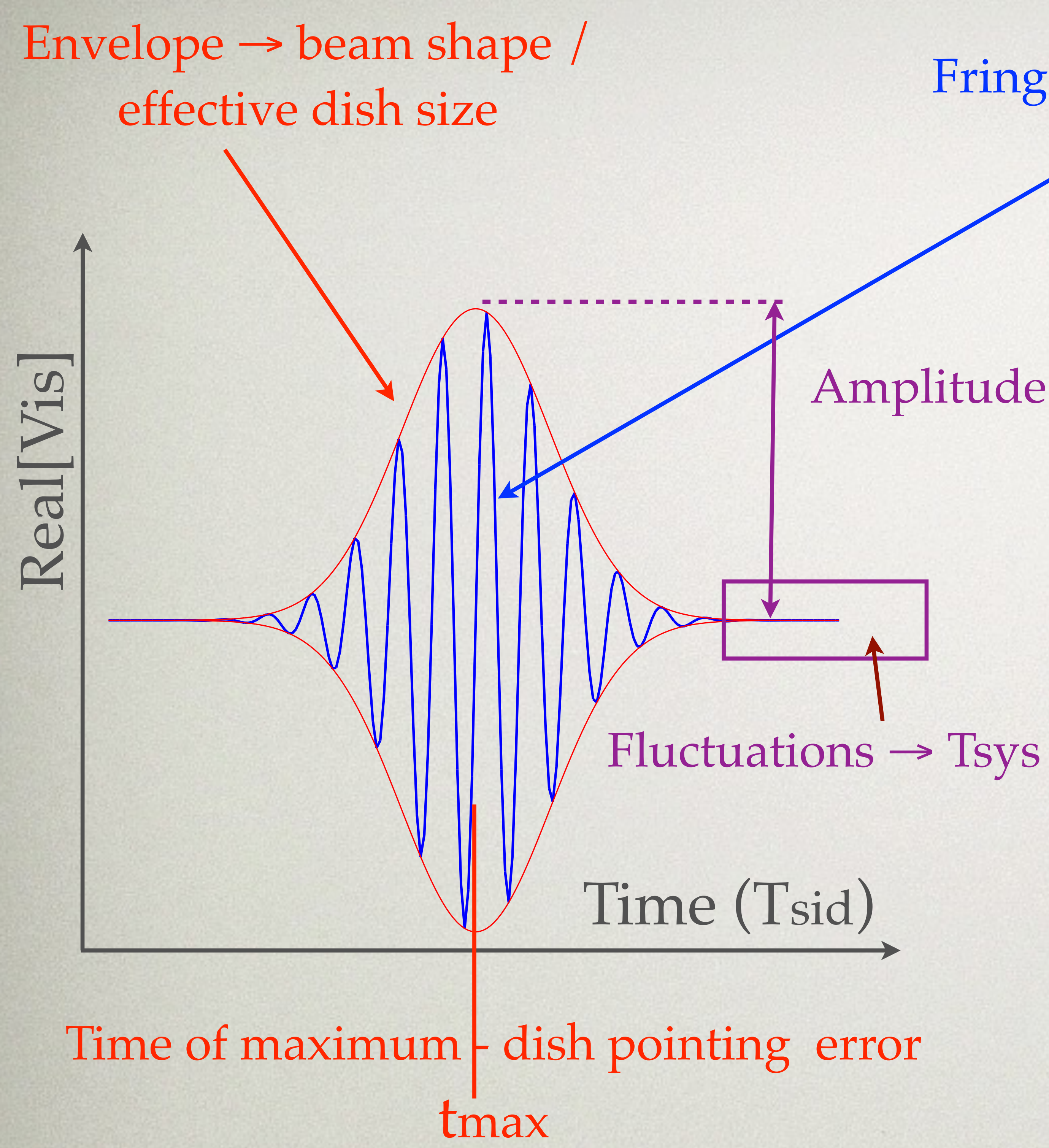
1300 MHz



Computation by Jiao Zhang

Applying a global weight function - circular configuration (b) - 1200 MHz, 1300 MHz

Calibration



- Determine g(ν) using auto-correlation + filetring
- Determine phase difference using fringes
- Determine / check beam and array geometry using the fringes
- Determine gain (fringe amplitude) & Tsys (fluctuations before / after transit

Application to PAON4 preliminary results

BAORadio 21 cm

LAL - IN2P3/CNRS

R. Ansari
J.E. Campagne
M. Moniez
A.S. Torrento
D. Breton
C. Beigbeder

T. Cacaceres
D. Charlet
B. Mansoux
C. Pailler
M. Taurigna

IRFU - CEA

C. Magneville
C. Yèche
J. Rich
J.M. Legoff

P. Abbon
E. Delagnes
H. Deschamps
C. Flouzat
P. Kestener

Observatoire de Paris

P. Colom
J.M. Martin
J. Borsenberger
J. Pezzani
F. Rigaud
S. Torchinsky
C. Viou

PAON Test Interferometer

(J.M.Martin, J.E. Campagne)

PAON-4

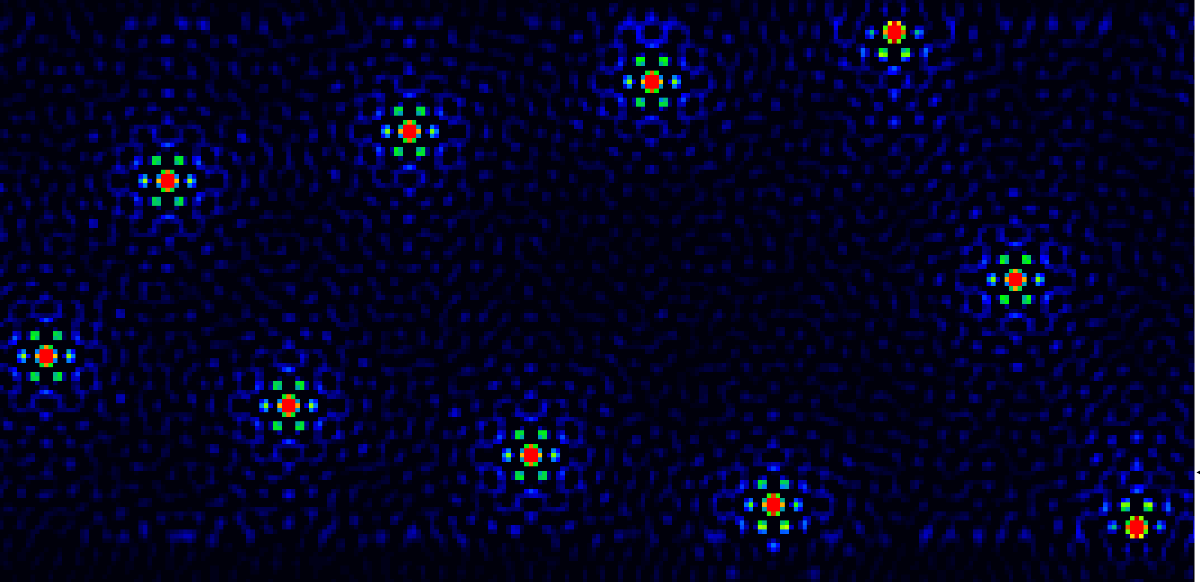
(F. Rigaud)

