Global (3)mm VLBI : a brief summary and overview of the standard data analysis path

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The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

100 – 300 mJy

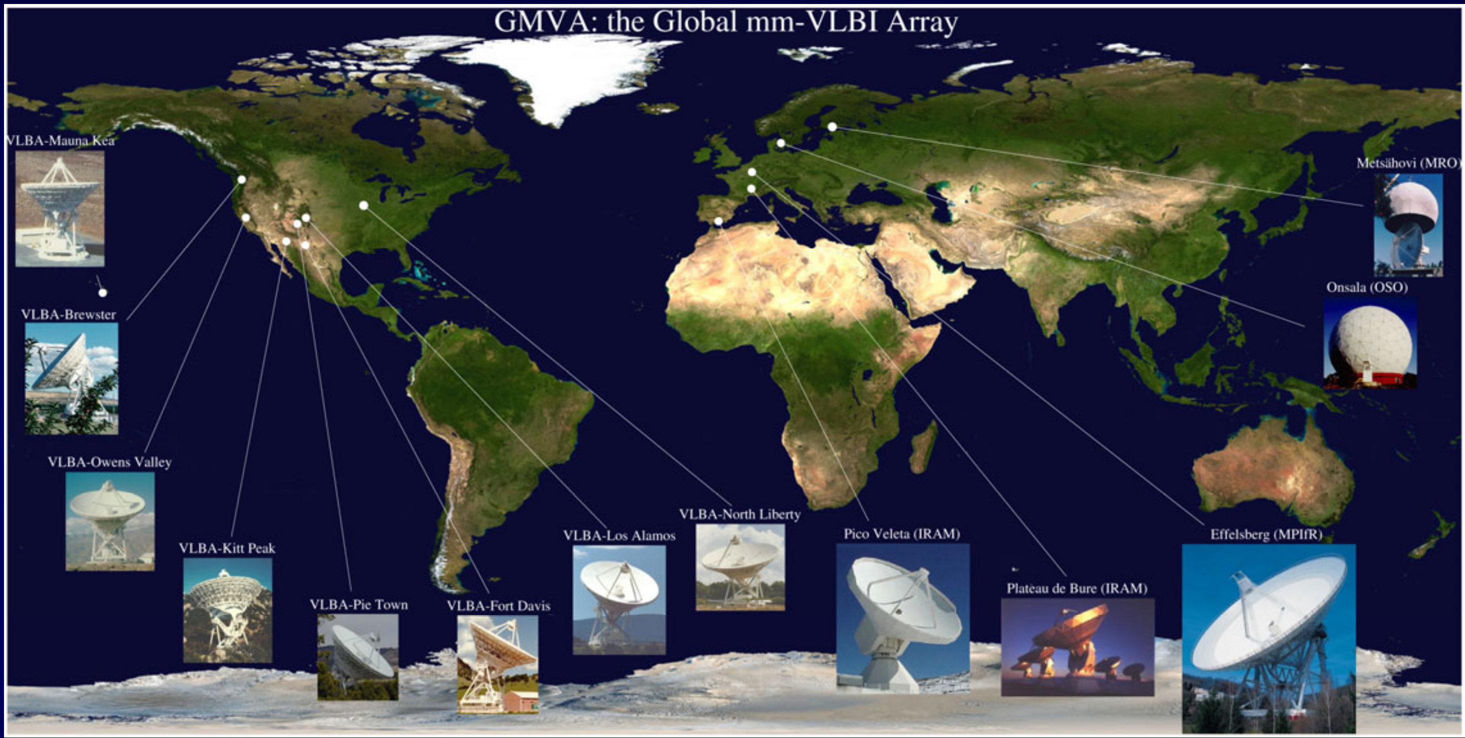
transatlantic:

50 – 300 mJy

Array:

1 – 3 mJy / hr

(assume 7σ, 100sec, 512 Mbps)



http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), Yebes (40m), GBT (100m), planned: KVN, SRT, ALMA, ...
- USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, August 1st

What does the GMVA offer ?

- a global 14 station VLBI array allowing high dynamic range imaging with an angular resolution of up to 40 μas at 86 GHz

- 3 – 4 times higher sensitivity than stand-alone VLBA (standard 2 Gbps recording, max. 7σ baseline sensitivity is ~ 25-150 mJy)

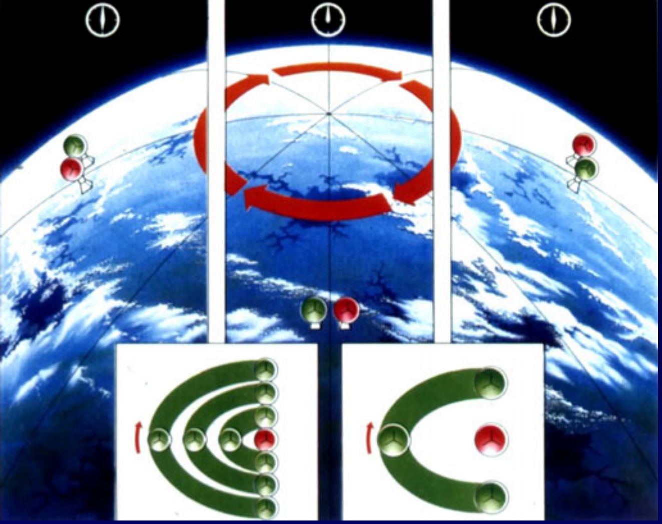
- 2 epochs/year, each session ~ 3 – 5 days long (limitation by proposal pressure), single- or dual polarisation

- block schedule preparation by GMVA to optimize array calibration

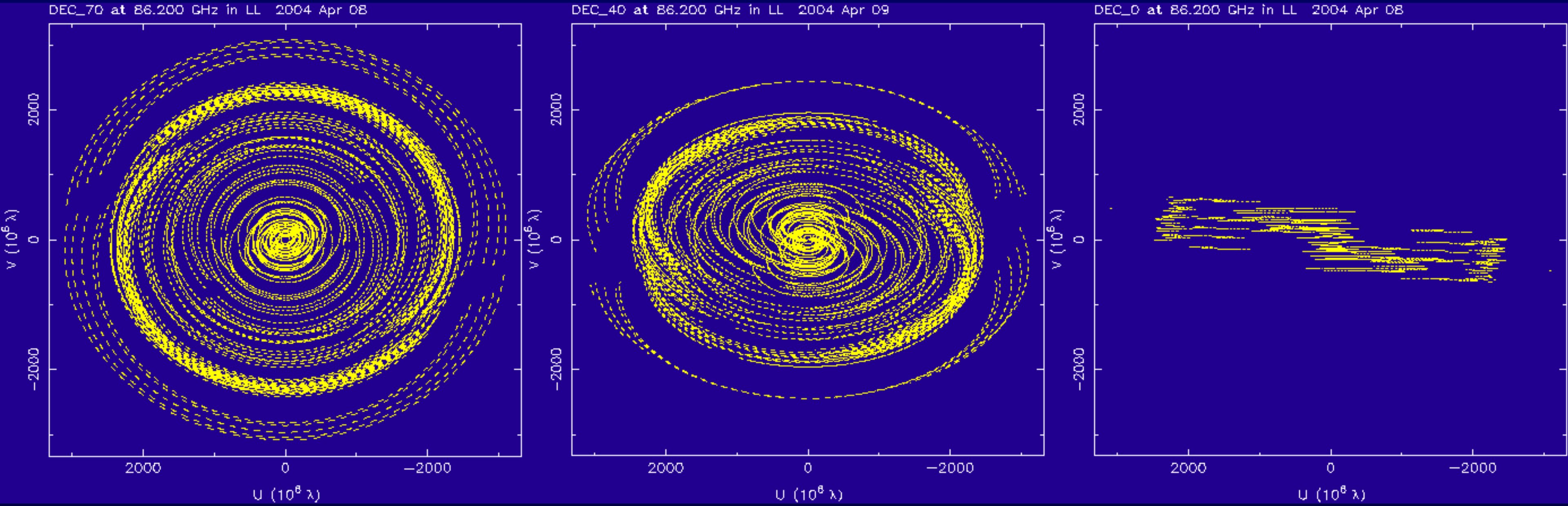
- correlation at MPIfR Bonn correlator (including quality control)

- UV-FITS formated AIPS data files provided to user (FITLD)

- open to community by usual proposal procedures (proposal deadlines Feb. 1st for observation in autumn and Aug. 1st for observation in spring)



Typical uv-coverages of the Global 3mm VLBI Array

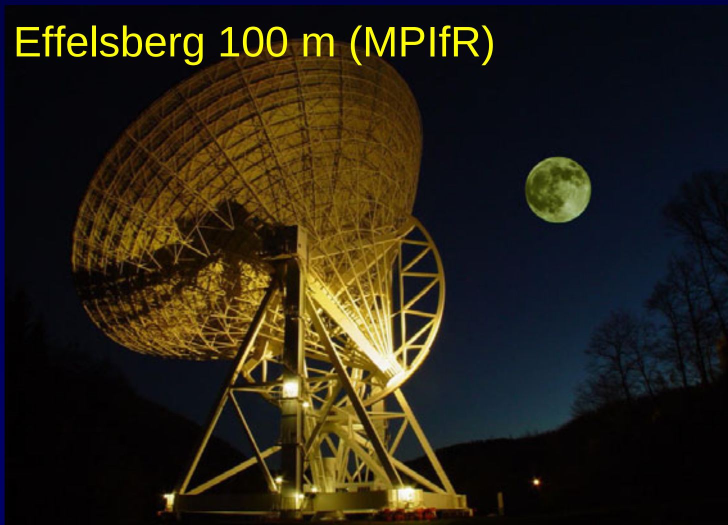


Dec. +70

Dec. +40

Dec. 0

3mm VLBI sensitivity enhanced by inclusion of large European mm-telescopes:


Effelsberg 100 m (MPIfR)


Plateau de Bure, 6 x 15 m (IRAM, France)


Pico Veleta 30 m (IRAM, Spain)


Yebes 40 m (OAN, Spain)

participating on best effort basis since 2011

Baseline lengths (km):

	PV	PdB	Yb
EB	1700	658	1352
PV		1146	384
PdB			866

fringe spacing: 0.4 – 1.8 mas,

sensitivity > 35 - 65 mJy (7σ, 512 Mbps)

