Calibration of Radio Astronomical Phased Arrays

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Calibration challenges

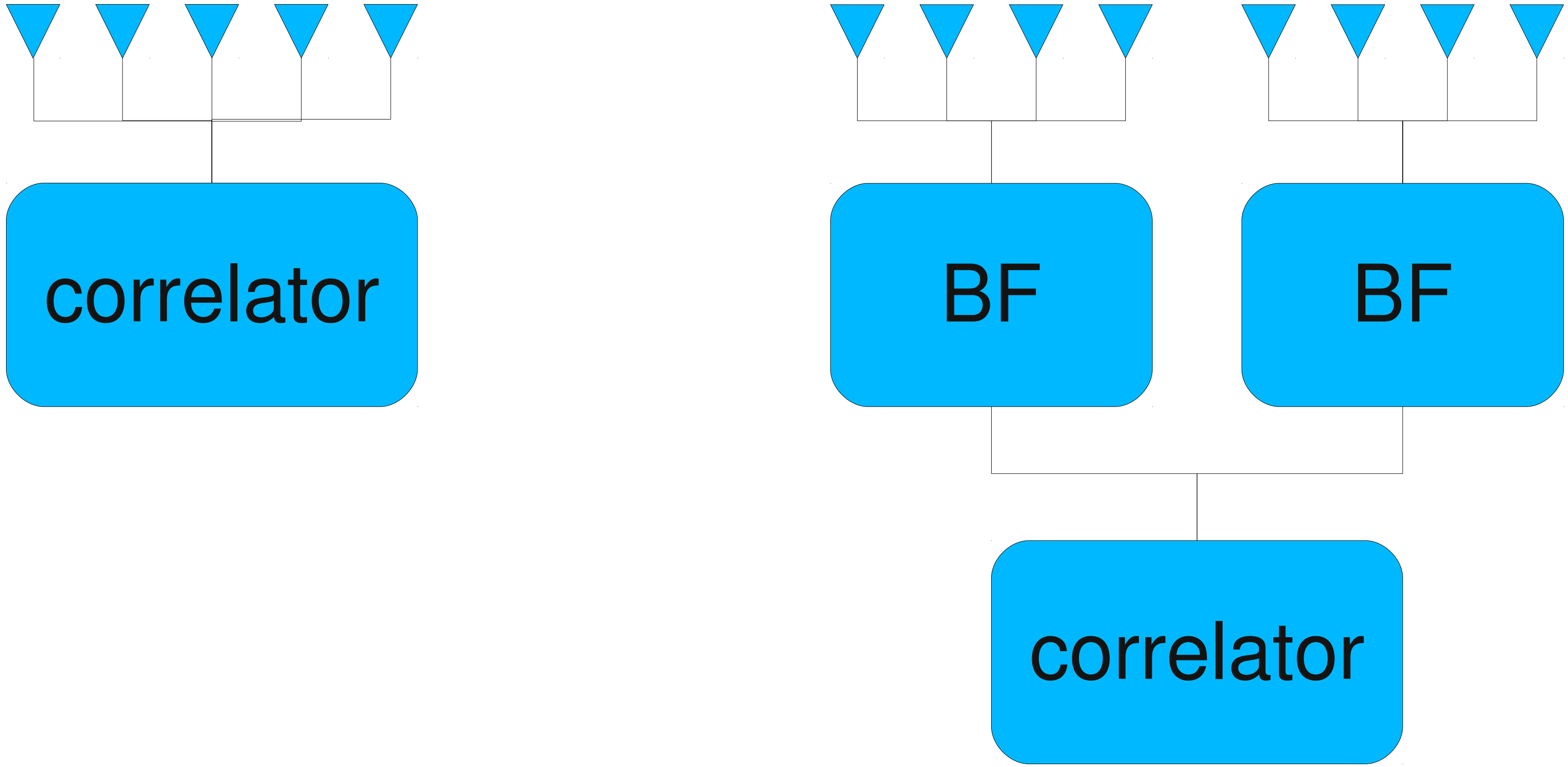
- Wide Field-of-View
  - Direction Dependent Effects
  - Multiple sources
- New problems
  - AA: coupling, complex source structure
  - PAF: coupling, “pixel based”-calibration
- High DR requirements
- Huge data rates
  - e.g.: LOFAR-NL: 6912 signal paths @ 2.4 Gbps