installation Nov 2013 -
June 2014
4 D=5m dishes

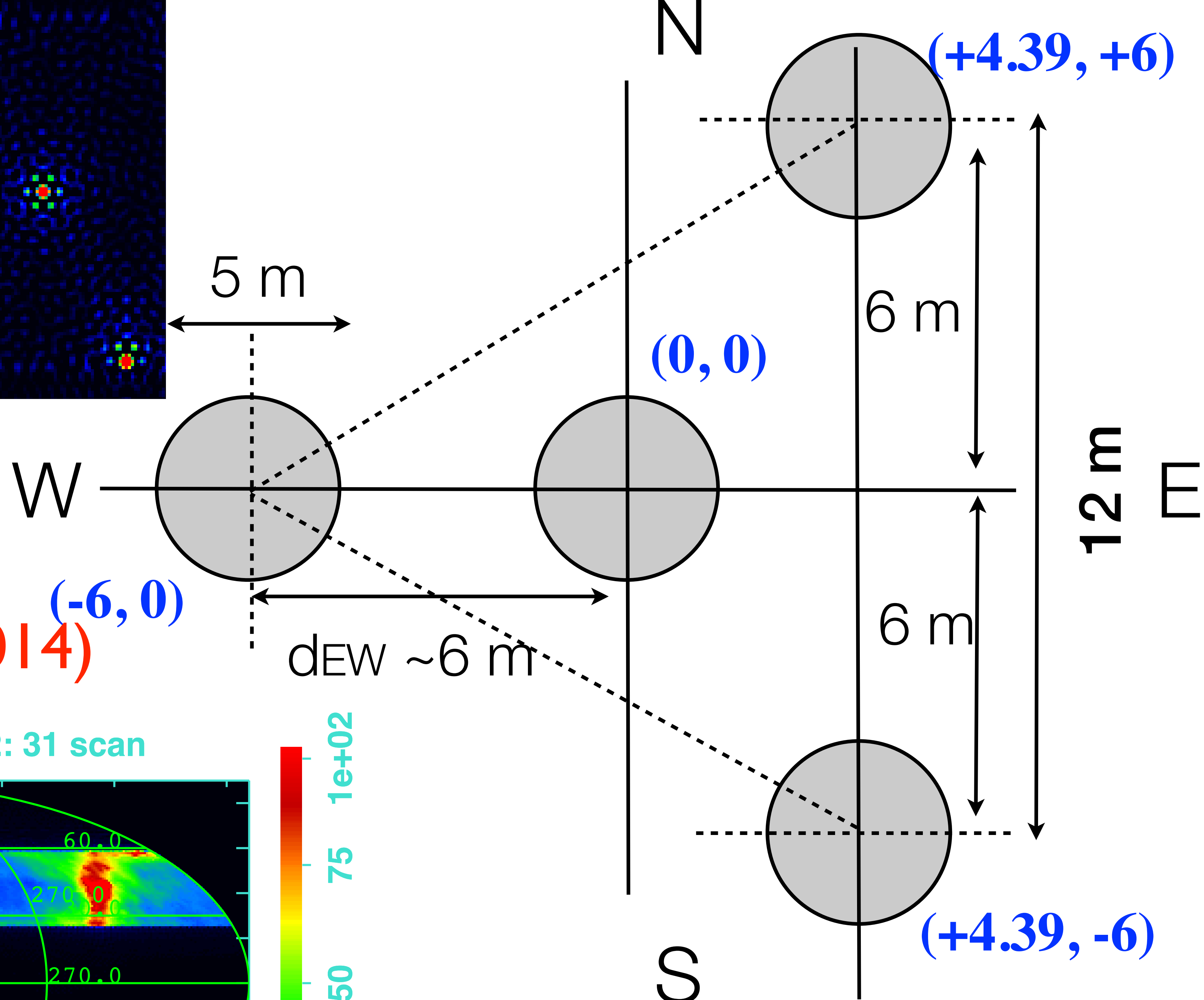
PAON-2 →

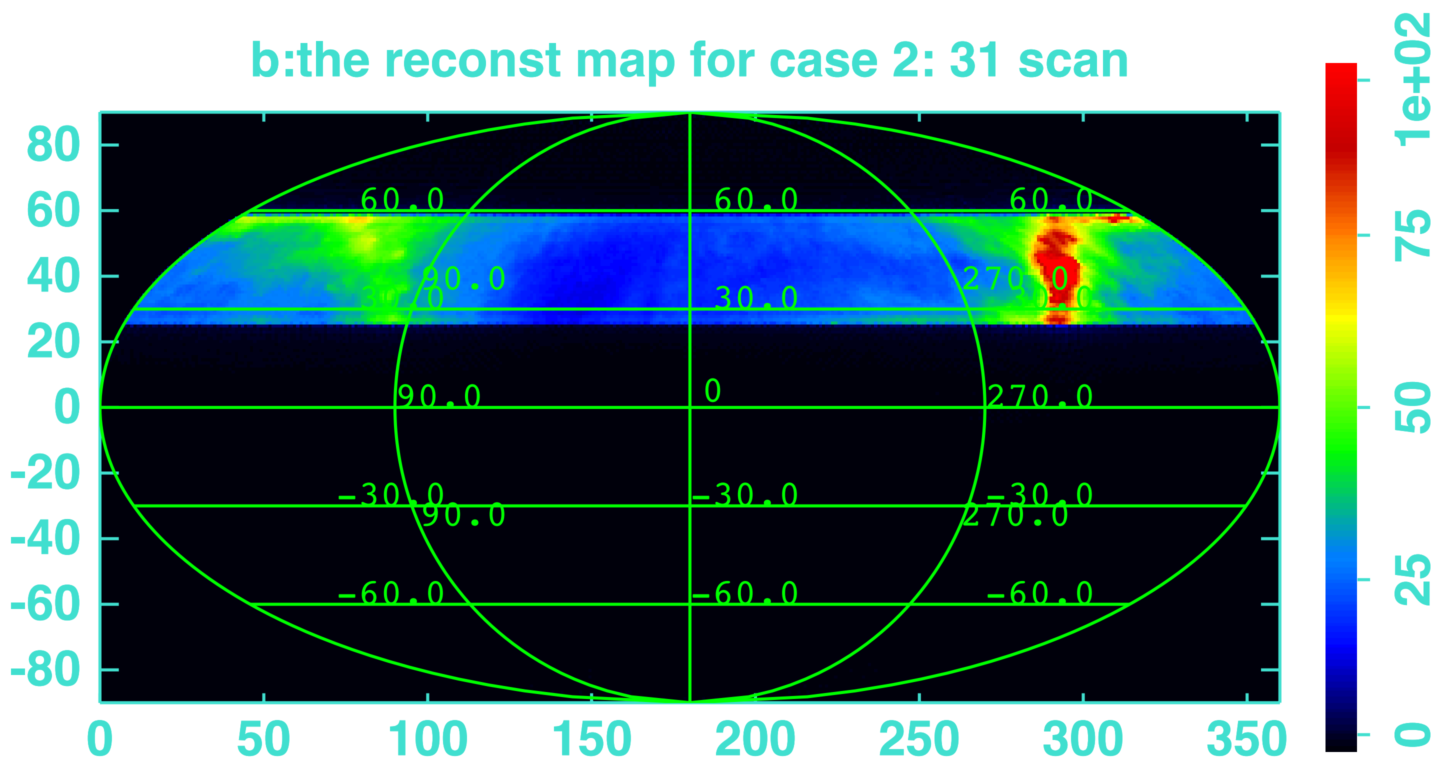
installed September 2012


PAON-4 Test Interferometer
November 2014



Beam & Sky map reconstruction by **Jiao Zhang** (Spring 2014)





