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
Scenarios 1 and 2
Direction indep.

Scenario 3
Direction dependent
Same for all antennas

Scenario 4
Direction dependent
Differs per antenna
Recipe

1. Form superposition/beam

2. Measure
   - $s_{12}$-measurement
   - correlate with reference

3. Repeat steps 1 and 2
   (more linear combinations)

4. Extract gains
 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 interferometric 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

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
Calibration problem: solve

\[ \theta = \arg\min \| W( R_{\text{obs}} - R(\theta) ) W \|_F^2 \]

**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

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

right: short baseline (< 4\lambda) 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

- 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

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
Source powers (left) and gain phases (right)

Source power estimate stabilized gain solutions
Phenomenological description of ionosphere

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

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