System architecture

S.J. Wijnholds, URSI Benelux Forum, 30 May 2008

Left: normal array, all elements connected to correlator

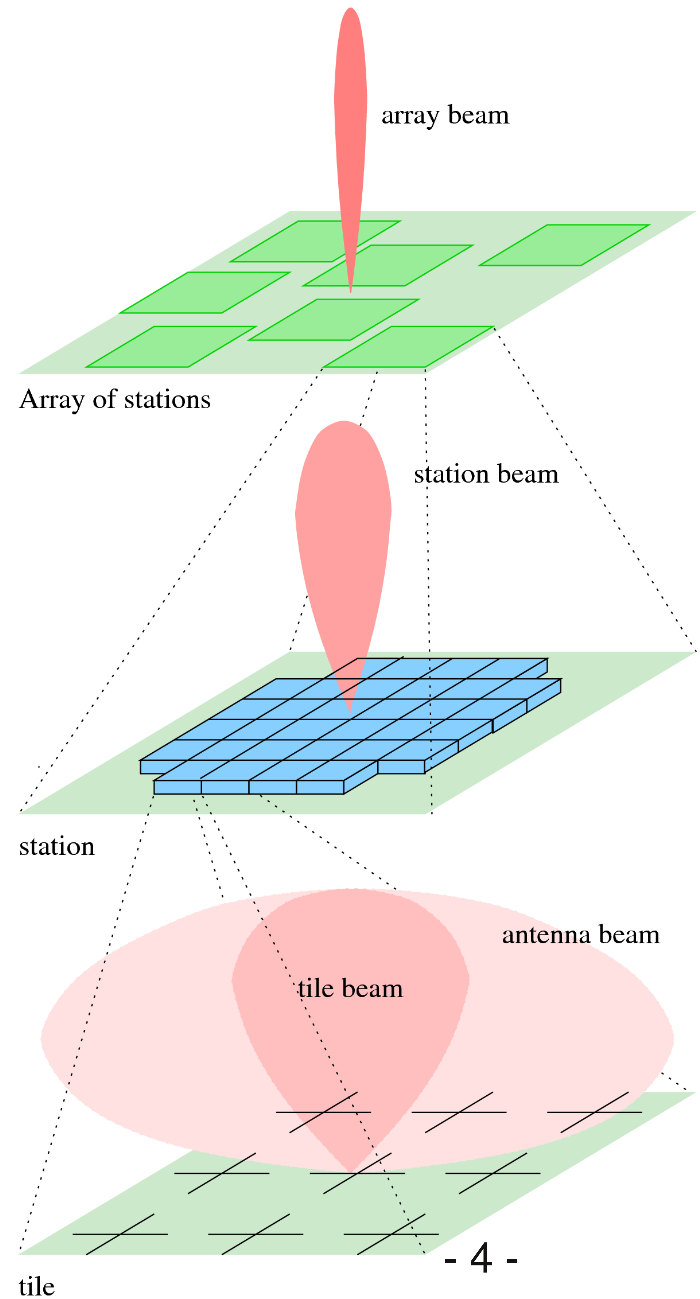
Right: compound elements, correlation of sums of signals



Calibration hierarchy

S.J. Wijnholds et al., IEEE SPM, January 2010

- **array calibration**
  - After central correlator
- **station calibration**
  - group of (compound) elements
  - locally beam former
- **compound element calibration**
  - phased array feed
  - aperture array tile



Calibration scenarios

Colin Lonsdale, LFD memo 015, December 2004
S.J. Wijnholds et al., IEEE SPM, January 2010

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Scenarios 1 and 2

Direction indep.