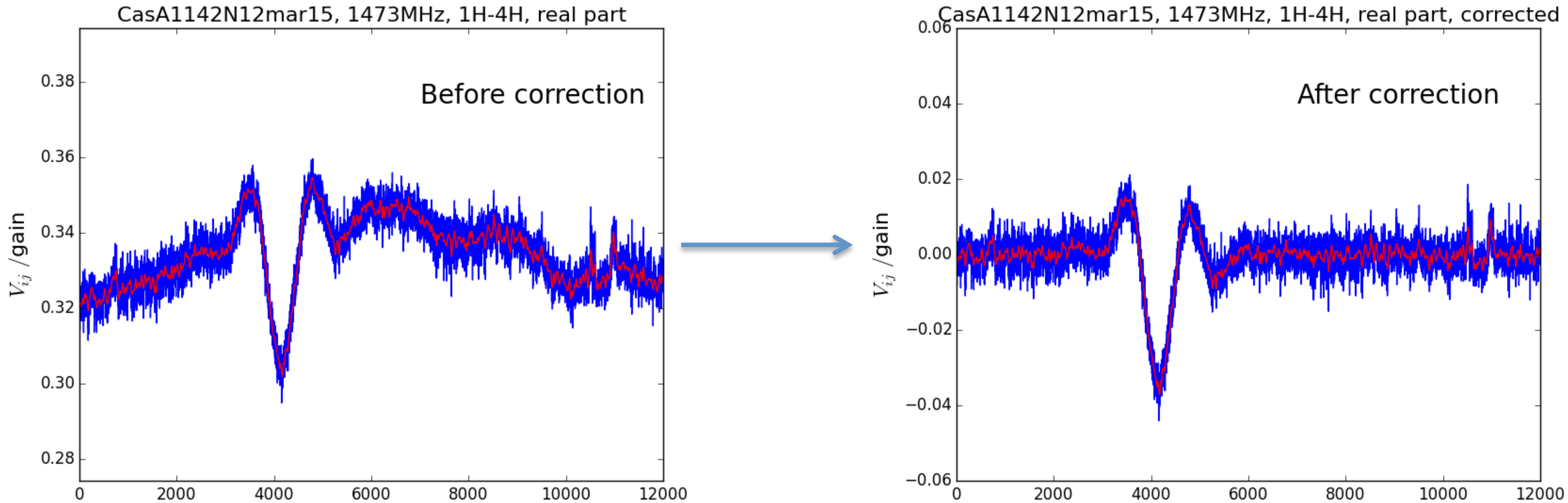
(x, y) : Antenna position in meters (x:WE, y:SN)

PAON-4 configuration at Nançay -

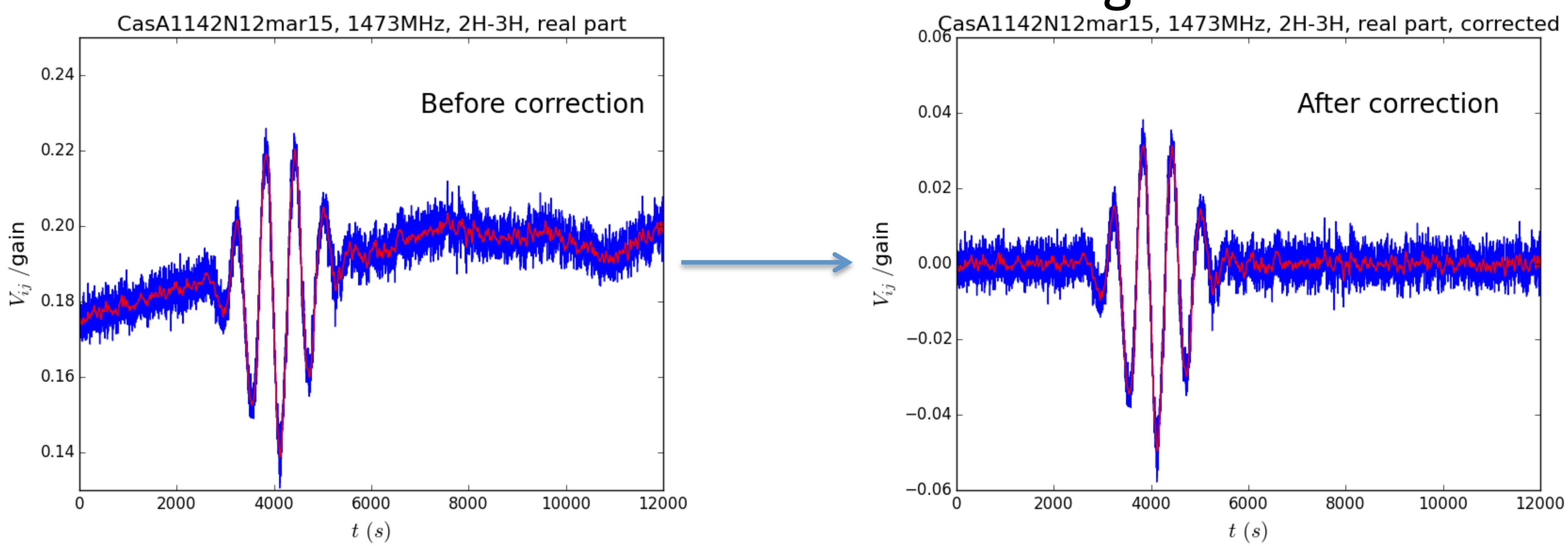
Latitude 47 deg 23' - Longitude 2 deg 12' E

PAON-4 preliminary analysis

Correct data (2)



Note that we need to rotate the fringe a little.