Green Bank 100m telescope participates in GMVA 3mm VLBI observations

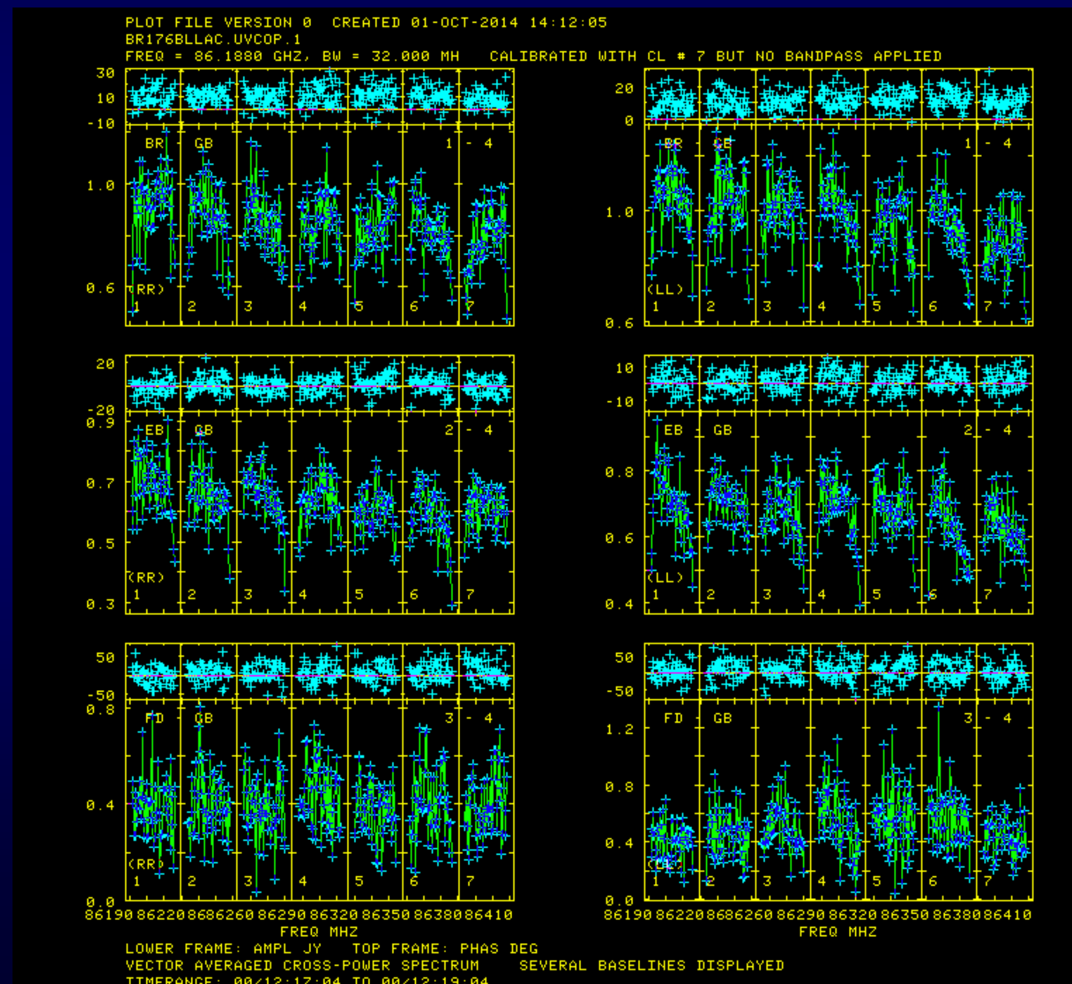
1st test observations in Feb. 2013

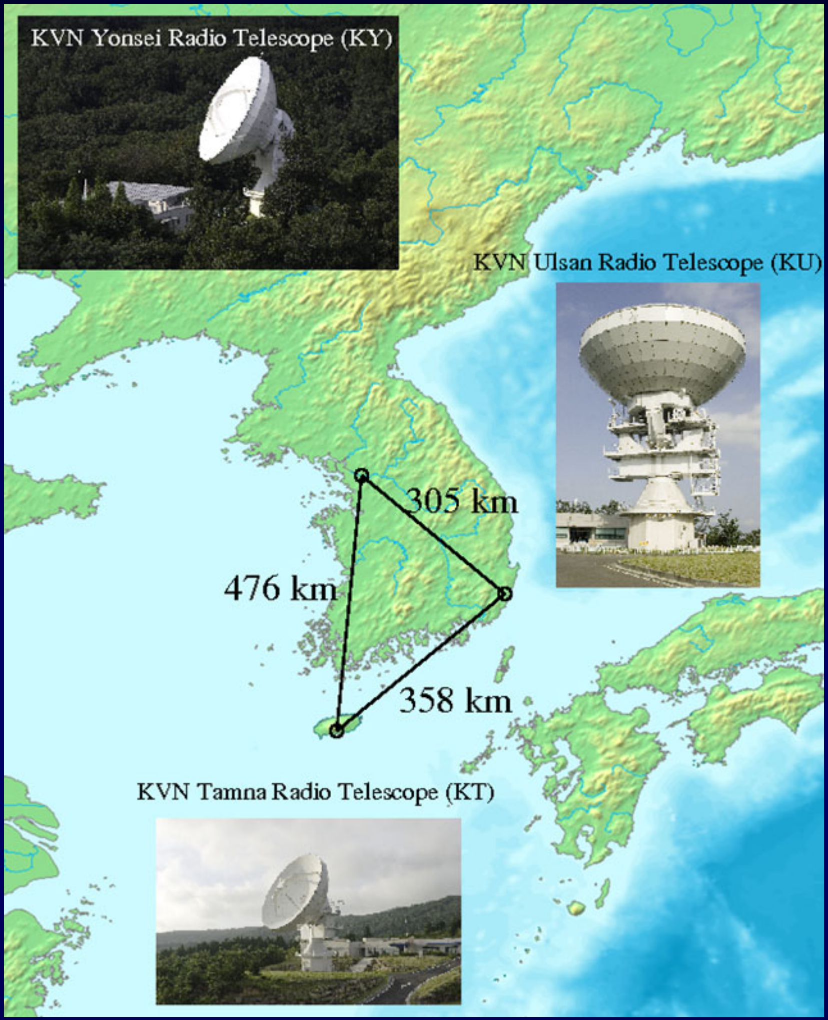
2 Gbps, 1 RDBE, PFB mode

SEFD ~ 164 K

app. eff ~ 0.26 (for σ = 173 mm)

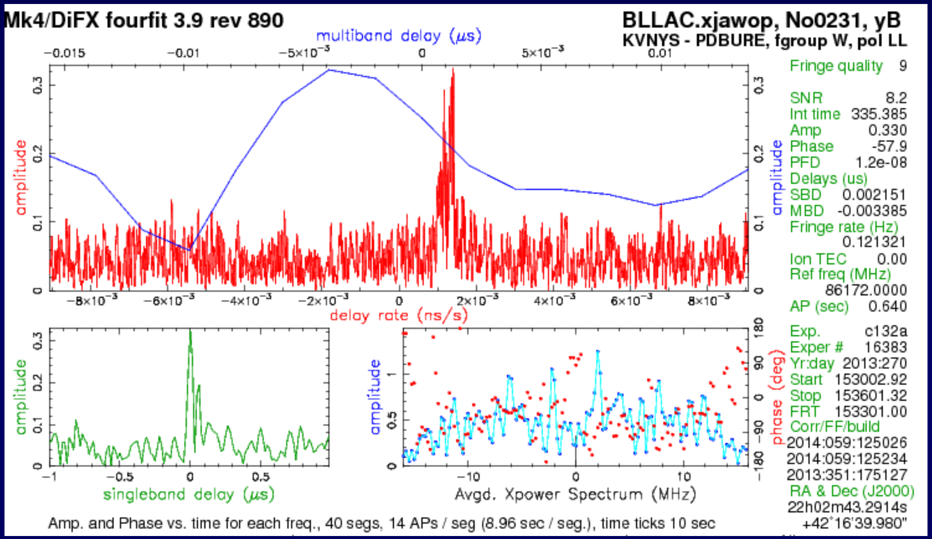
POSSM plot after FRING:





First fringes between KVN and GMVA at 86 GHz in spring 2013:

KVN Yonsei - P. de Bure (256 Mbps)