Scenario 3

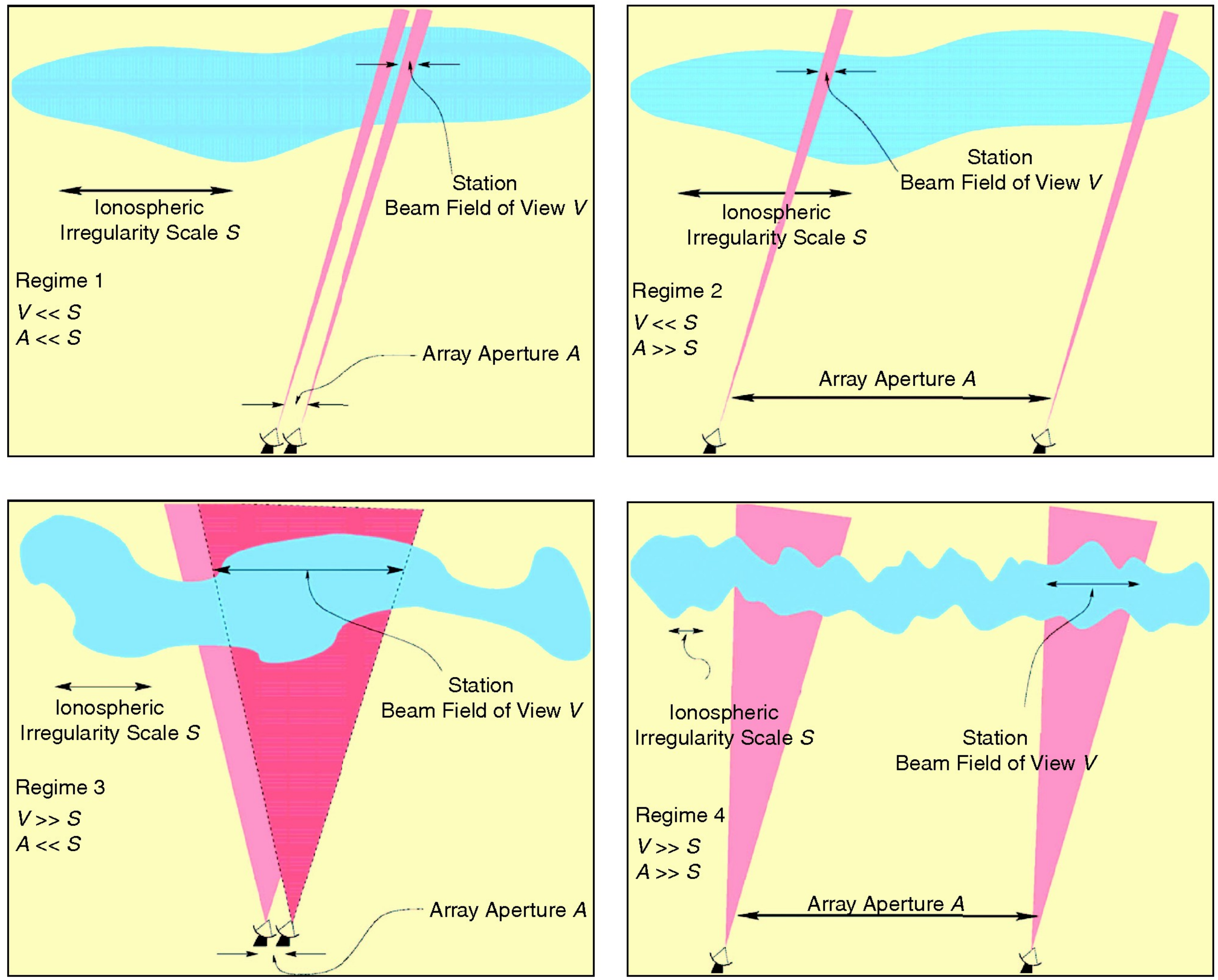
Direction dependent

Same for all antennas

Scenario 4

Direction dependent

Differs per antenna



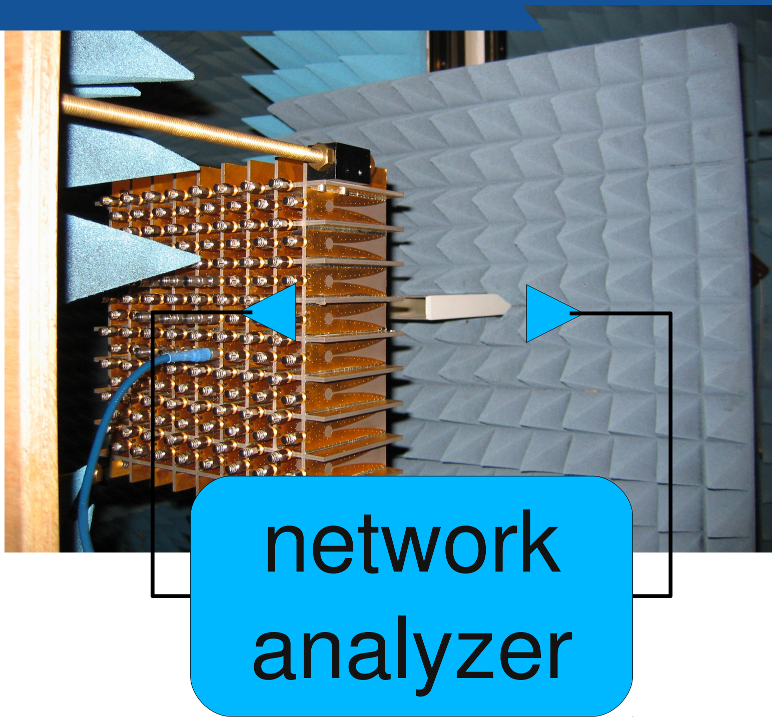
AA compound elements

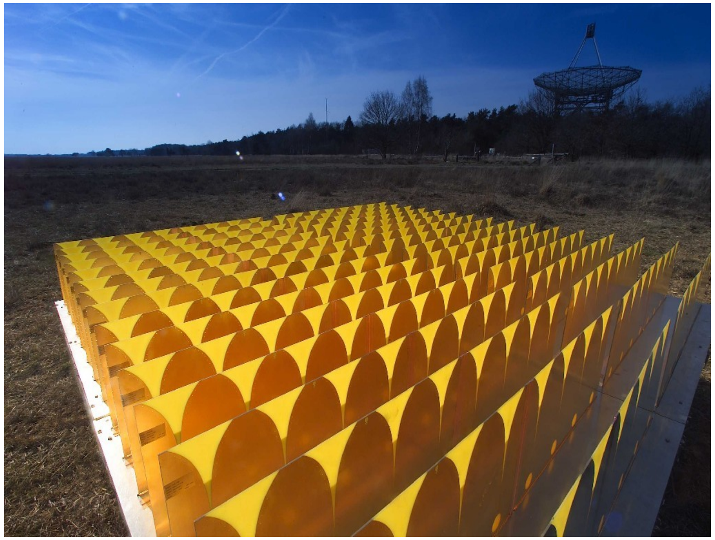
G.A. Hampson & A.B. Smolders, IEEE AP-S, July 1999
S.J. Wijnholds, M.Sc. Thesis, 2003

Recipe

1. Form superposition/beam
2. Measure
    - s12-measurement
    - correlate with reference
3. Repeat steps 1 and 2

   (more linear combinations)
4. Extract gains





PAF compound elements

Brian Jeffs et al., IEEE JSTSP, October 2008
Mike Elmer et al., this workshop

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Calibration implicitly included in BF scheme

- Only on-source meas.: conjugate field matching
- On-source and off-source meas.: max-SNR
- Additional modification: beam shape constraints

Open issues

- Tracking of gains during observations
- From single dish to inferferometric calibration
- Optimization criterion
- Full polarization calibration

Sparse AA station calibration (1)

Wijnholds and Van der Veen, IEEE TrSP, September 2009
Wijnholds and Van der Veen, EuSiPCo, 24 – 27 August 2009