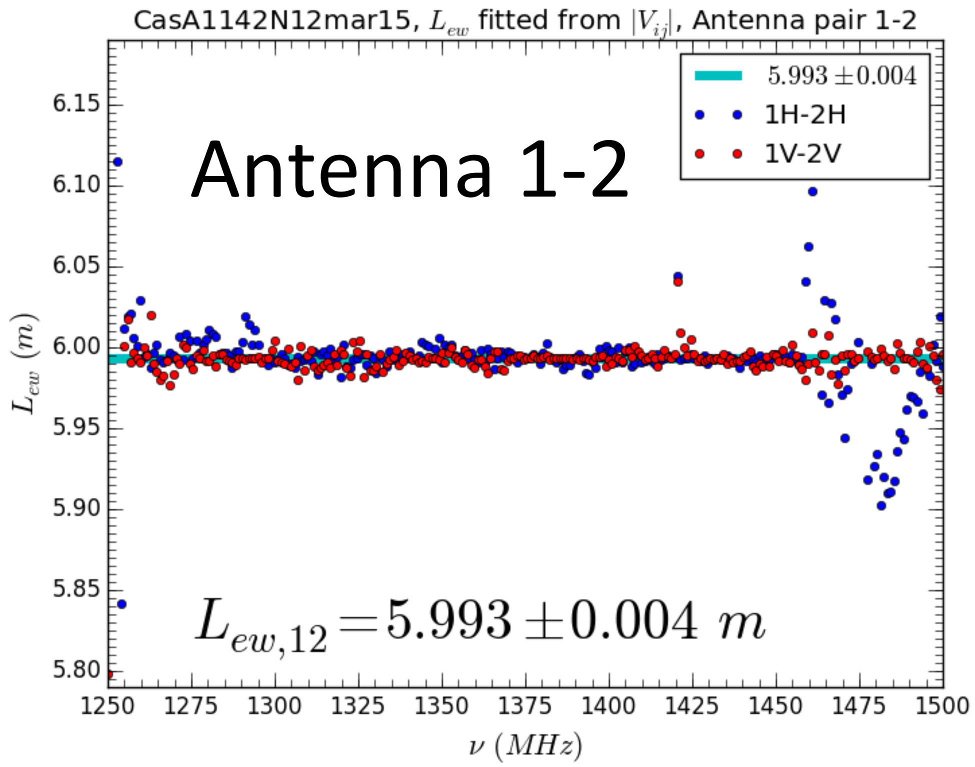


PAON4 data, fringe analysis by **Qizhi Huang**

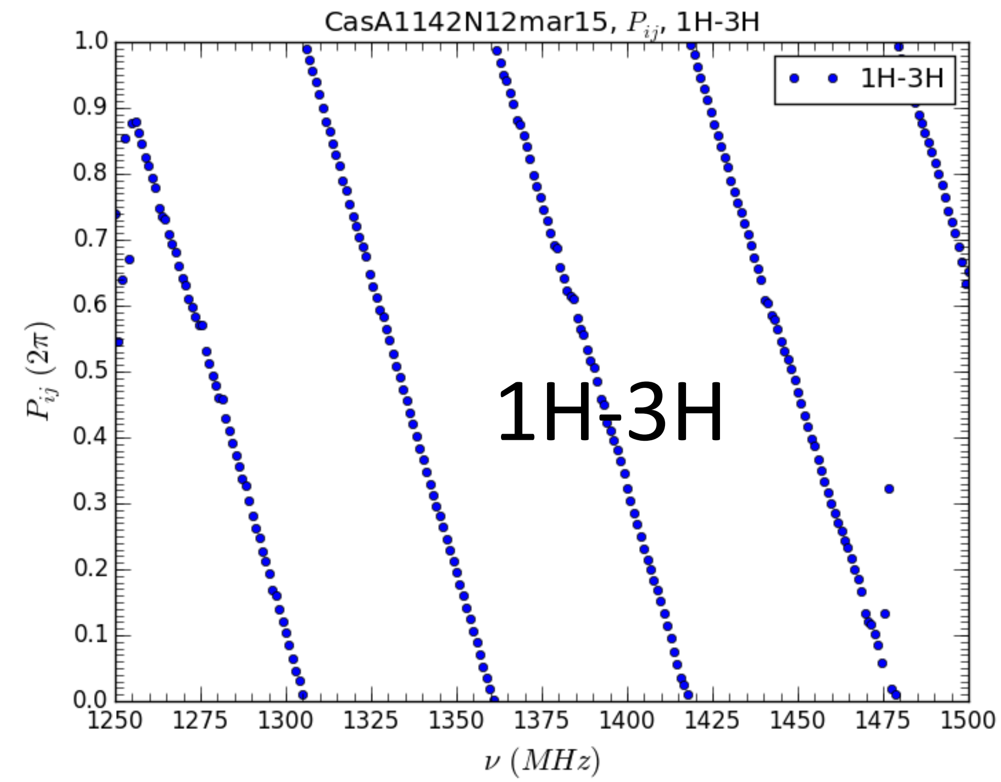
Extract array geometry, Tsys …

(June 2015)

