# Phasing up the superterp

## . . . and notes on calibration and S/N improvement

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# Phasing up the Superterp
# (notes on calibration and S/N improvement)

- Motivation
- How to do it
- Calibration
- Actual S/N improvement

# Superterp: 6/12 stations

# Motivation

Adding up $n$ stations coherently is as good as a station $n$ times larger.

- for autocorrelations (e.g. pulsars): sensitivity $\times n$
- for baselines to other stations: factor of $\sqrt{n}$
- for the superterp: $\sqrt{6} = 2.45$ and $\sqrt{12} = 3.46$
- but this is only true for
  - ⋆ perfect calibration of phase offsets
  - ⋆ uncorrelated noise
- can be done before or after correlation

⇝ LBG asked the LCCG to provide phasing-up option in NDPPP

# Meanwhile . . .

- wrote own script to demonstrate the idea
- . . . and to convince the LCCG/ASTRON to allow Ger van Diepen to implement it
- can also be used for real data!
- limited efficiency (pyrap script, single-core)
- tested also in ‘Long Baseline Week I’ May 2012
- Seems to work!

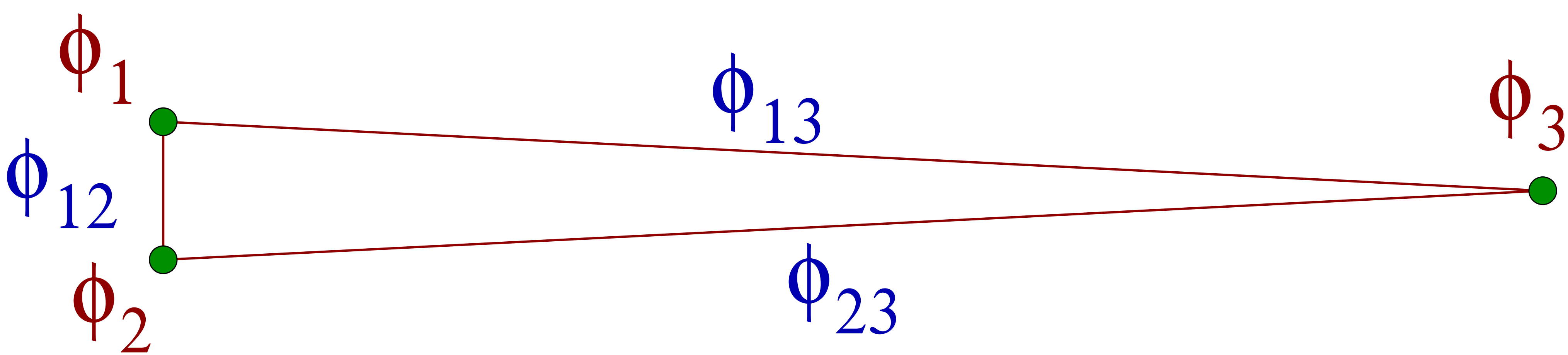
# Features

- can select stations to add up
- can correct for offsets between stations
  (or only correct without phasing up)
- can produce autocorrelations
- can correct weights for correlated noise
  (highly significant for TauA!)

# Determining the offsets

- done in separate script
- fits phase and delay offsets
- does not use intra-superterp baselines ($\phi_{12}$)
- instead differential phases to external reference station(s)
- no model needed, assume true $\phi_{13} \approx \phi_{23}$