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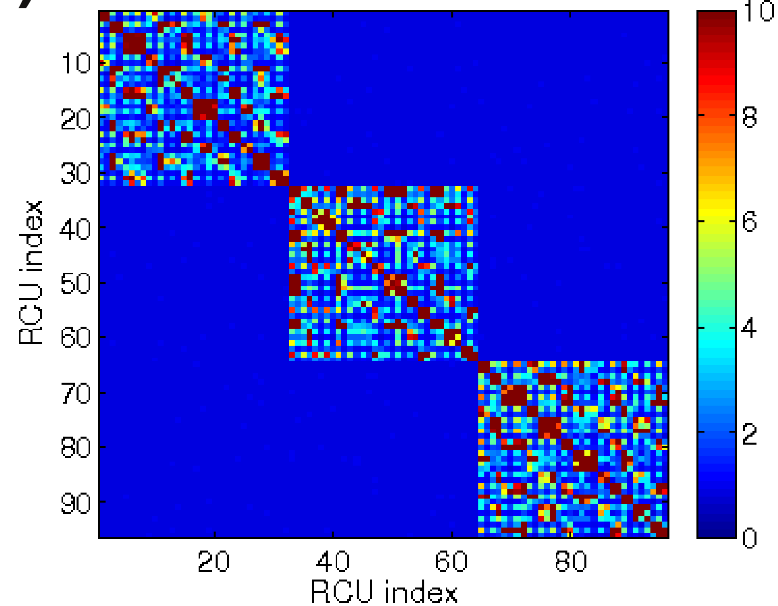
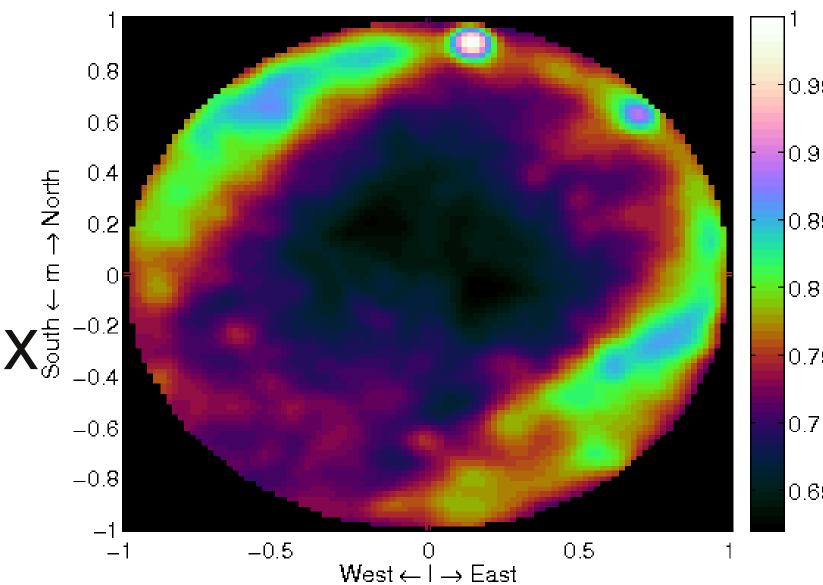
Short baselines, large FOV (2π sr!) → scenario 3

- Complex source structures
- Crosstalk in receiver paths

Parameters to estimate

- Dir. indep. gain per element
- Dir. dep. gain of array
- Sometimes: source locations
- Noise/nuisance covariance matrix





Sparse AA station calibration (2)

S.J. Wijnholds and A.J. van der Veen, IEEE TrSP, Sep. 2009

S.J. Wijnholds, Ph.D. Thesis, March 2010

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Calibration problem: solve

$$\boldsymbol{\theta} = \operatorname{argmin} \| \mathbf{W} (\mathbf{R}_{obs} - \mathbf{R}(\boldsymbol{\theta})) \mathbf{W} \|_F^2$$

Weighted Alternating Least Squares (WALS)

- Recipe
  - Alternatingly optimize for groups of parameters
  - Use closed form solution per group
  - Iterate until convergence
- Statistically and computationally efficient

LOFAR station calibration example (1)