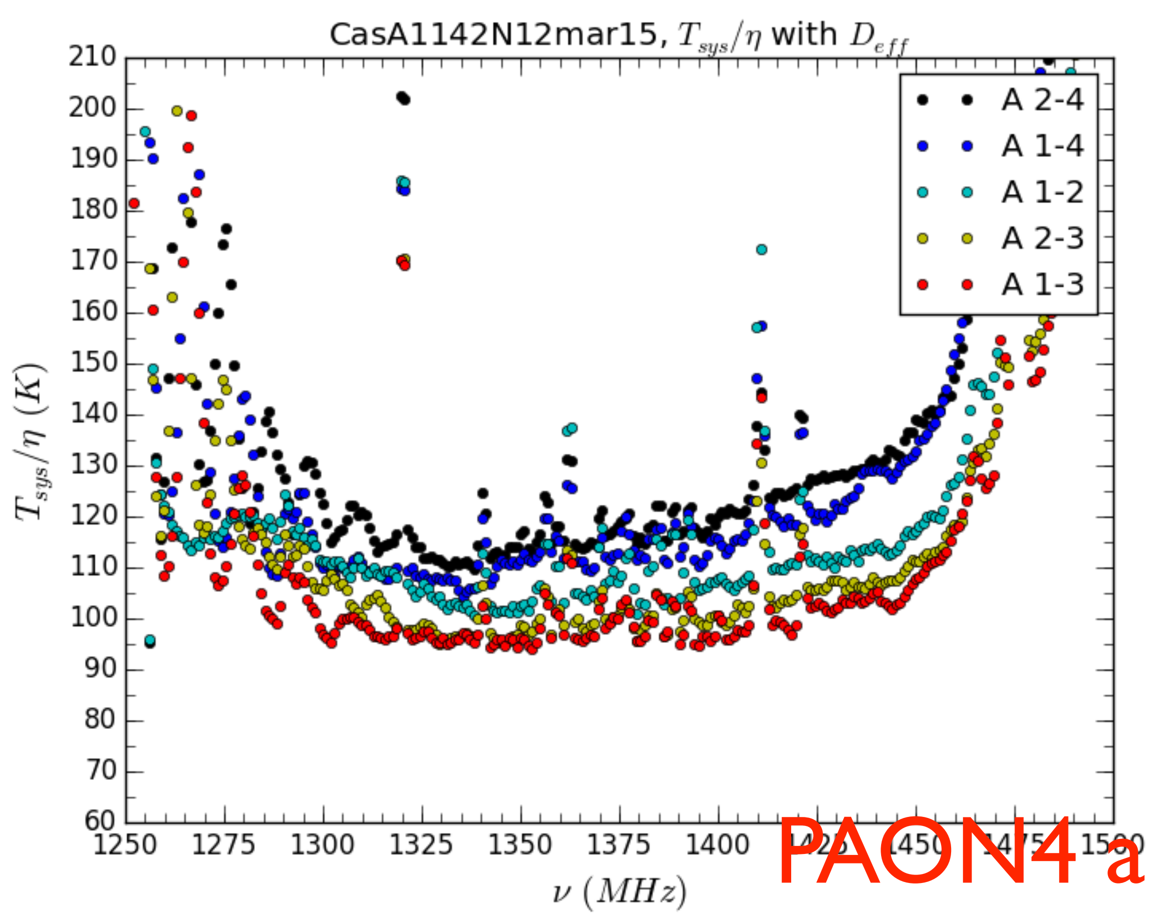
E-W baseline

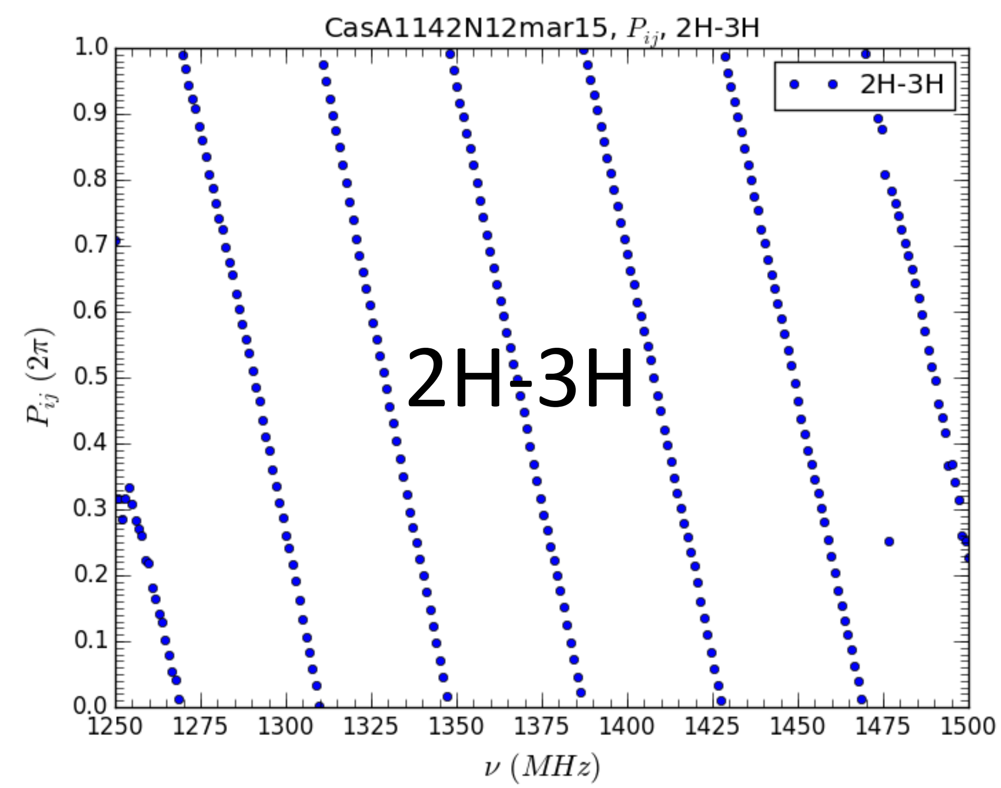


Phase calibration



Gain / Tsys





PAON4 analysis by **Qizhi Huang** (June 2015)

PAON-4 sysytem stability (gain/phase)

