Deep Calibration & Imaging With SKA

Where we are and where we should be going

Stefan J. Wijnholds
e-mail: wijnholds@astron.nl

SKA Calibration & Imaging Workshop
Cape Town (SA), 3-7 December 2012

Introduction

ASTRON

- AAVP Calibration & Imaging Working Group
  - core: Grainge, Nijboer, Wijnholds
  - contributors: van Ardenne, Bregman, Carozzi, Craeye, Dulwich, Ivashina, Kazemi, de Lera-Acedo, Maaskant, Mort, Noorishad, Razavi-Ghods, Salvini, Smirnov, Yatawatta, Zarb-Adami
- Wrap-up: AA Calibration & Calibratability Meeting
  - 12 & 13 July 2012, Schiphol Airport
  - Summarizing report by Wijnholds, Grainge & Nijboer
    - submitted as SKA memo
    - foundations of this presentation

Recent Highlights (1)

ASTRON

- IXR (Carozzi, IEEE TAP, Jun 2011)
- Imaging bandwidth (Carozzi, AACal, Jul 2012)
- Calibratability (Wijnholds, Bregman, ...,
  Radio Science 2011, URSI GASS 2011, AAVP 2011)
  - station size
  - aperture efficiency
  - side lobe level
  - station beam accuracy
- Error prop. PAF and AA beams (Wijnholds, CalIm 2011)

Recent highlights (2)

ASTRON

- DR 1.6M with WSRT (Smirnov, A&A 2011)
- DR 1M with LOFAR (Labropoulos, A&A in prep.)
- StefCal (Salvini, AAVP 2011 and AACal, Jul 2012)
- Redundancy calibration (Noorishad, A&A, Sep 2012)
- OSKAR-2 (Dulwich, Mort & Salvini, AACal, Jul 2012)
- MeqTrees (Noordam & Smirnov, A&A, Dec 2010)
- CBFPs (Maaskant et al., IEEE TAP, Aug 2012)
- Low-order beam modeling (De Lera Acedo, Razavi-Ghods, Craeye, ..., AACal 2012 and 3GC-II 2011)

Fundamental questions (1)

ASTRON

How accurate should we calibrate the system?

- Advanced methods available to calibrate TDDEs
- More params = more information = higher estimation noise
- Extensive calibration reduces DR!
- Reduction of parameter space is important
  - system stability
  - system (beam) modeling
- Risk: low level calibration artifacts (Smirnov, AACal, Jul 2012)

Fundamental questions (2)

ASTRON

How independent are our calibration parameters?

- Key assumption in current analysis
- May lead to calibration artifacts (Smirnov, AACal, Jul 2012)
- Known covariance allows rigorous error propagation

Fundamental questions (3)

ASTRON

How accurate should the station beams be (known)?

- In general: higher accuracy is better (less estimation noise)
- LOFAR (SAGECal): 20 min update rate for beam deviations
- Requirement: beam errors < thermal noise after 20 min
- This gives: $\varepsilon_{stat} \leq \frac{1}{2} (\Delta S / S_{tot}) (B \tau)^{-\frac{1}{2}}$ (Wijnholds, AAVP 2011)
- For 24-tile HBA stations: $\varepsilon_{stat} = 0.56\%$
- This allows for 2.7% gain error per tile (easily achievable)

Fundamental questions (4)

ASTRON

How do we assess image fidelity?

- Hard to do on actual data
- Simulation: comparison between sky model and imaging result
- Validate imaging procedure by simulation
- Requires
  - end-to-end simulation of the imaging process
  - pipeline based on well established SP techniques

Fundamental questions (5)

ASTRON

What polarimetric accuracy is required?

- figure-of-merit: IXR
- 25 dB IXR limits increase in thermal noise to 22%
- Science reqs. seem to translate to 20 – 25 dB IXR (Carozzi)
- dipoles in bore sight: 25 dB IXR → 16° alignment accuracy (Wijnholds et al., IEEE TAP, Oct 2012)
- LOFAR: 1° alignment accuracy
- Behavior over FoV currently being studied (de Lera Acedo, Arts, Fiorelli, Virone)

Fundamental questions (6)

ASTRON

Which array configuration is optimal?

- Ideal (?): full (u,v)-coverage with space taper
  - low psf side lobes
- Carozzi: imaging bandwidth
  - Does this lead to new insights?
- Redundancy
  - Allows redundancy calibration
  - May have negative impact on (u, v)-coverage

Practical questions

ASTRON

- Can we calibrate the stations on the southern hemisphere?
- Can we do in-situ calibration of each signal path inside a tile?
- How do we computationally efficiently deal with TDDEs?
- How do we deal with crosstalk and mutual coupling?
- How do we deal with side and grating lobes in channel imaging?
- What antenna placement accuracy is required?
- What are the tolerances on the electronic components?
- ...

Risks (1)

ASTRON

Low-level calibration artifacts

- Issue raised by Oleg Smirnov (AACal, Jul 2012)
- Violation of assumption that calibration errors average out
- Implies bias in estimation processes
- Questions:
  - At what level does this issue bite us?
  - Can we reduce this level by system design?
  - Can we improve our estimation processes?

Risks (2)

ASTRON

Far side lobe confusion noise (FSCN)

- Issue raised by Yatawatta and Smirnov (both AACal, Jul 2012)
- Integral of all side lobe sources raises "noise" floor in main beam
- Questions
  - At what level should we expect FSCN?
  - What side lobe level (station, dish, psf) is required to reduce FSCN to a non-limiting level?
  - Can we achieve this level by system design?

Risks (3)

ASTRON

Psf confusion noise (PCN)

- Issue raised by Jaap Bregman (Ph.D. Thesis, Dec 2012)
- Integrated power in psf side lobes for all “weak” sources in FoV
- Conclusion: we need low psf side lobes
- Questions
  - How do we quantify “low” side lobes?
  - What are the implications on system design?

Risks (4)

ASTRON

Time and direction dependent effects (TDDEs)

- TDDEs may cause proliferation of calibration parameters
- TDDEs increase computational costs of imaging
- Trade-off between construction costs and data quality
- We need quantitative analysis to make this trade-off
- We need an end-to-end analysis / simulation of the full system

Risks (5)

ASTRON

Crosstalk, coupling, intermodulation and aliasing

- Unmodeled instrumental effects
- Currently "solved" by flagging
- Question
  - Does this approach still work at higher DR?
  - At what level do they escape detection?
  - How do they effect our data?
  - What system requirements should be formulated?

Next steps

ASTRON

- Can we extrapolate current successes to the SKA?
- Best guess system model with assumptions on
  - (u, v)-coverage
  - station side lobe level
  - …
- Use this model to
  - Assess identified risks
  - Develop calibration and imaging strategy
  - Translate results to system (hardware) requirements
- MeqTrees and OSKAR-2 are useful tools

Conclusions

ASTRON

- Impressive progress has recently been made
- Fundamental questions have been (partially) answered
- With “design for calibratability” we seem on the right track
- Risks
  - low-level calibration artifacts
  - FSCN
  - PCN
  - TDDEs
  - unmodeled instrumental effects