Wijnholds and Van der Veen, EuSiPCo, 24 – 28 Aug. 2009

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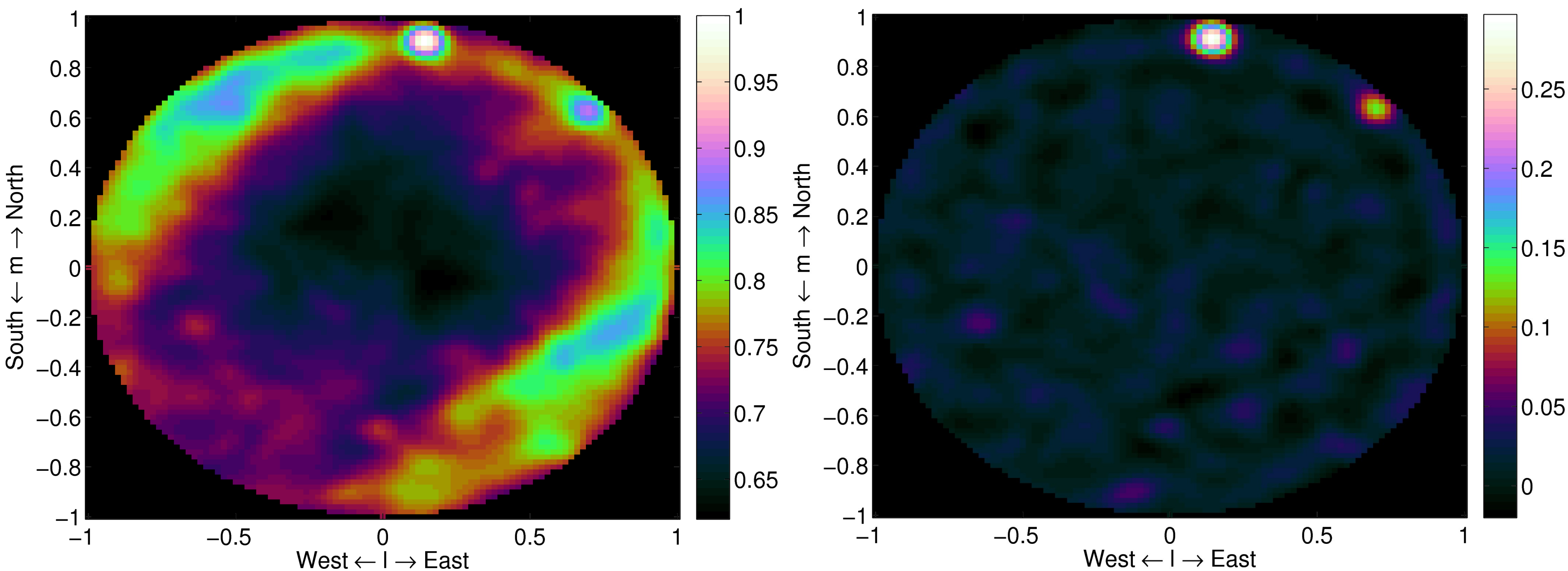
left: all sky image at 50 MHz with 48-element 65 m array

right: short baseline (< 4λ) effects subtracted

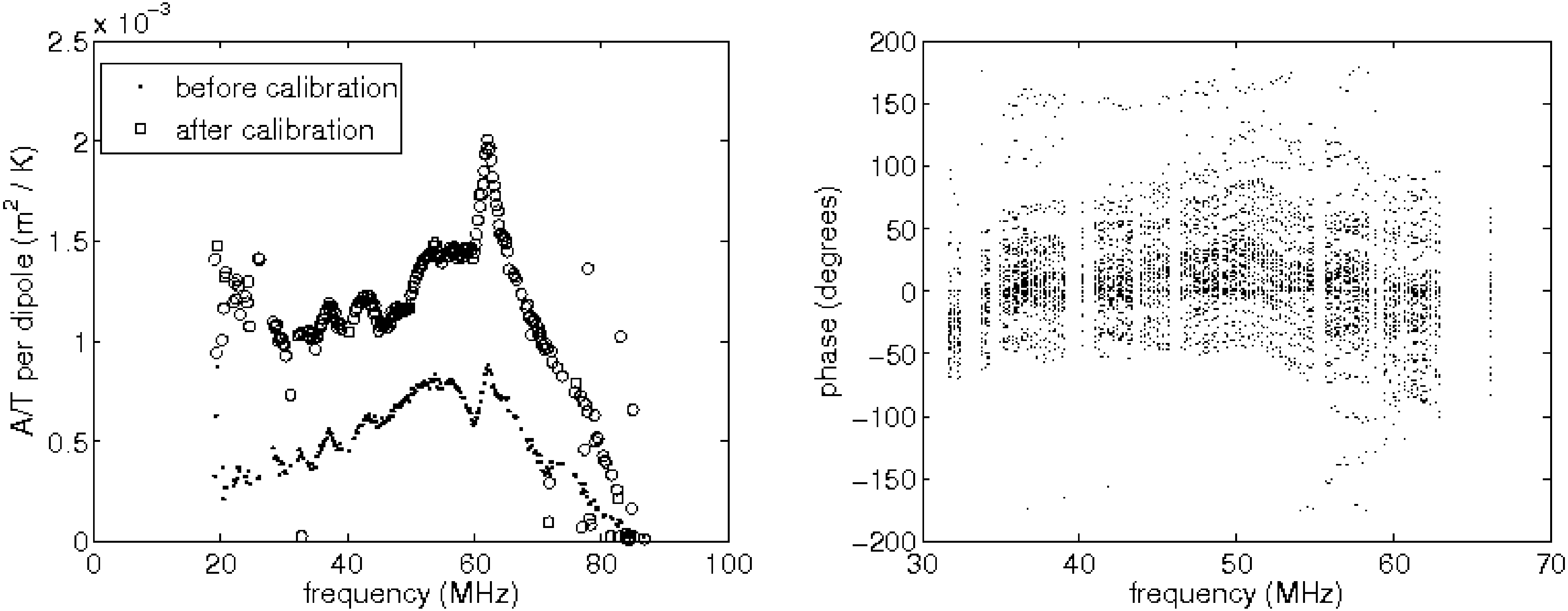


860 parameters solved in 0.4 s on single 2.4 GHz core

Sensitivity improvement by calibration

Left: A/T of CS10 before and after calibration

Right: typical phase solutions for CS10



Dense AA calibration

Parisa Noorishad, SKA2010, 22 – 25 March 2010
J.E. Noordam & A.G. de Bruyn, Nature, 14 October 1982