$\leadsto$ $\phi_1 - \phi_2 = \phi'_{13} - \phi'_{23}$



# Mathematical model for fits

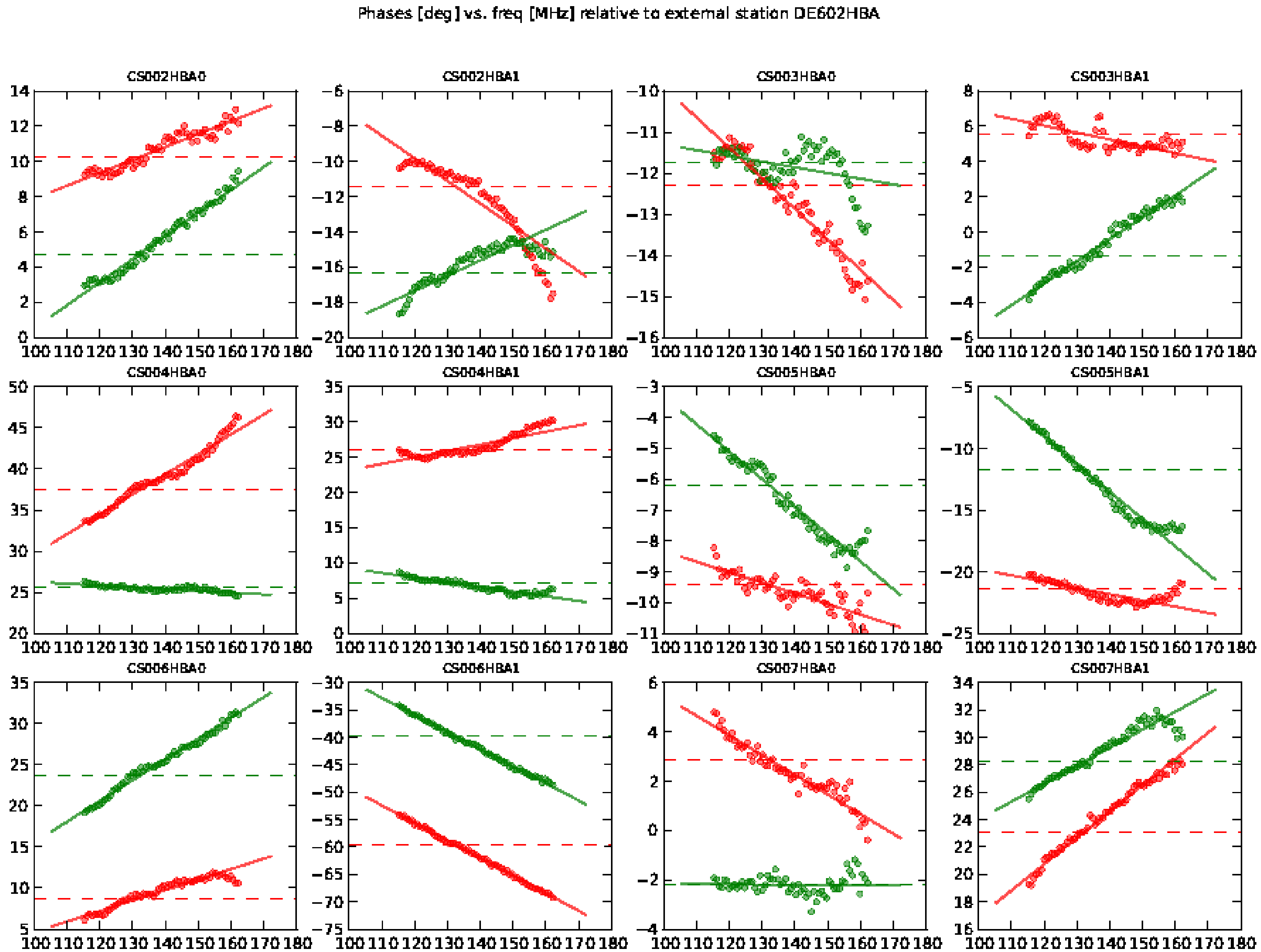
- index for superterp station: $j$
- integration, frequency: $t$ and $\nu$
- unknown visibility superterp–reference: $\tilde{V}(t,\nu)$
- calibrated measurement: $V_j'(t,\nu)$

$$V_j'(t,\nu) = \mathrm{e}^{\mathrm{i}(\phi_j + 2\pi\nu'\tau_j)}\, V_j(t,\nu)$$

$$\chi^2 = \sum_{t,\nu,j} w_j(t,\nu) \left| V_j'(t,\nu) - \tilde{V}(t,\nu) \right|^2$$

- fit $\tilde{V}(t,\nu)$ implicitly, then $\phi_j$ and $\tau_j$ with Newton-CG method (using gradient and Hessian)