Stability of the gain

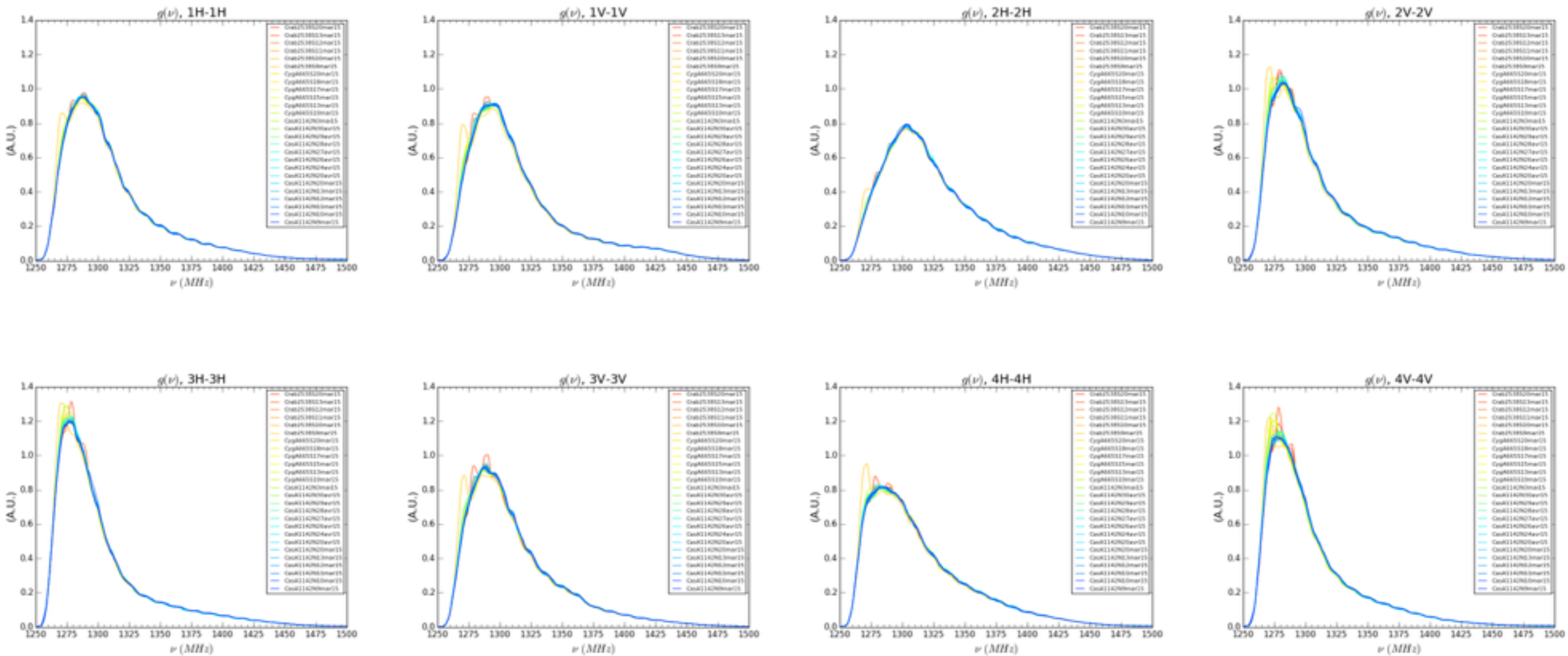
- The auto correlation can be express as

$$V_a(t,\nu) = G(t,\nu)\cdot(T_{\rm sky}\otimes A + T_{\rm sys}) = G(t)\cdot g(\nu)\cdot(T_{\rm obs} + T_{\rm sys})$$

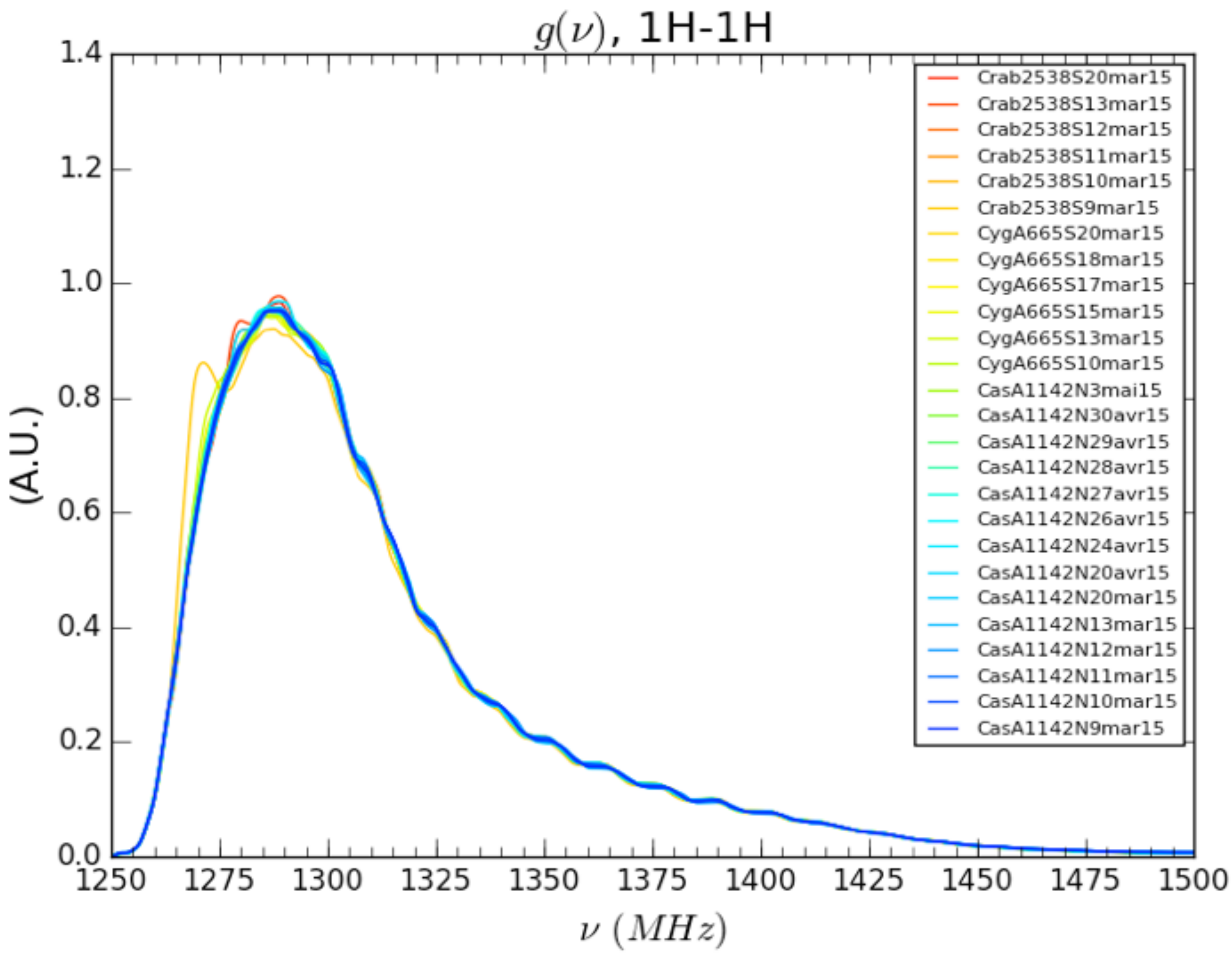
where $g(\nu)$ is the response of the electric system with frequencies. Base on dozens of observation data, we can find that $g(\nu)$ is reasonable stable over days and to different sources.