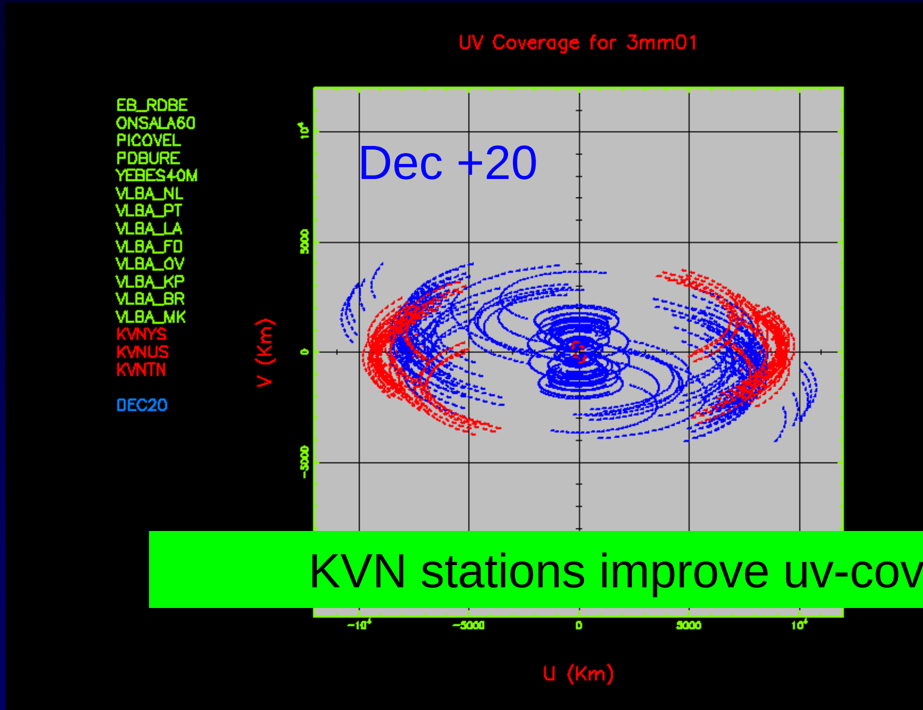
<u>baseline sensitivities:</u>

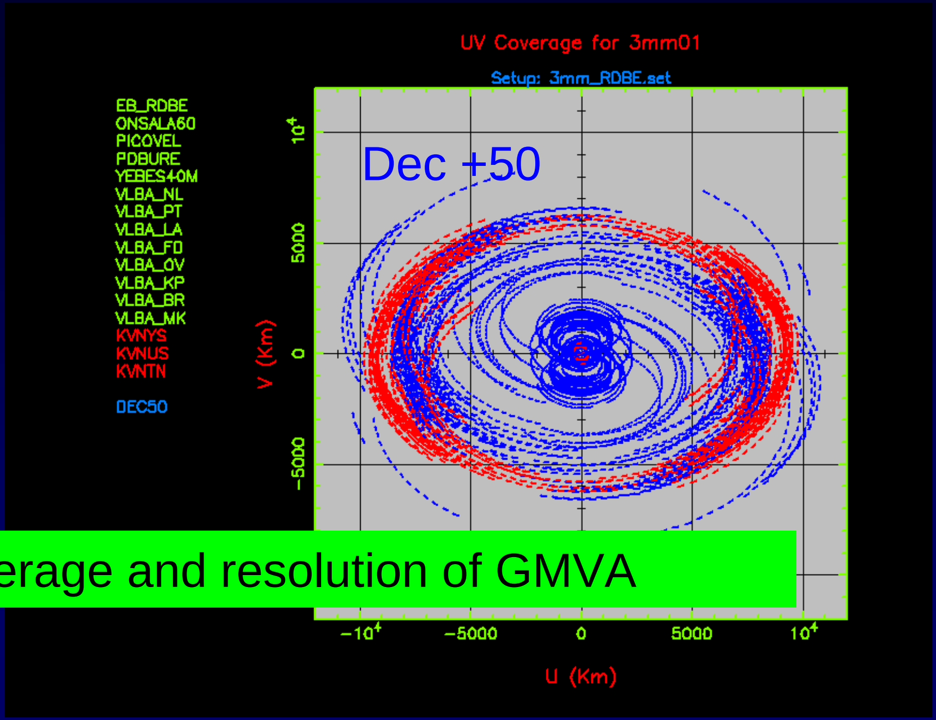
KVN – GBT ~0.07 Jy

KVN – IRAM ~0.15 Jy

KVN – VLBA ~0.35 Jy

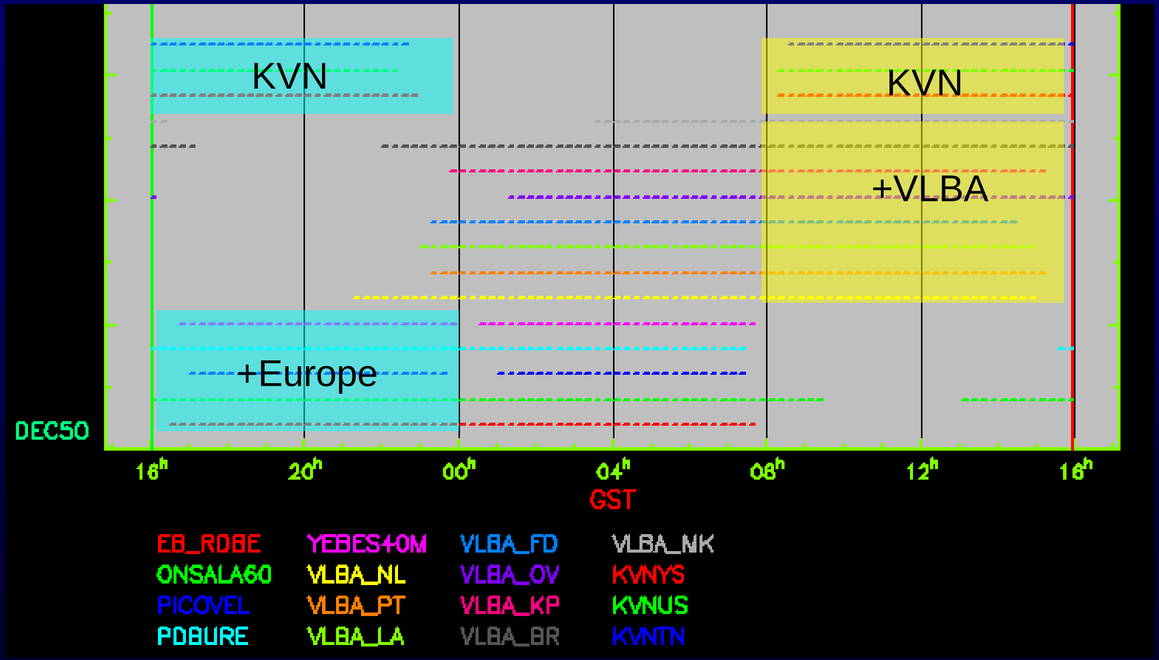
(7 σ, t=10 sec, 1024 Mbps)





KVN stations improve uv-coverage and resolution of GMVA

long baselines with Europe at start



long baselines with VLBA at end

after correlation:

Data export

From correlation to fringe fitting

- MK4 correlator (< 2013) and DifX correlator (> 2012)
- VLBI standard: correlators should deliver IDI-FITS files to user

  (Flatters 1998, AIPS Memo 102; Greisen 2009, AIPS Memo 114)

- export from old MK4 correlator: via FITLD into AIPS or through HOPS into AIPS with MK4IN (Alef & Graham)
- export from new DifX correlator: via difx2fits (into AIPS) or difx2mk4 (into HOPS)
- at present there is no 'official' path from HOPS into IDI-FITS and AIPS
- at least 3 data paths possible:

  1) difx2fits -> AIPS (FITLD, FRING)

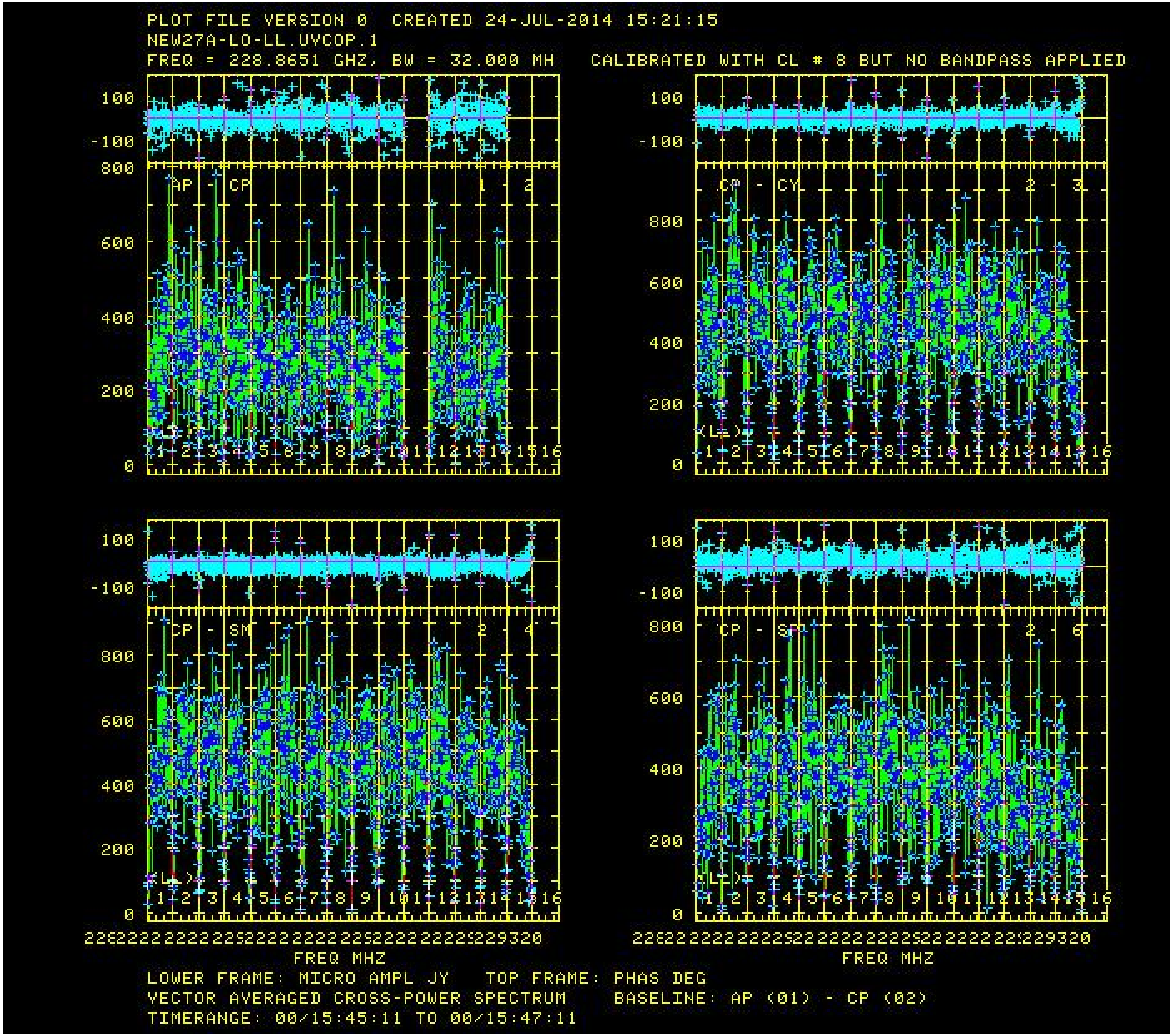
  2) difx2mk4 -> Fourfit -> Fringex -> frx2uvf -> AIPS / Difmap

  3) old MK4 -> Fourfit –X -> MK4IN -> AIPS (FRING)

  or -> FITLD -> AIPS(FRING)

unfortunately the correlated raw amplitudes after export using method 1, 2 and 3 seem to be not always identical, with differences of up to ~20%. This needs further investigation.