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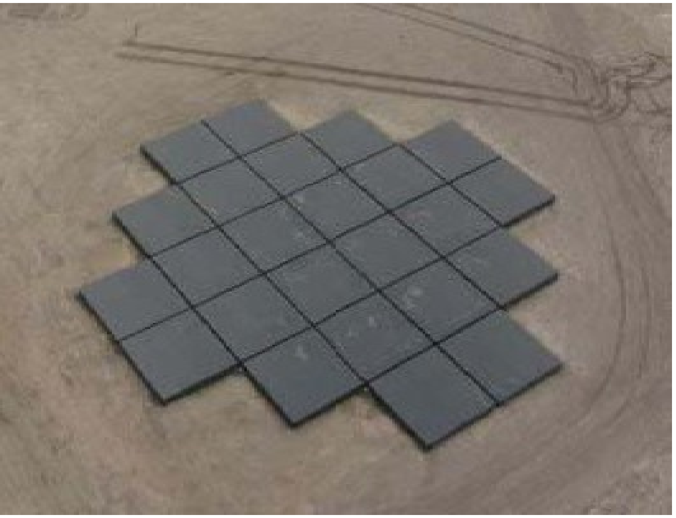
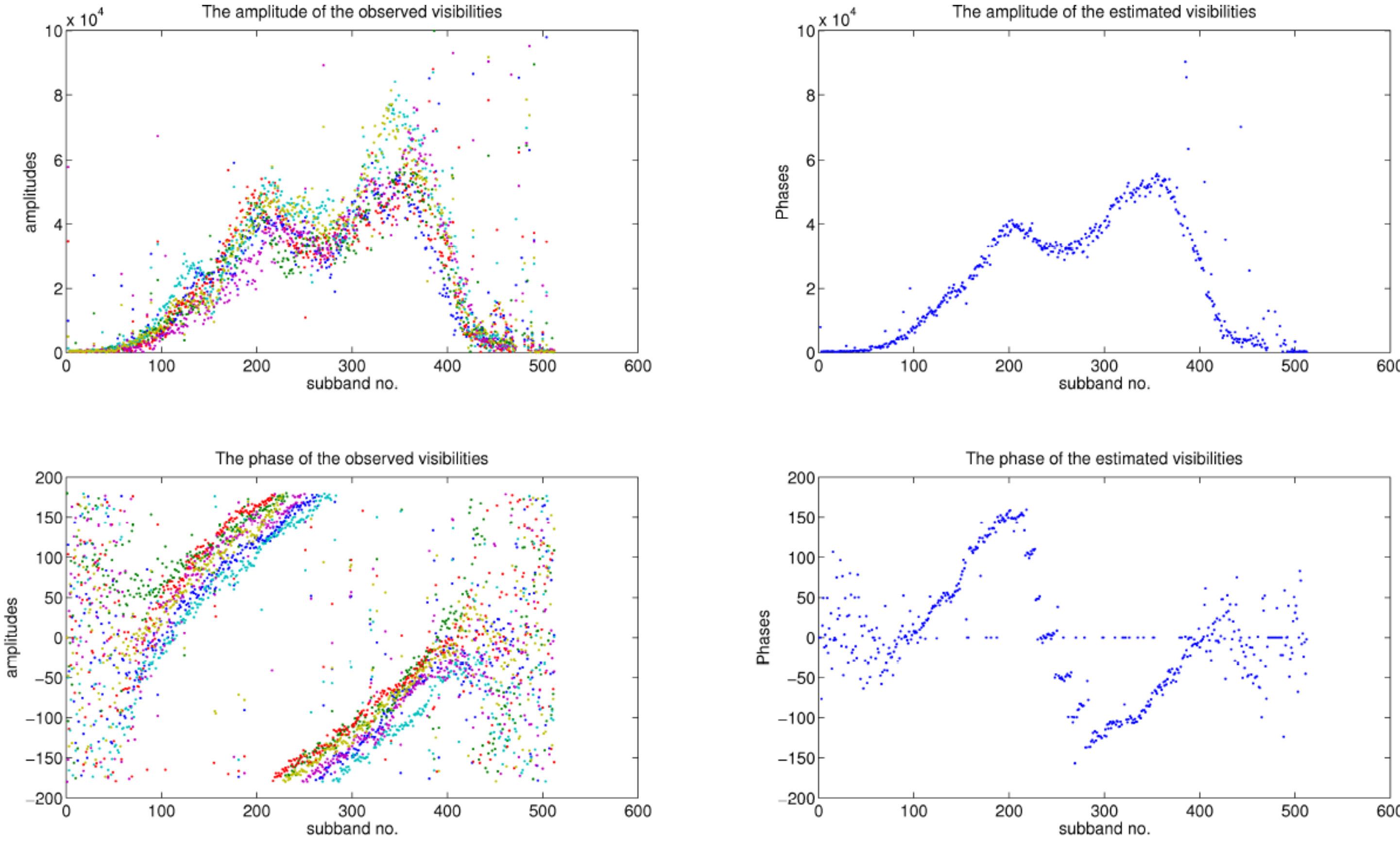
- Model based approach (as for sparse AAs)
- Redundancy: exploit redundant baselines

Example:

LOFAR HBA





Array calibration

Van der Tol, Jeffs & Van der Veen, IEEE TrSP, Sep. 2007
S.J. Wijnholds et al., IEEE SPM, January 2010

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Long baselines, large FOV → scenario 4

- Requires a gain factor per antenna per source
- General problem not solvable

Solutions

- Calibrate the core first (scenario 3) and work outwards
- Use frozen flow turbulence model (spatial continuity)
- Exploit spectral and temporal continuity

LOFAR ionospheric calibration (1)

S.J. Wijnholds, CalIm, 4 – 7 April 2008
S.J. Wijnholds, URSI Benelux Forum, 30 May 2008