PAON4 analysis by **Qizhi Huang** (July/September 2015)

Stability of the gain



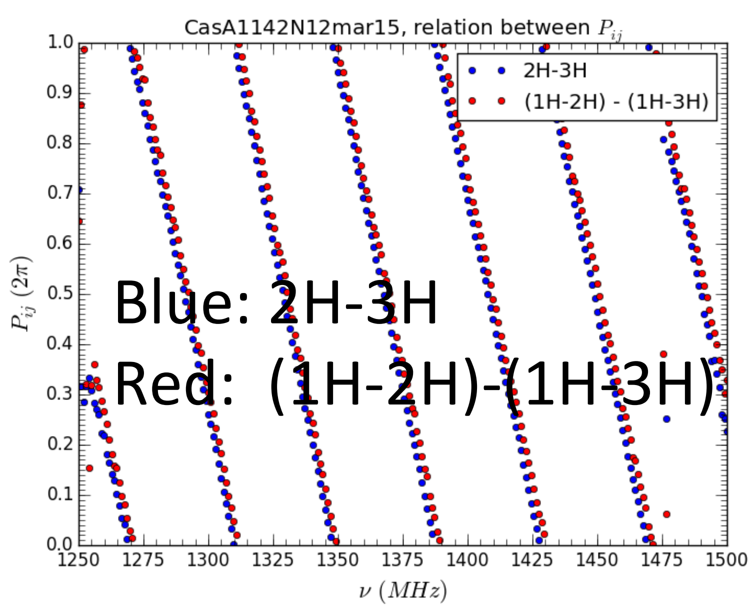
PAON4 analysis by **Qizhi Huang** (July/September 2015)

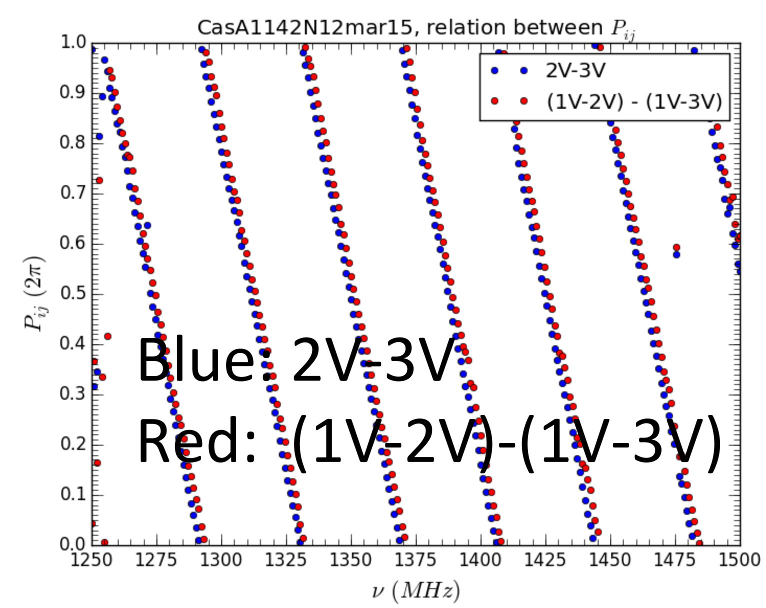


PAON4 analysis by **Qizhi Huang** (July/September 2015)

Check the phase fitting (1)

- Phase delay is most due to the different lengths of the cables.
- However, also because the lengths of the cables won't change, phase delays of different channels should have a stable relation.
- Obviously, we should have: $P_{ij} - P_{ik} = P_{kj}$
- Finally, we find our phase fittings satisfy this relation.





Check the phase fitting (2)

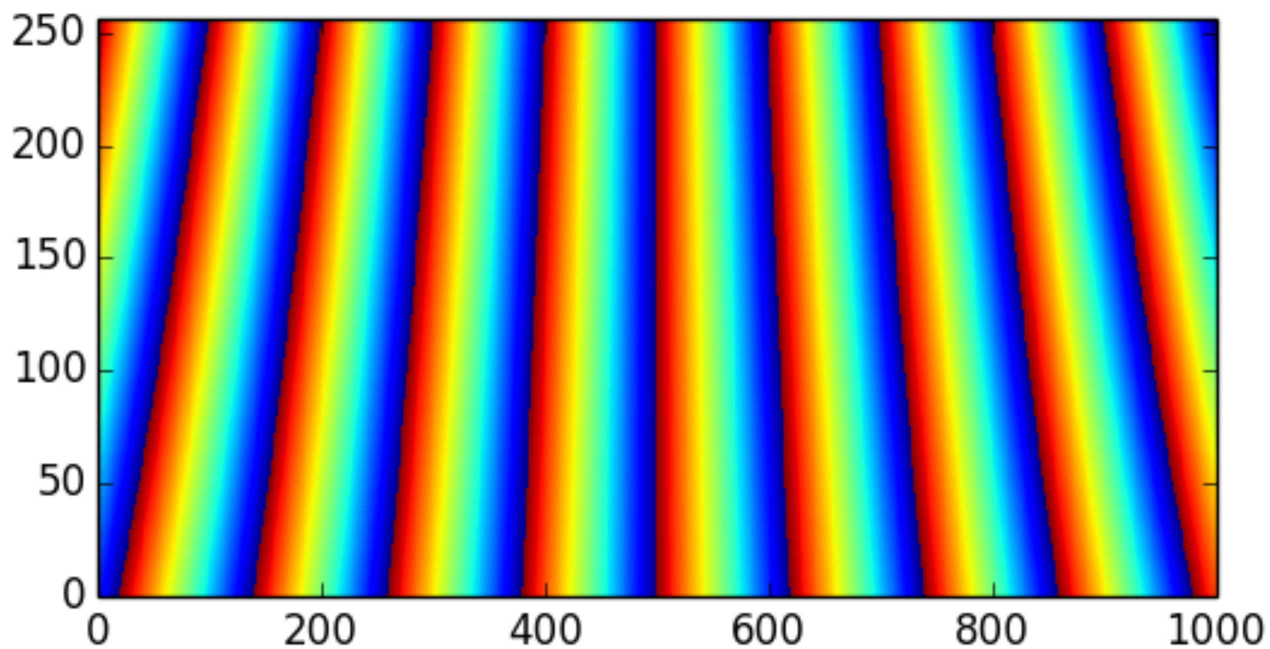
- Total phase:

$$\Phi_{tot,ij} = \frac{2\pi}{c} \cdot \nu \cdot [L_{ew,ij} \sin(\theta) - L_{ns,ij} \cos(\theta)] + \Delta\Phi_{ij}$$