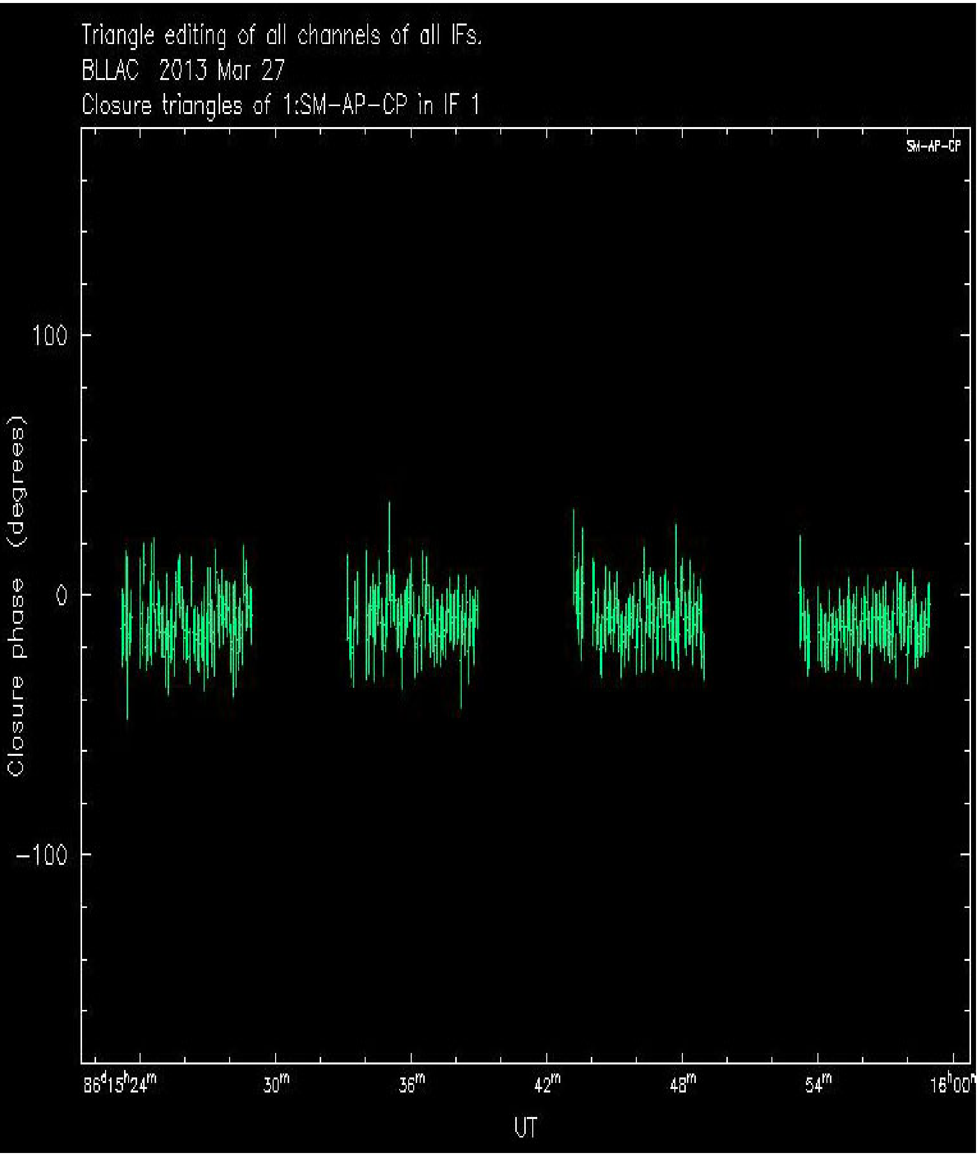
difx2fits, FITLD, FRING

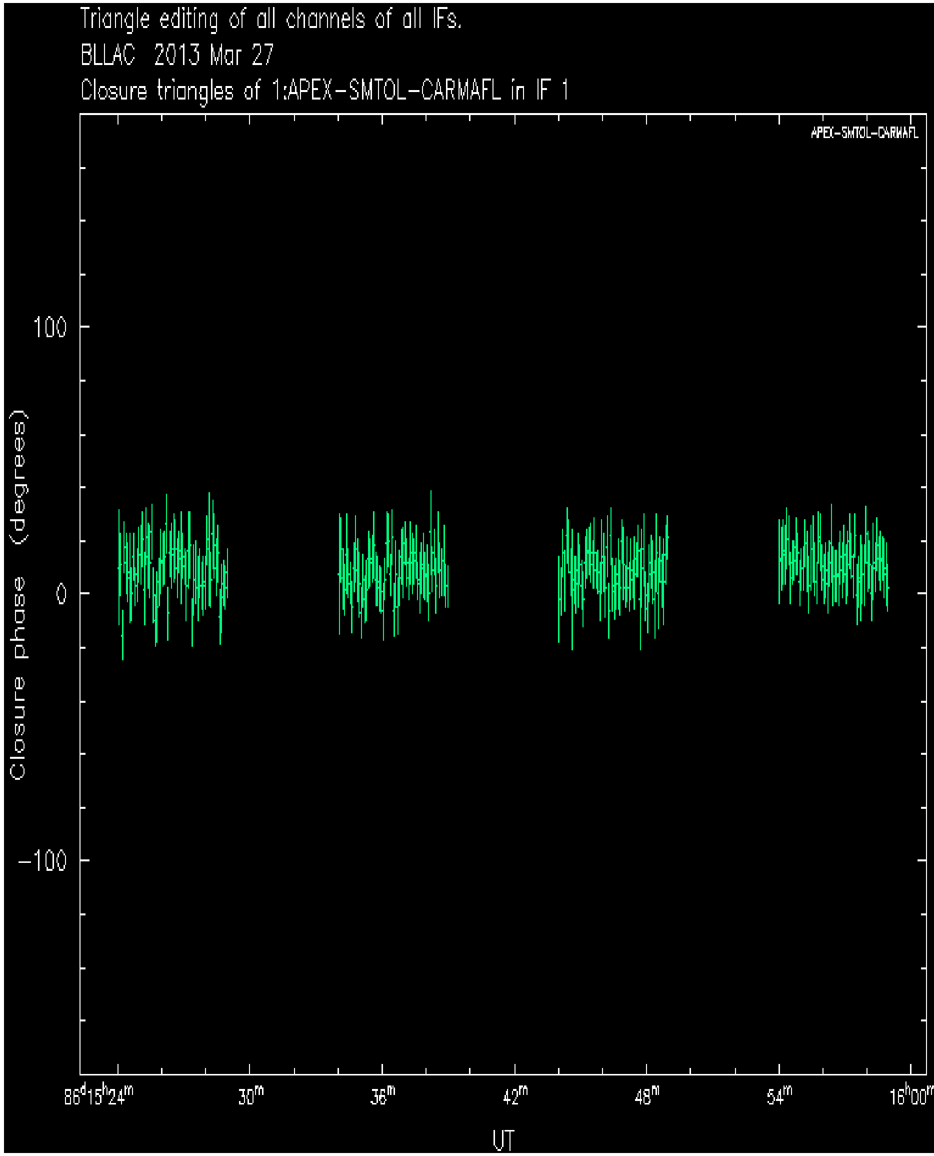


test data: BLLac at 230 GHz, March 27, 2013

DIFX

MK4IN



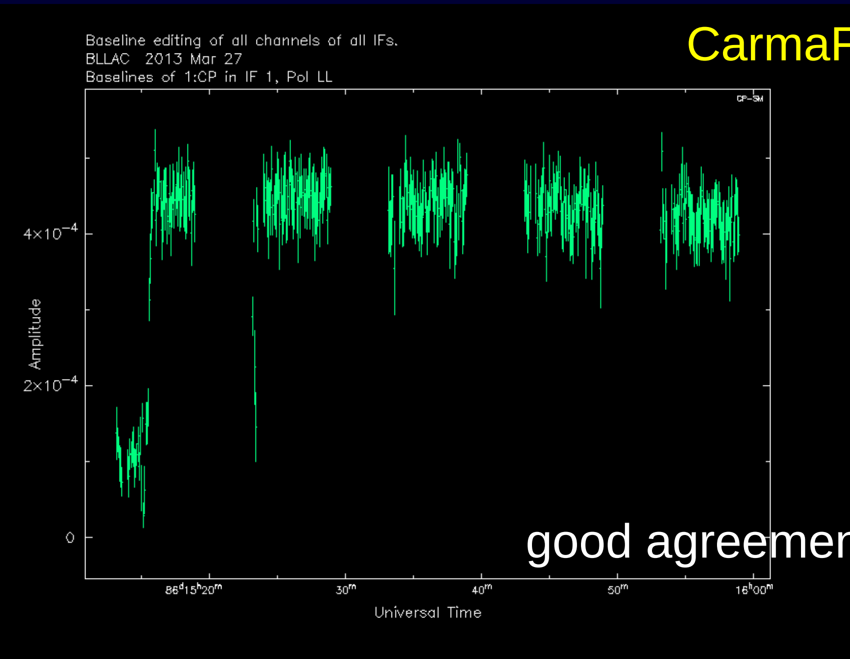


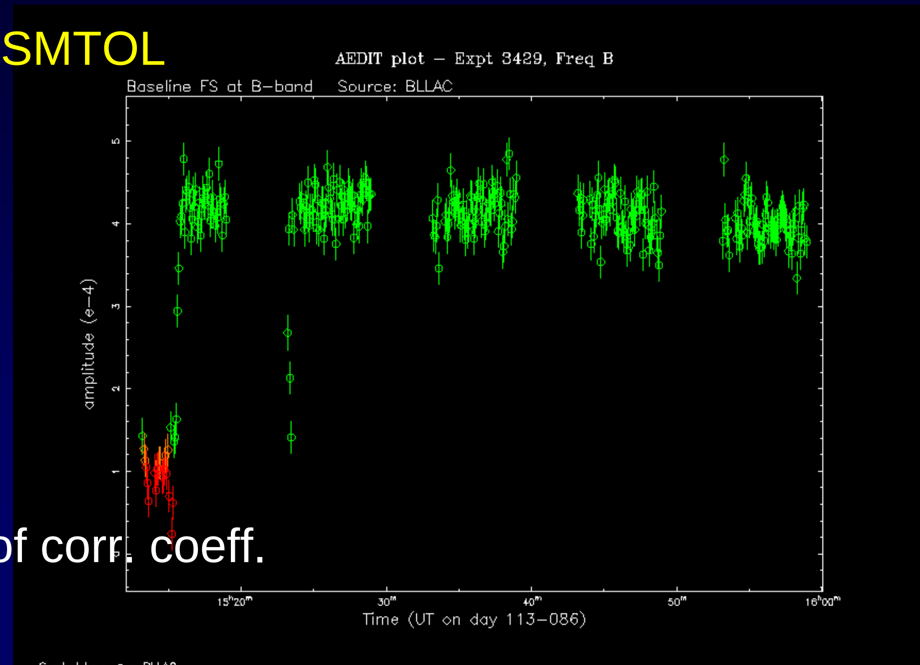
comparison of closure phase

AIPS: difx2fits/FRING

HOPS: difx2mk4/fourfit

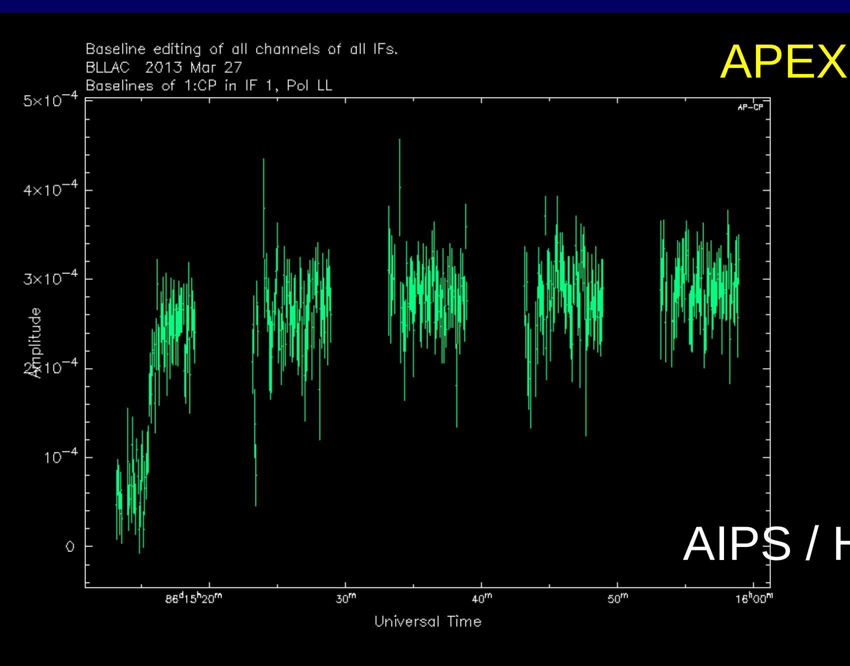
CarmaF - SMTOL

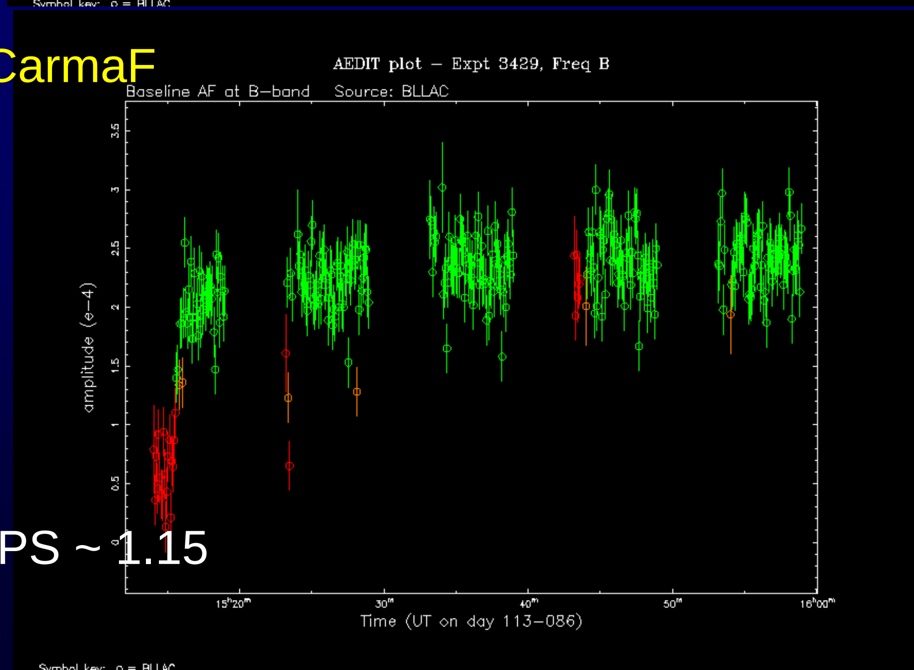




good agreement of corr. coeff.