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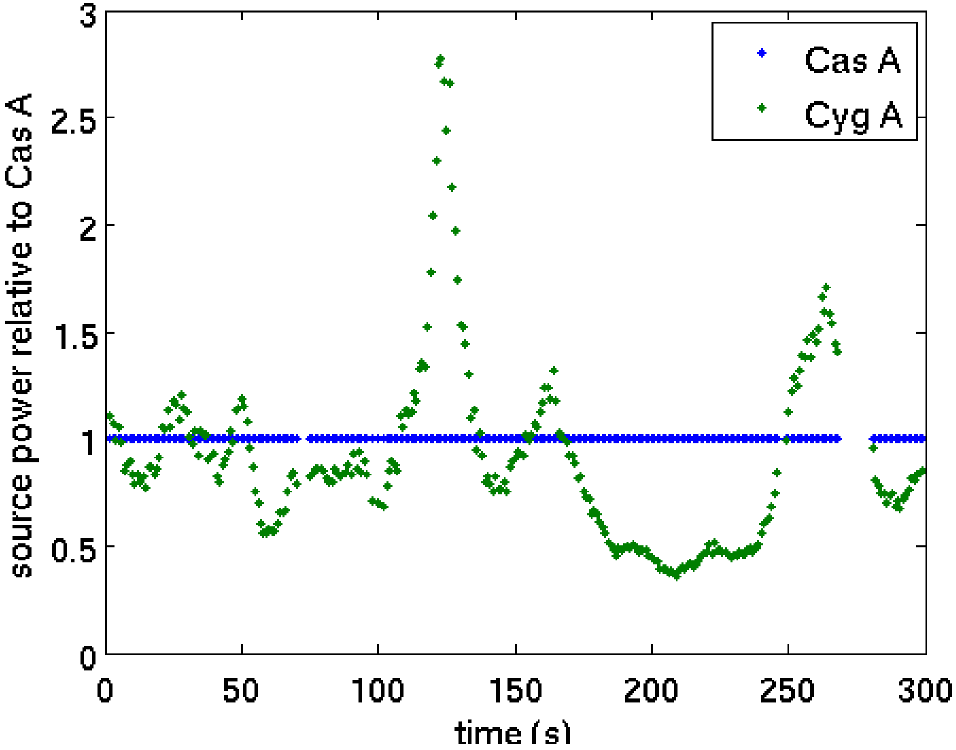
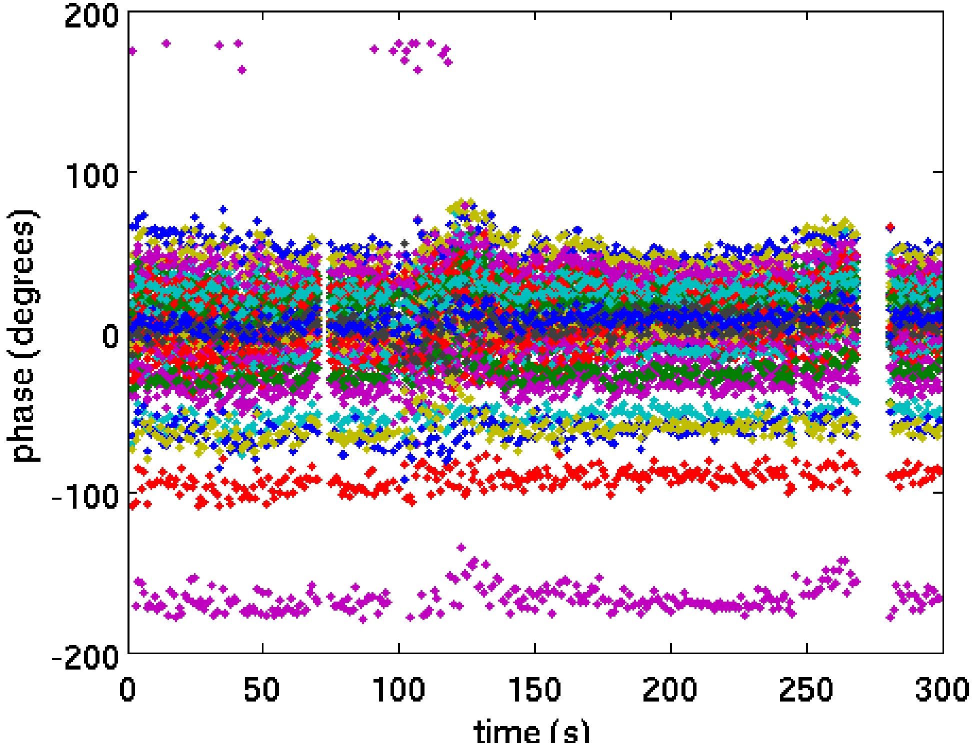
Source powers (left) and gain phases (right)