# Example: fits for TauA in L45786 (to DE602)



# Example: results (1)

```
# fit for delays and phases
# good data points: 31071412, parameters: implicit 2622894 + explicit 22
# chi^2  no correction 3.212521e+07  with correction 2.329588e+07
#        diff 8.829331e+06  diff/22 4.013332e+05
#        diff relative to phases 9.848838e+04  diff/11 8.953489e+03
# reduced chi^2  no correction 1.129241e+00  with correction 8.188790e-01
# (error bars assuming reduced chi^2 of unity)
# phases in deg and delays in nsec (phases XX and YY, delays XX and YY):
# reference frequency in MHz (fitted over 114.966-162.573 MHz)
phase_delay_offsets= dict (
    reffreq= 138.769531,
    CS002HBA0= [   10.728372 ,    5.595891 ,      0.203229 ,   0.363467 ],
    CS002HBA1= [  -12.226986 ,  -15.731574 ,     -0.356111 ,   0.240983 ],
    CS003HBA0= [  -12.776805 ,  -11.840582 ,     -0.205941 ,  -0.038600 ],
    CS003HBA1= [    5.296623 ,   -0.581472 ,     -0.108467 ,   0.346829 ],
    CS004HBA0= [   39.052095 ,   25.414495 ,      0.674259 ,  -0.060649 ],
    CS004HBA1= [   26.677695 ,    6.676455 ,      0.253863 ,  -0.183799 ],
    CS005HBA0= [   -9.663662 ,   -6.778751 ,     -0.095212 ,  -0.247486 ],
    CS005HBA1= [  -21.756341 ,  -13.219949 ,     -0.141094 ,  -0.617608 ],
    CS006HBA0= [    9.597167 ,   25.344461 ,      0.354160 ,   0.702026 ],
    CS006HBA1= [  -61.627535 ,  -41.753241 ,     -0.890461 ,  -0.866817 ],
    CS007HBA0= [    2.359800 ,   -2.205662 ,     -0.222073 ,  -0.003485 ],
    CS007HBA1= [   24.339576 ,   29.079928 ,      0.533848 ,   0.365139 ],
    )
```

# Example: results (2)

```
# phase_delay_errors= dict (
#      CS002HBA0= [    0.016306 ,    0.015814 ,       0.003141 ,    0.003049 ],
#      CS002HBA1= [    0.016509 ,    0.016449 ,       0.003195 ,    0.003187 ],
#      CS003HBA0= [    0.016401 ,    0.015892 ,       0.003164 ,    0.003069 ],
#      CS003HBA1= [    0.016504 ,    0.016414 ,       0.003178 ,    0.003168 ],
#      CS004HBA0= [    0.016383 ,    0.015891 ,       0.003161 ,    0.003074 ],
#      CS004HBA1= [    0.016100 ,    0.016332 ,       0.003108 ,    0.003155 ],
#      CS005HBA0= [    0.017283 ,    0.017326 ,       0.003352 ,    0.003364 ],
#      CS005HBA1= [    0.016460 ,    0.015729 ,       0.003176 ,    0.003041 ],
#      CS006HBA0= [    0.016386 ,    0.016543 ,       0.003169 ,    0.003199 ],
#      CS006HBA1= [    0.016185 ,    0.015573 ,       0.003118 ,    0.003004 ],
#      CS007HBA0= [    0.019326 ,    0.019308 ,       0.003809 ,    0.003791 ],
#      CS007HBA1= [    0.016553 ,    0.015859 ,       0.003194 ,    0.003069 ],
#      )
```

# Correlated noise

- also produce data weights, first assumed independent noise
- too high residuals in subsequent fits (e.g. $X - Y$ offsets)
- I found S/N increase of about 2.0 for TauA (HBA)
  - ⋆ should be $\approx 3.5$
- George Heald found following S/N increase (baseline)
  - ⋆ almost none for CygA (HBA)
  - ⋆ 2.99 for 3C295 (HBA)

# Data weight with correlated noise

- from Gaussian noise (modulo constant factors)
- 1/weight = variance of baseline noise: $\mathrm{ACF}_1 \cdot \mathrm{ACF}_2$
- ACF of superterp

$$\left\langle \left| \sum_j V_j \right|^2 \right\rangle = \sum_{jk} \langle V_j \overline{V}_k \rangle$$
$$= \sum_j \langle |V_j|^2 \rangle + \sum_{j \neq k} \langle V_j \overline{V}_k \rangle$$

ACF plus cross-correlations (intra-superterp)

- corrections explain empirical values

# NDPPP

- Ger van Diepen implemented phasing-up in NDPPP
- `StationAdder`
- takes care of meta data for proper station beam models (tested and confirmed by George)
- data weights do not take correlations into account!
- have to calibrate before!
- please use and *test* it!
- have to compare with my script

# Summary

- phasing up the superterp provides more (baseline-) sensitivity
- reduces the data volume
- can be done after shifting the phase centre
- we can calibrate before phasing up
- correction terms can be determined
  BBS (George Heald) and my script agree now
- a priori calibration generally bad
  - ⋆ but seems to be stable over $\sim$ weeks
- correcting improves the beam shape (Jason's daily image)
- use NDPPP (preferred) or my script (for correct weights)