APEX - CarmaF





AIPS / HOPS ~ 1.15

Sampler correction using autocorrelations

task ACCOR must be applied to correct the amplitudes in the cross-correlation spectra due to errors in the sampler thresholds using measurements of the auto-correlation spectra.

correction factors:

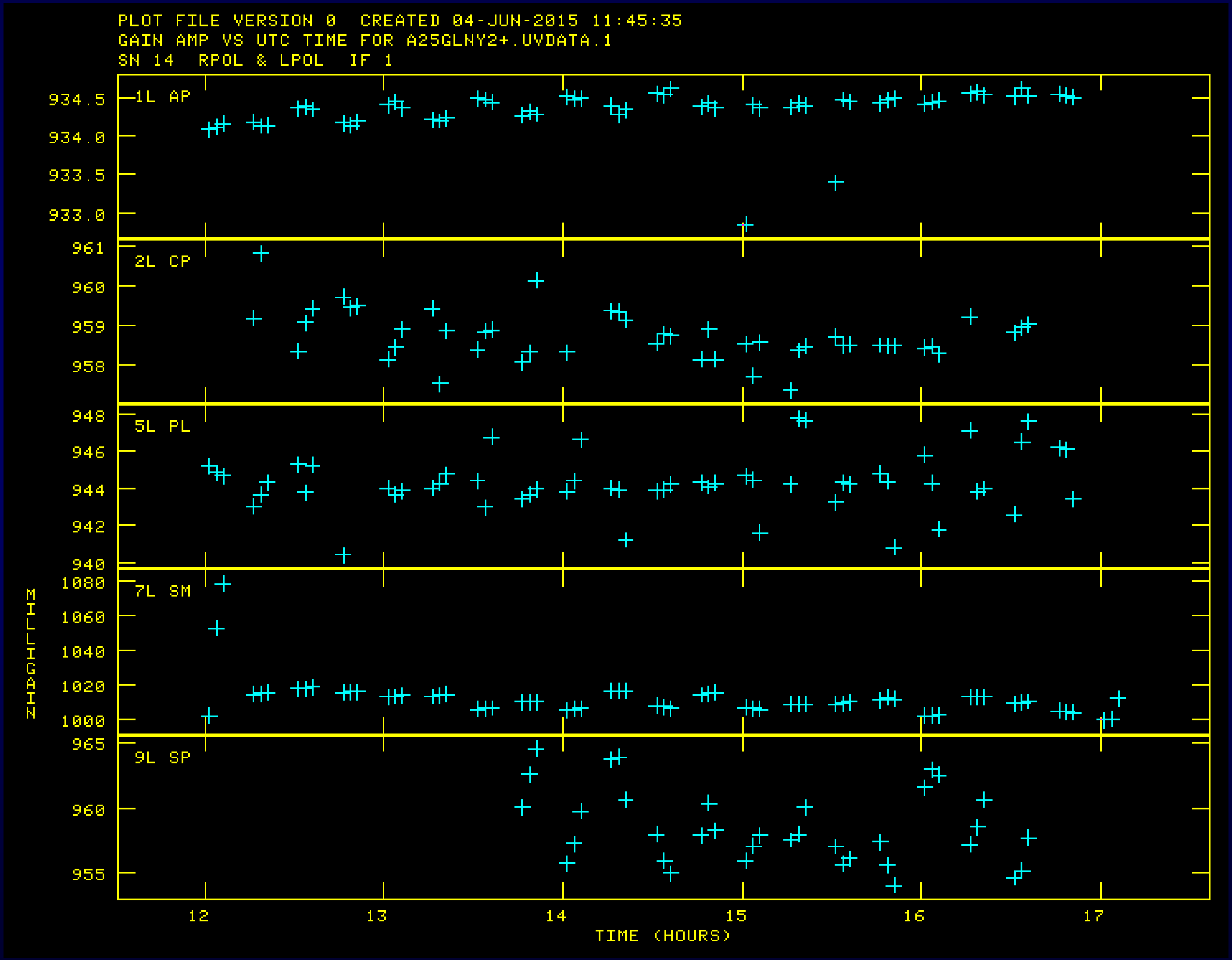
e.g.:

CarmaF – SMTO:

0.959 x 1.01=0.97

CarmaF – APEX:

1.01 x 0.934=0.94



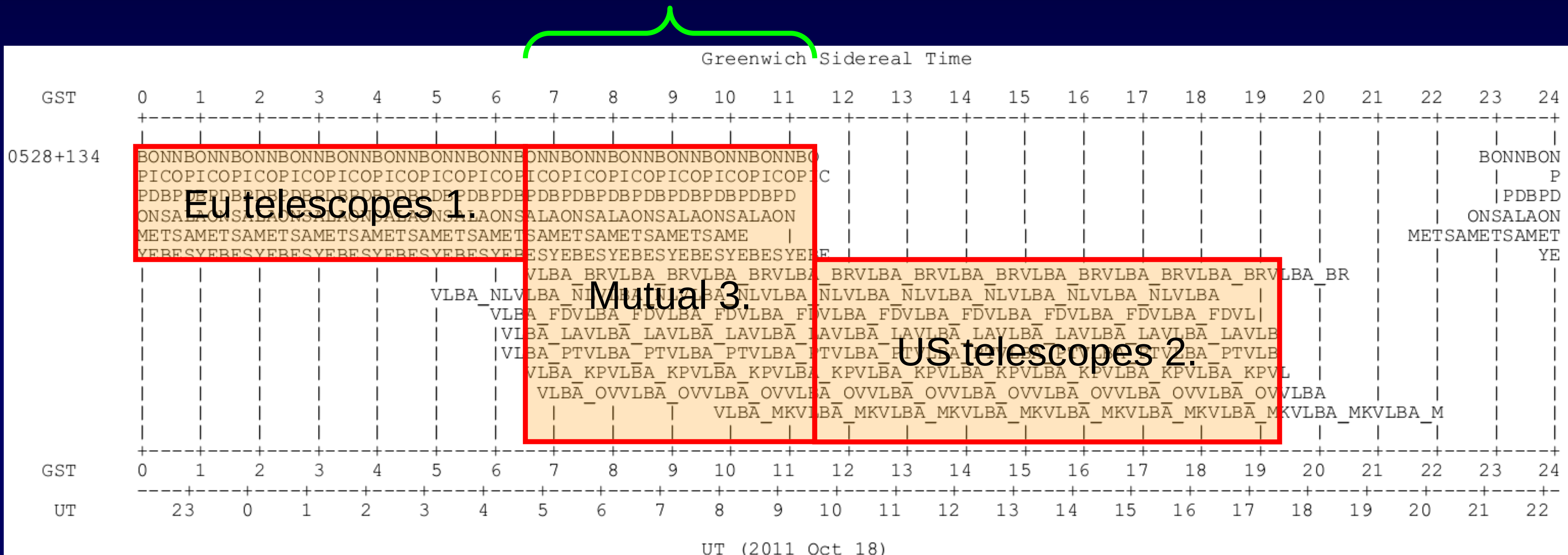
Global Fringe fitting

GMVA/VLBA standard data analysis path

- **FITLD** — load uv-fits data
- **POSSM** — also INDXR, LISTR, USUBA
- **ACCOR** — sampler correct.
- **CLCOR (PANG)** — apply parall. angle correction
- **FRING (AP5=0)** — aligne IFs, remove overall delay (man. pcal)
- **CLCAL** — apply solutions
- **FRING (AP5=1)** — global fringe fitting (over all IFs), iterative
- **ANTAB, APCAL** — load and apply ampl. calibration
- **RLDLY** — remove R-L phase & delay offsets
- **BPASS** — apply bandpass corrections
- **SPLIT** — average in frequency, and export
- **CALIB, IMAGR or Difmap** — Intensity Imaging: hybrid phase self-cal plus CLEAN (or MEM)

Method to apply manual phasecal

only data during this time can be used to
connect phases of EU/US sub-arrays

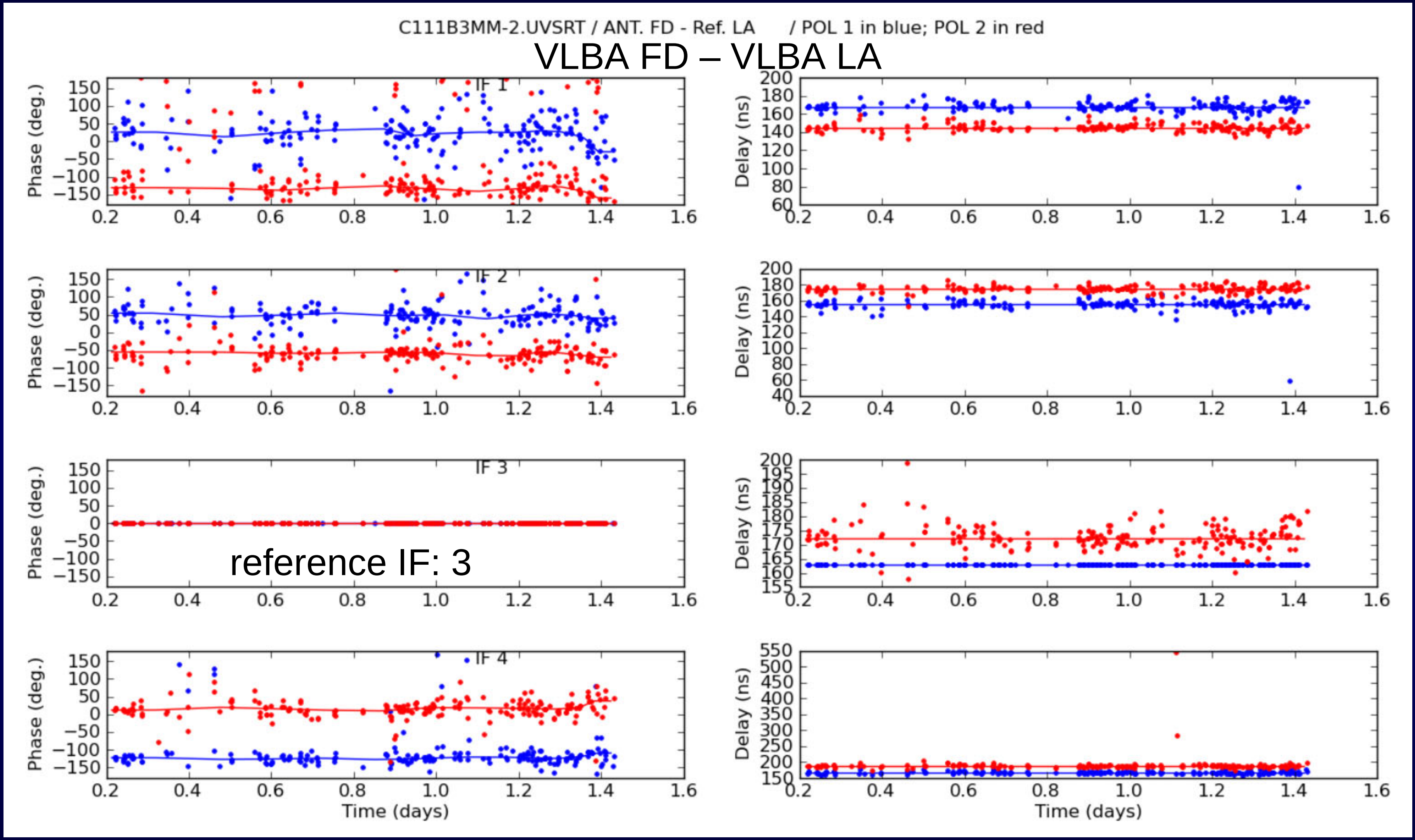


1. manual phasecal for European subarray (refant 1)

- manual phasecal for US subarray (refant 2)
- find at least one STRONG scan which connects the 2 subarrays
- often more than these 3 steps are necessary to calibrate all stations (eg. MK)