Source power estimate stabilized gain solutions



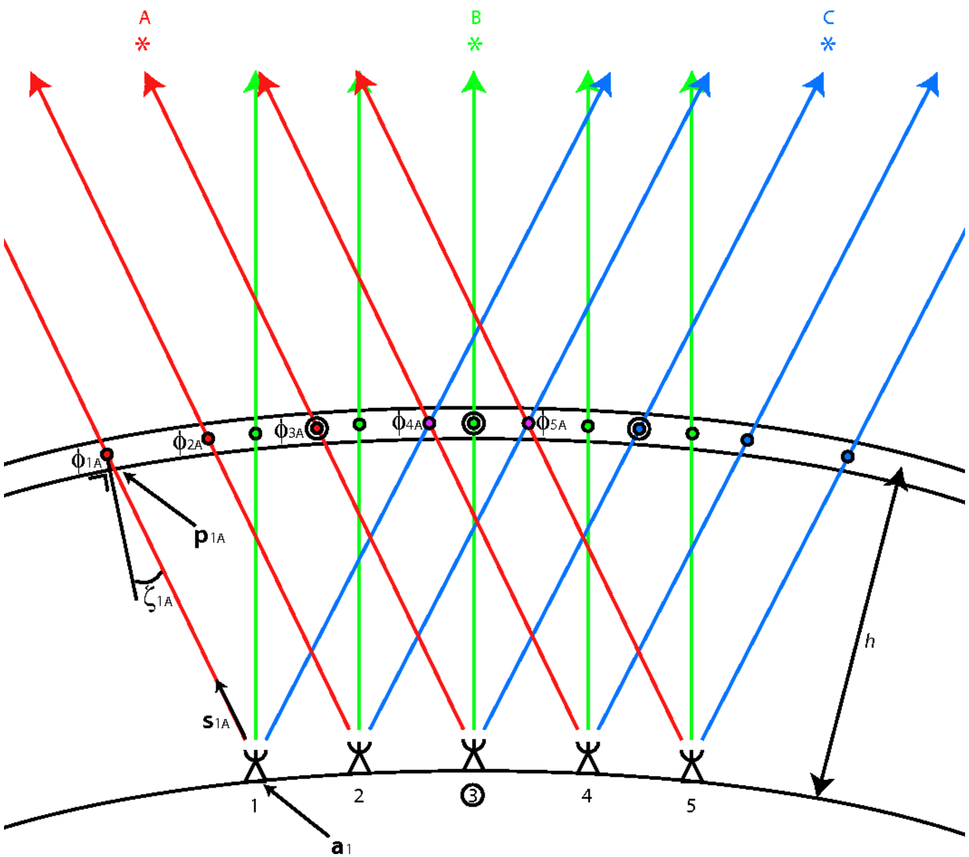


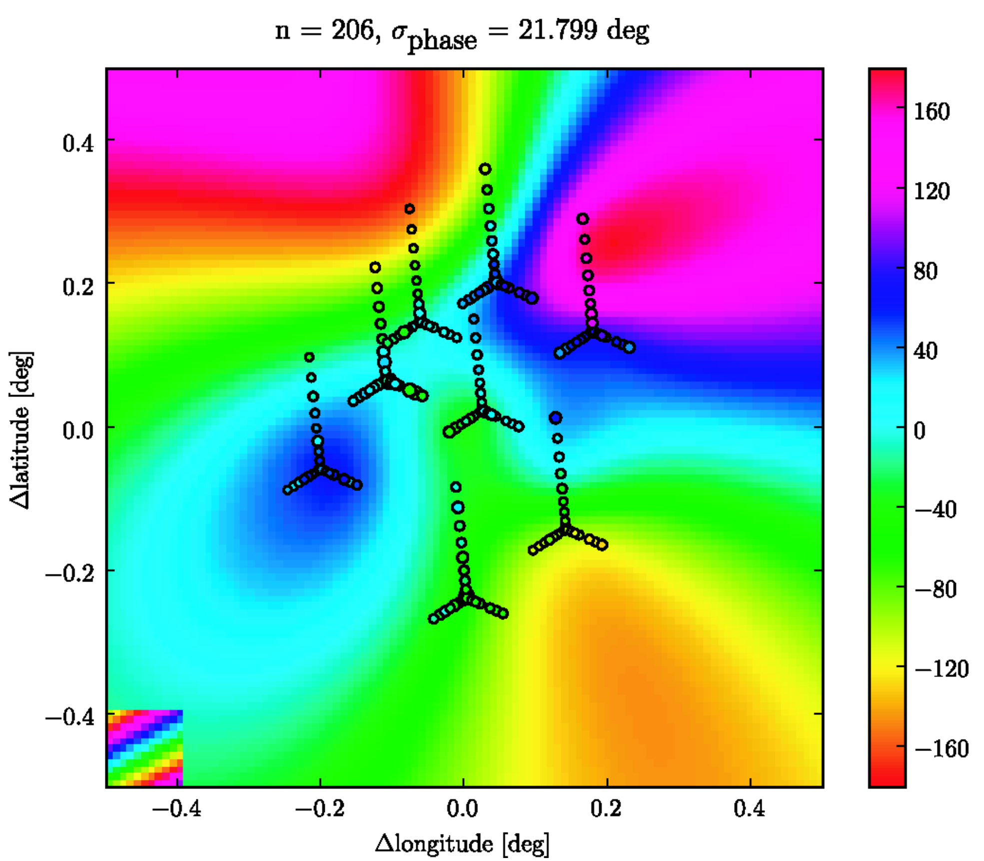
LOFAR ionospheric calibration (2)

H.T. Intema and S. van der Tol et al., A&A, May 2009

Phenomenological description of ionosphere

Use puncture points (left) to find phase screen (right)





Summary

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System level considerations

- Beam forming hierarchy
- Compound elements vs. single antennas
- Atmo-/tropo-/ionospheric scenarios

Hierarchical calibration of phased array systems

- Compound elements: tiles and PAFs
- Station calibration
- Central calibration