- The phase due to the East-West baseline:

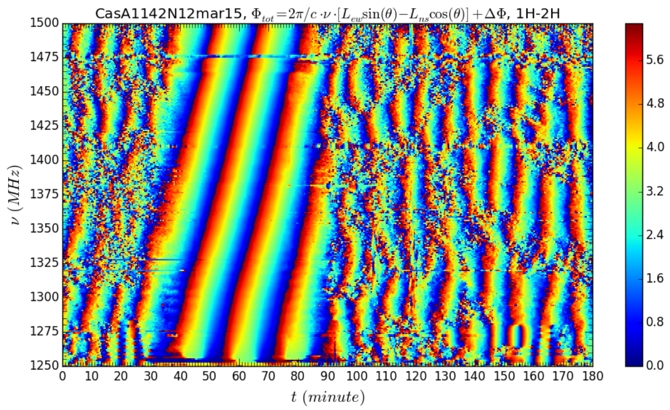
$$\Phi_{ew,ij} = \frac{2\pi}{c} \cdot \nu \cdot L_{ew,ij} \cdot \sin(\theta)$$

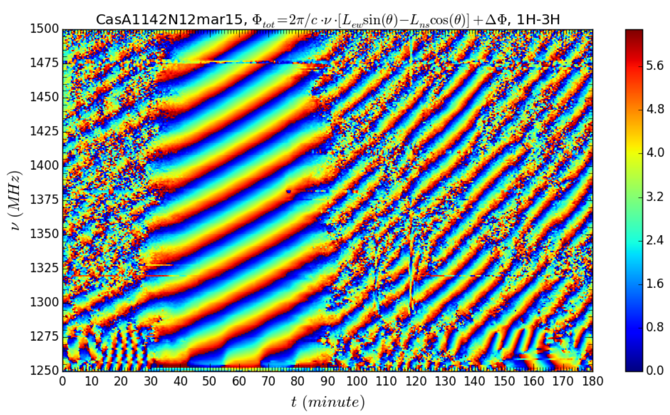
- Therefore, the theoretical image of $\Phi_{ew,ij}$ will be:

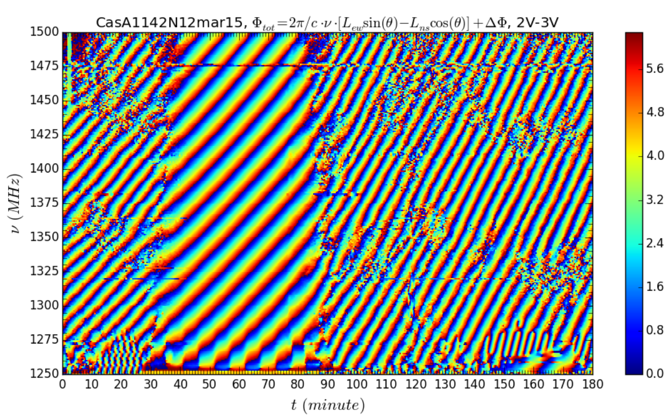


Check the phase fitting (2)

- Here, we use total phase to minus the additional phase due to the cable and the phase due to North-South baseline, then we can find that our fittings are coincident wih the theoretical image above.

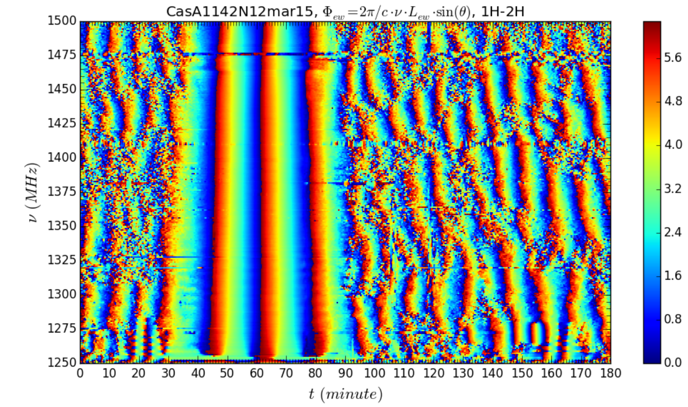


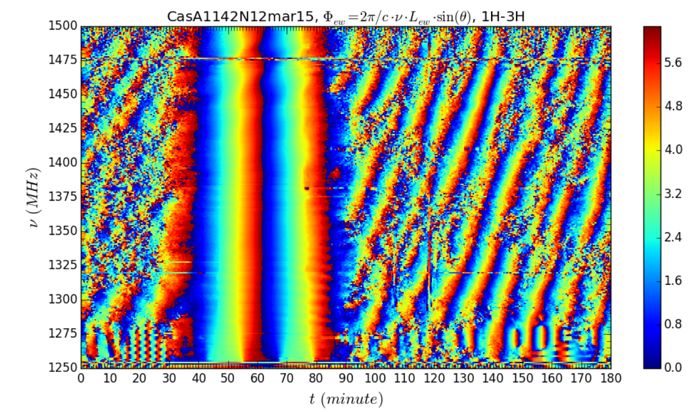


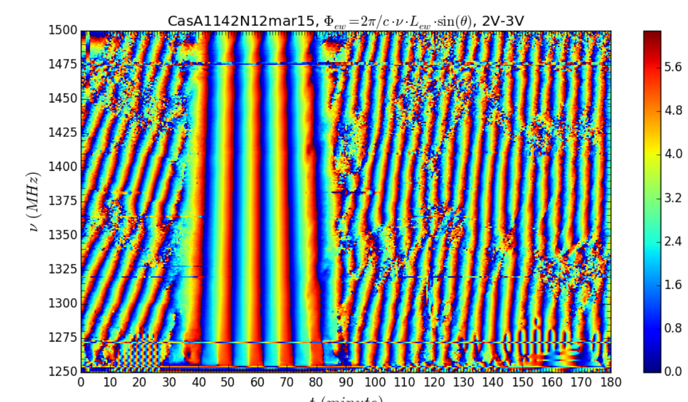


$$\Phi_{tot,ij}$$

$$\Phi_{ew,ij}$$







- Parallel (multi-thread) Map making software operational *(J. Zhang, R.A. J.E. campage, C. Magneville)*
- Despite many problems, some encouraging preliminary results on PAON-4 concerning the calibration *(Q. Huang + C. Pailler, D. Charlet, J.E. Campagne, C. Magneville …)*
- Still a lot of work to be done on PAON-4 and many problems to be solved
- Expecting application to Tianlai data soon
- new NEBULA digitization board should be ready in 2016