Phase and Delay variations per IF versus time

Marti-Vidal+ 2012

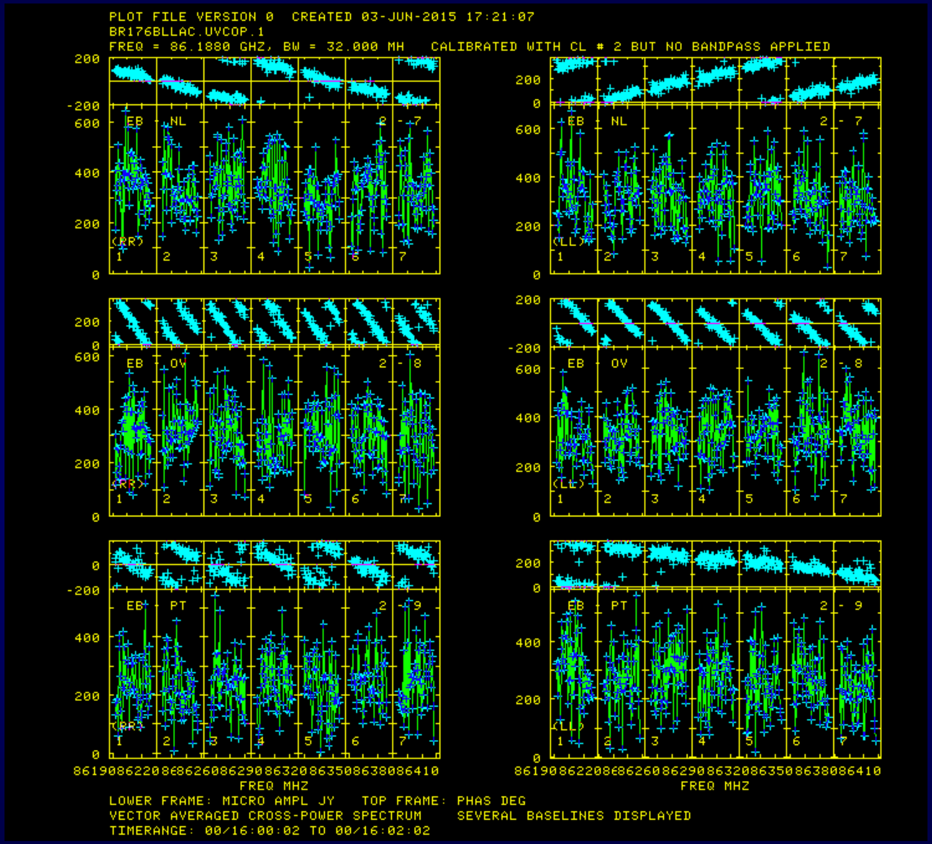


the relative phase alignment between IFs varies on time scales of 0.5 – 1 day

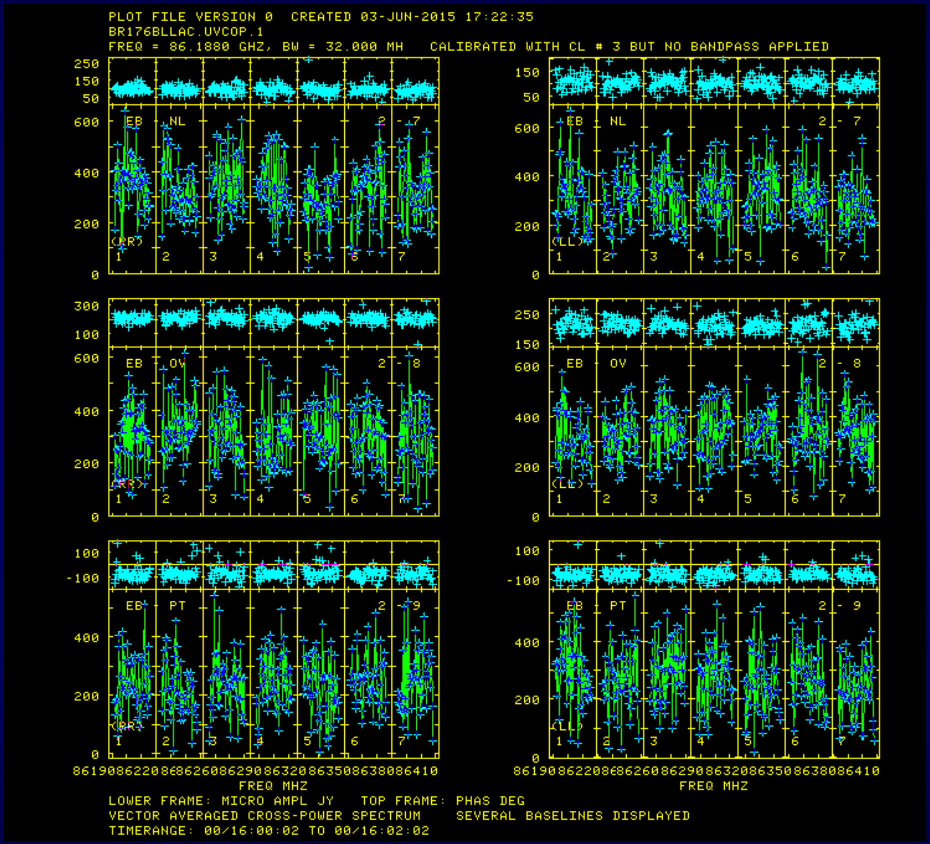
need to find suitable source and reference antenna to track the phase variations!

Fringe fitting: The manual phasecal step

before



after



critical: must detect the signal in each IF, so need a bright source

FRING is run with APARM(5)=0, phase and delay offsets are applied and the fringe rate is zero'ed.

After the manual phasecal has been applied, the whole data set is fringe fitted globally, make full use of the closure relations for SBD, MBD, and FRATE and the station weights. While in AIPS global fringe fitting (GFF) is station based (method Schwab & Cotton), the GFF in HOPS is baseline based (method Alef & Porcas 1986). HOPS does not yet a provide a full least square fit based GFF solution.

Experience shows that it is better to perform the amplitude calibration after GFF.

Detection threshold for VLBI:

Defining the system equivalent flux density $\mathrm{SEFD_i}$ [Jy] of the i-th antenna of an interferometer

$$\mathrm{SEFD_i} = \frac{\mathrm{T^i_{sys}}}{\mathrm{g_i}}$$

one obtains for a single VLBI baseline between antenna i and antenna j the $1\,\sigma$-detection threshold σ_{ij} [Jy]:

$$\sigma_{ij} = \frac{1}{\eta_c} \cdot \sqrt{\frac{\mathrm{SEFD_i} \cdot \mathrm{SEFD_j}}{2 \cdot \Delta\nu \cdot \tau_{\mathrm{integ}}}}$$

where the factor η_c corrects for the correlator losses due to sampling ($\eta_c = 0.64$ for 1-bit smapling, $\eta_c = 0.88$ for 2-bit sampling), $\Delta\nu$ is the observing bandwidth [Hz] and τ_{integ} is the coherent integration time [sec]. In practice, the solution interval for fringe fitting could be $5 - 10$ times longer than the coherence time.

100 m telescope: T_{sys} = 100 K, η=0.5 → g = 1.4 K/Jy

SEFD = 100/1.4 Jy = 71 Jy

VLBI of two 100m RT 's: σ = 0.4 mJy (for $\Delta\nu$=256 MHz, τ=100 sec)

Rayleigh-Jeans: $$S = \frac{2kT}{\lambda^2}\Omega_A = \frac{2kT}{A_{eff}};$$

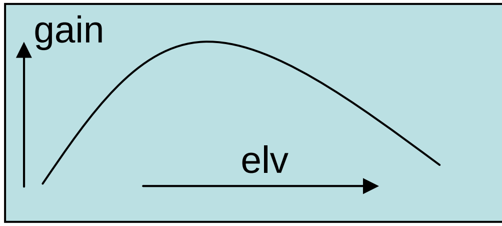
Antenna Calibration:

$$A_{eff} = \eta_A A_{geom}$$

An antenna i of diameter D_i [m] and aperture efficiency η_A [%] measures for a source of flux density S [Jy] an antenna temperature T_A [K]. The gain of the antenna g_i [K/Jy] is then given by:

$$g_i = \frac{T_A}{S} = 2.845 \cdot 10^{-4} \cdot \eta_A^i \cdot {D_i}^2$$

The aperture efficiency η_A and therefore the gain g_i are for most antennas elevation dependent, with a maximum typically at $30 - 45°$ elevation. The gain therefore often is given as a (polynomial) function of elevation $g_i = f(elv)$ or zenit angle $g_i = f'(z)$. If $f(elv)$ or $f'(z)$ are the gain curves normalized to 1 at their peak, the gain is often given as:



$$g_i = \mathrm{DPFU} \cdot f(elv) = \mathrm{DPFU} \cdot f'(z)$$

with the peak gain being called DPFU (degrees per flux unit). In practice on measures the gain, or the aperture efficiency, using sources of known brightness (primary calibrators), which at mm-wavelengths could be the planets (e.g. Mars, Uranus), some minor planets (e.g. Ceres), planetary nebula (e.g. NGC 7027), compact H II regions (e.g. K3-50 A), etc.

Amplitude Calibration: AIPS task ANTAB reads Tsys and gain information

Calibration file:

possible inputs are on a per station basis

Tsys vs. time

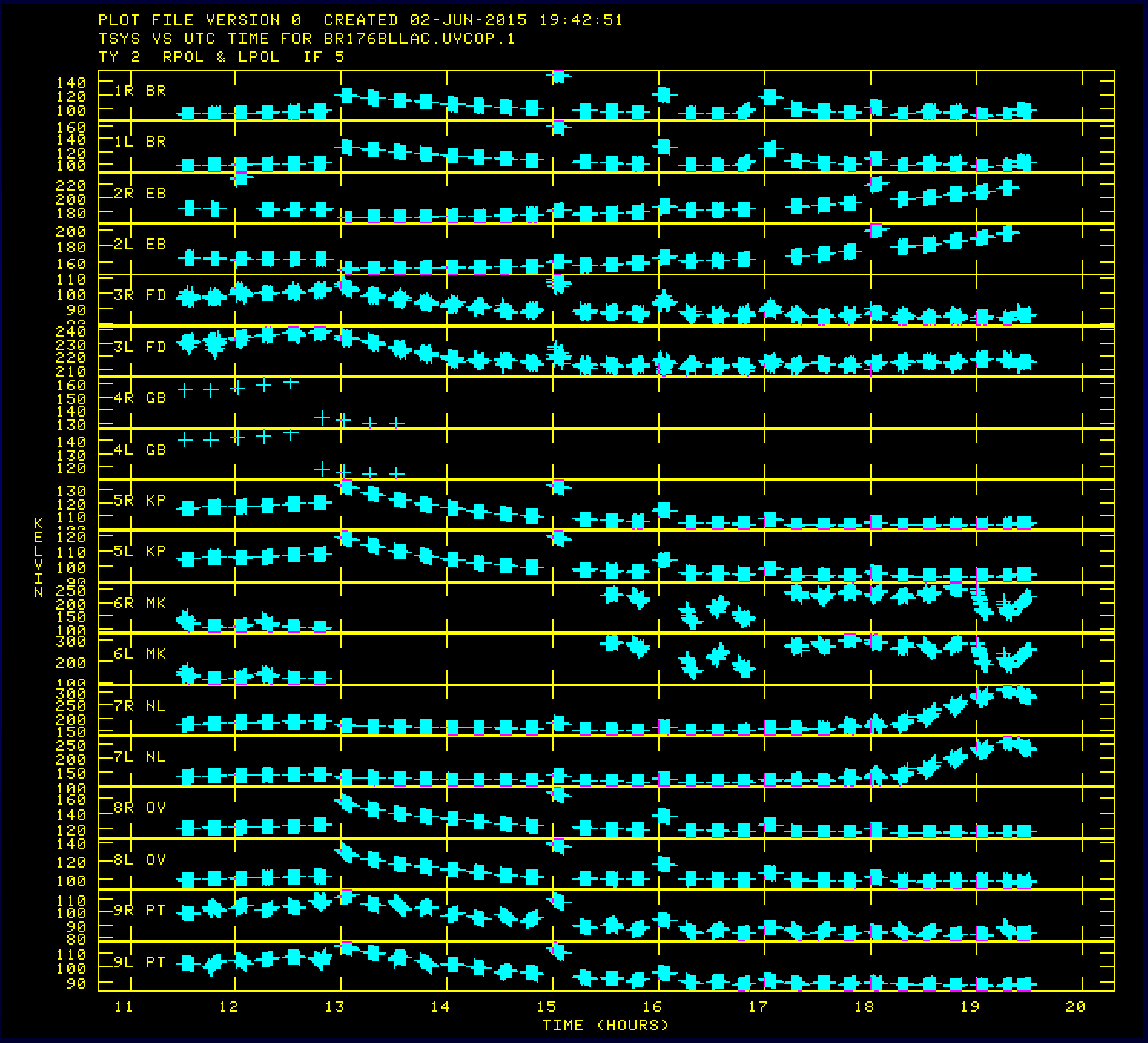
Gaincurve (elv,t)

or:

Tant (t)

or SEFD(t)

the output is a SN-table, which can be edited and smoothed



Atmospheric attenuation and opacity:

Observing the "empty sky" at a given elevation elv yields an observed antenna temperature

$$T_A = T_{\rm Rx} + T_{\rm Atm} \cdot \eta_l \cdot (1 - e^{-\frac{\tau_0}{\sin(elv)}}) + T_{\rm amb}(1 - \eta_l)$$

where $T_{\rm Rx}$ is the receiver temperature, $T_{\rm Atm}$ is the effective temperature of the atmosphere, $T_{\rm amb}$ is the ambient temperature, and η_l is the feed efficiency (typically $\eta_l = 0.9$). The atmospheric opacity is given by $\tau = \tau_0 A$, where τ_0 is the zenit opacity and the airmass is approximated by

$$A \simeq \frac{1}{\sin(elv)}.$$

The atmospheric zenit opacity is usually determined from tipping scans $T_{\rm sys} = f(elv)$, which measure the system temperature as a function of elevation (sky dip). For $A < 3$ the following linearization allows an easy deterimination of τ_0 and $T_{\rm Rx}$ from a fit of a straight line to $T_{\rm sys}$ versus A

$$T_{\rm sys} = T_{\rm Rx} + T_{\rm Atm} \cdot \tau_0 \cdot A = T_{\rm Rx} + T_{\rm Atm} \cdot \frac{\tau_0}{\sin(elv)}$$

Opacity fit done either manually or with AIPS task "APCAL" (opac; dofit 1)

Correction for atmospheric absorption in AIPS: APCAL

Task APCAL: writes a new SN-table

OPCODE: 'opac' or 'grid'

SOLINT: several hours

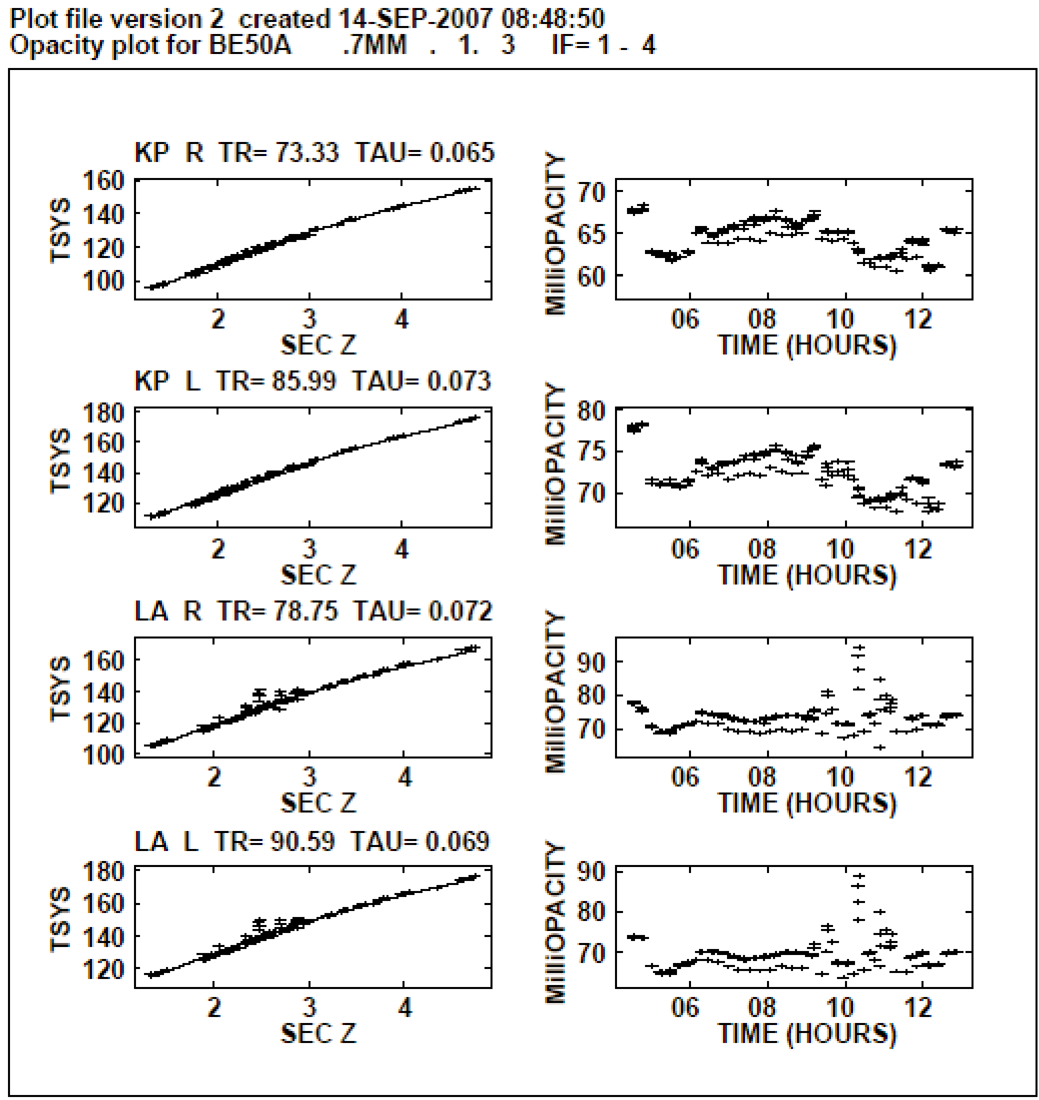
TRECVR: reasonale start value, eg. 100

TAU0: reasonable start value, eg. 0.08

DOFIT: 1 (or 0 if TRECVR and tau0 are known)

Weather table or ASCII file if available

Stat.	Pol.				Receiver Temp.		Zenit Opacity
BR	RCP	0/ 8h 1m	Trec	(K):	64.61	Zen. opac.:	0.077
BR	LCP	0/ 8h 1m	Trec	(K):	77.17	Zen. opac.:	0.112
HN	RCP	0/ 8h 1m	Trec	(K):	104.89	Zen. opac.:	0.140
HN	LCP	0/ 8h 1m	Trec	(K):	95.70	Zen. opac.:	0.144
KP	RCP	0/ 8h 1m	Trec	(K):	73.33	Zen. opac.:	0.065
KP	LCP	0/ 8h 1m	Trec	(K):	85.99	Zen. opac.:	0.073
LA	RCP	0/ 8h 1m	Trec	(K):	78.75	Zen. opac.:	0.072
LA	LCP	0/ 8h 1m	Trec	(K):	90.59	Zen. opac.:	0.069
MK	RCP	0/ 8h 1m	Trec	(K):	59.83	Zen. opac.:	0.033
MK	LCP	0/ 8h 1m	Trec	(K):	67.51	Zen. opac.:	0.036
NL	RCP	0/ 8h 1m	Trec	(K):	71.03	Zen. opac.:	0.172
NL	LCP	0/ 8h 1m	Trec	(K):	61.28	Zen. opac.:	0.187
OV	RCP	0/ 8h 1m	Trec	(K):	85.46	Zen. opac.:	0.067
OV	LCP	0/ 8h 1m	Trec	(K):	88.08	Zen. opac.:	0.066
PT	RCP	0/ 8h 1m	Trec	(K):	75.54	Zen. opac.:	0.063
PT	LCP	0/ 8h 1m	Trec	(K):	74.11	Zen. opac.:	0.060
SC	RCP	0/ 8h 1m	Trec	(K):	89.40	Zen. opac.:	0.179
SC	LCP	0/ 8h 1m	Trec	(K):	93.60	Zen. opac.:	0.182
FD	RCP	0/10h 2m	Trec	(K):	74.33	Zen. opac.:	0.089
FD	LCP	0/10h 2m	Trec	(K):	77.14	Zen. opac.:	0.105

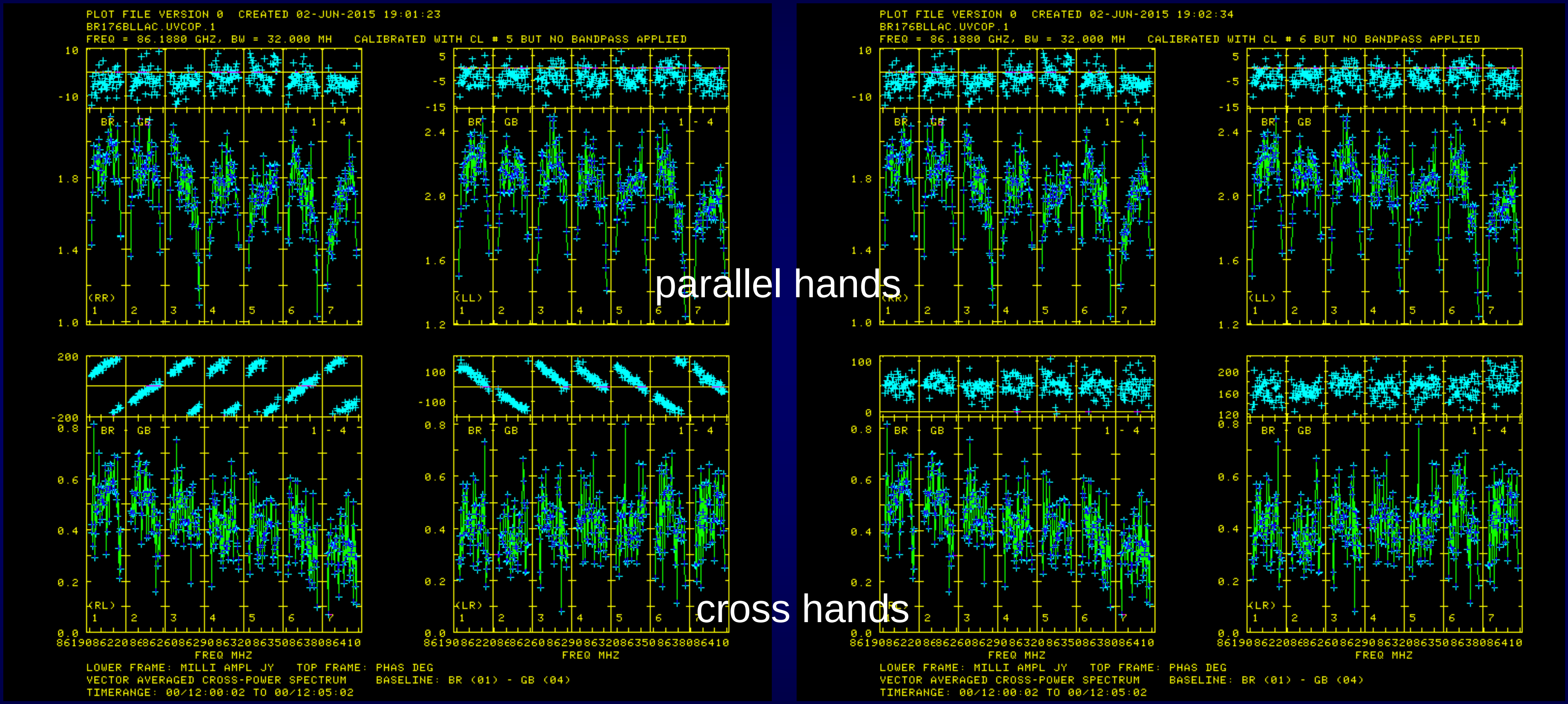


Note: don' forget to set source fluxes with SETJY before running APCAL

Polarisation calibration

Polarisation: remove right-left phase and delay difference

before after



AIPS task: RLDLY

note: works best on highly polarized sources and/or stations with high instrumental polarization. Assumption: R-L differences are constant.

Polarisation: Feed selfcal for antennas

AIPS task LPCAL:

determine D-terms using an I-map (of a compact source)

assume that source brightness distribution can be separated in a finite set of N (≤ 10) compact and polarized regions.

task determines the complex (amp & phase) D-terms for each antenna (new AN-table).

other AIPS tasks can correct for instrumental polarisation (DOPOL > 1)

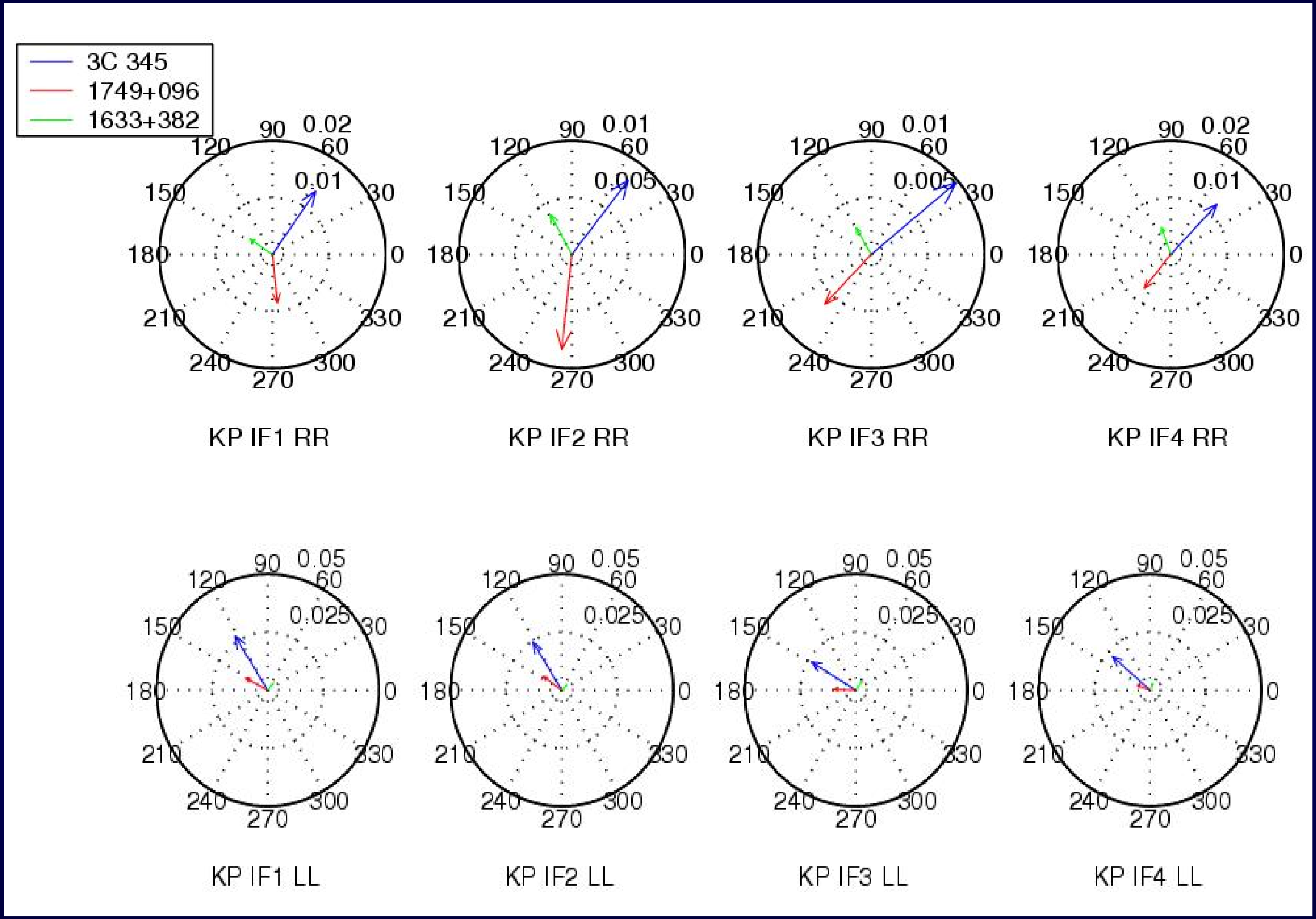
```
Ant    1 = BR       BX= -2112065.2071 BY= -3705356.5016 BZ=  4726813.6687
Mount=ALAZ  Axis offset=  2.1290 meters     IFA                 IFB
Feed polarization type =                     R                   L
Lin. approx. IF(  1) as amp, phase =  0.1626, -111.2    0.1330,  -61.0
Lin. approx. IF(  2) as amp, phase =  0.1636, -105.5    0.1358,  -67.0
Lin. approx. IF(  3) as amp, phase =  0.1685, -124.2    0.1402,  -48.8
Lin. approx. IF(  4) as amp, phase =  0.1706, -110.0    0.1493,  -67.6
Lin. approx. IF(  5) as amp, phase =  0.1745, -114.1    0.1511,  -70.0
Lin. approx. IF(  6) as amp, phase =  0.1700, -122.5    0.1552,  -76.0
Lin. approx. IF(  7) as amp, phase =  0.1347, -141.4    0.1562,  -58.4
Type Q to stop, just hit RETURN to continue

 vlb056     PRTAN(31DEC15)     459      02-JUN-2015  19:19:16    Page    2
File=BLLAC-IT4    .MULTI .    1      An.ver=    1      Vol= 6      User=  459
Array= VLBA         Freq= 86203.875000 MHz      Ref.date= FUNNY DATE

Ant    2 = EB       BX=  4033947.2570 BY=   486990.7907 BZ=  4900430.9946
Mount=ALAZ  Axis offset=  0.0130 meters     IFA                 IFB
Feed polarization type =                     R                   L
Lin. approx. IF(  1) as amp, phase =  0.0292,  124.3    0.0668,   58.4
Lin. approx. IF(  2) as amp, phase =  0.0184,  173.8    0.0653,   39.8
Lin. approx. IF(  3) as amp, phase =  0.0111,   88.6    0.0658,   72.0
Lin. approx. IF(  4) as amp, phase =  0.0278,  123.0    0.0581,   47.8
Lin. approx. IF(  5) as amp, phase =  0.0197,   90.9    0.0666,   72.1
Lin. approx. IF(  6) as amp, phase =  0.0165,   44.7    0.0662,   57.3
Lin. approx. IF(  7) as amp, phase =  0.0270,   94.1    0.0604,   86.4
```

Note: pay attention to antenna mount-type (e.g. ALAZ or NASMYTH) !!

Leppänen, Zensus, Diamond 1995 (AJ)

Instrumental Polarisation Calibration

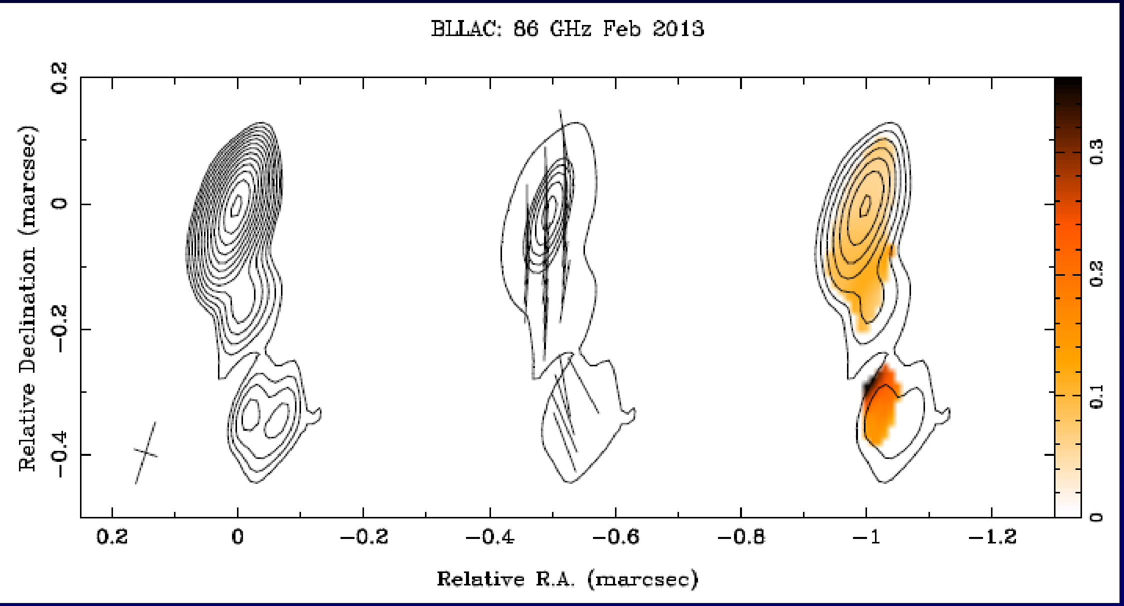
(complex D-terms per IF)

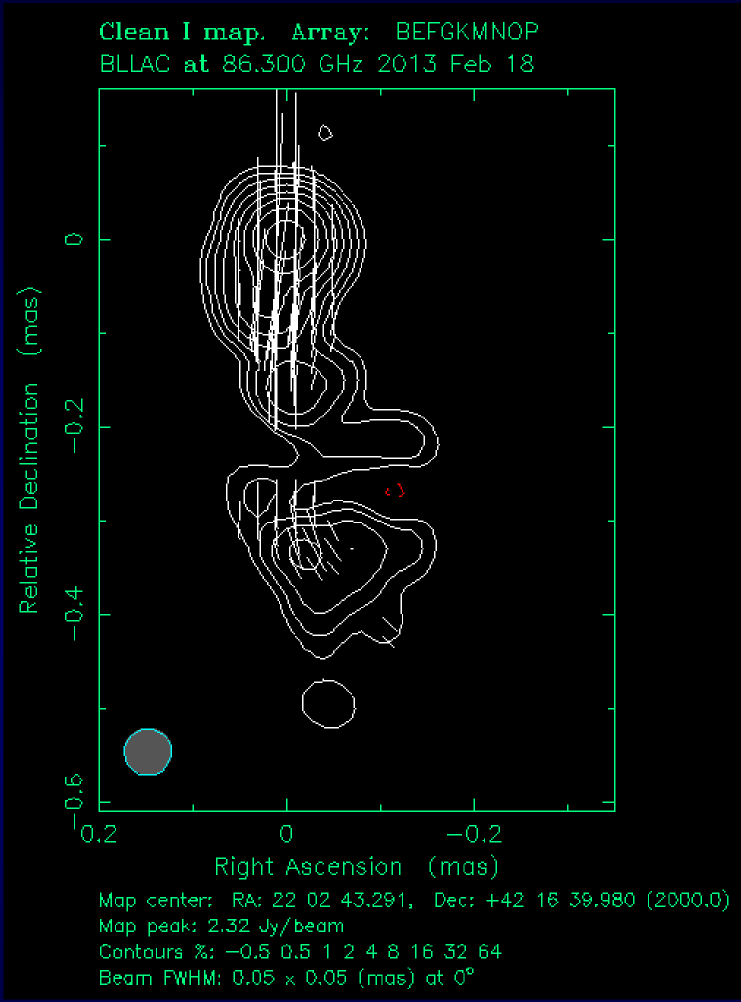


note: phase of D-term may vary with frequency (across IFs)

accuracy depends much on parallactic angle coverage of source, choose many sources and average

Polarimetry at 86 GHz: Example BLLac





Dterms:

Ant 1 = BR amp, phase = 0.1641, -117.6 0.1461, -64.2

Ant 2 = EB amp, phase = 0.0179, 101.7 0.0624, 64.2

Ant 3 = FD amp, phase = 0.1137, 8.8 0.0890, -142.3

Ant 4 = GB amp, phase = 0.0710, 46.9 0.1201, -95.9

Ant 5 = KP amp, phase = 0.0220, -143.4 0.0391, 107.9

Ant 6 = MK amp, phase = 0.0870, -4.3 0.0736, -101.4

Ant 7 = NL amp, phase = 0.0652, -34.3 0.0922, -144.1

Ant 8 = OV amp, phase = 0.0906, -168.3 0.0899, 75.4

Ant 9 = PT amp, phase = 0.1855, -9.6 0.1777, -134.2

z=0.0686

100 μas = 0.13 pc