The discrete charms of

Redundant Spacing Calibration (RSC)

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Outline

• What is RSC?
  – Advantages
  – Limitations

• The place of RSC in the GST
  – Diagnostic tool
  – Fast first calibration stage

• A second youth for RSC?
  – Built into SKA
Interferometer

- Consists of two antennas that look at the same source
- Essentially measures the phase-difference between two points in the incoming wavefront
- Important: Baseline length and orientation
- An array of N antennas can form N(N-1)/2 interferometers
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Redundant Baselines

- Two interferometers with the same baseline (length and orientation)...

- ...should measure the same phase
  - Any differences must be caused by instrumental errors
  - So these differences can be used for calibration

- ...provided their antennas “see” the same sky
WSRT: lots of redundancy
(because CLEAN did not exist yet in 1968)
Reduction of the number of unknown antenna phases

\begin{align*}
N=2 & \quad \text{2 unknown phases (abs and gradient)} \\
N=3 & \quad \text{2 unknown phases (abs and gradient)} \\
N=4 & \quad \text{3 unknowns (2 abs, one gradient)} \\
N=5 & \quad \text{still only 2 unknowns}
\end{align*}

So: \( N(N-1)/2 \) (=10) data-samples share only 2 unknown phases

\textbf{NB: 2D regular array: 3 parameters (abs phase and 2 gradients)}
A single time-slot

** RedunPlot "GerFest":

linear

logarithmic

nr of unknown phases

nr of unknown phases

nr of stations (N)

nr of stations (N)
The WSRT Dynamic Range skyrocketed

3C48
~1980
WSRT
610 MHz
1:10000

GerFest, Dwingeloo, 8 nov 2013
Some serendipity: RSC gave you WIFI (!)

- Hamaker, O'Sullivan, Noordam \(\text{(JOSA, 1977)}\)
  - Only one of these three got rich

- Triggered by Muller and Buffington \(\text{(JOSA, 1976)}\)
  - The use of sharpness criteria in optical telescopes
  - They work best for a fully sampled aperture
    - Like a lens or a mirror
  - Because it has redundant spacings
The Blue Riband
of Macho Imaging

• 1980: WSRT and “redundancy”: DR = 10.000
• 1990: WSRT and NEWSTAR: 1.000.000
• 2010: WSRT and MeqTrees: 2.000.000
• 2013: EVLA and MeqTrees: 3.000.000
• 201x: LOFAR and SageCal....?

• … but RSC did not play much of a role in all this...
  – (generalised selfcal with good sky models is enough)
VLA: no redundancy
(N=27: 351 different baselines, closure errors)
Self-calibration (selfcal)

- Solving for (antenna-based!) instrumental errors by comparing the measured data with predicted values from a model of the observed field.

- Selfcal was a game changer technique:
  - it saved the VLA, and made VLBI possible
  - “generalised” selfcal is the basis of all these wonderful LOFAR images

- Invented by Cornwell and Wilkinson (Jodrell Bank, ~1980)
  - Selfcal, “hybrid mapping” and “closure phase” are all the same thing

- Locally stumbled upon by yours truly, by way of RSC
  - with help from John O'Sullivan, Johan Hamaker and Ger de Bruyn
  - (we initially missed it because of Wim's frugality)
Selfcal and RSC

- Both require the assumption of antenna-based instrumental errors
  - To reduce the number of unknowns
  - RSC has even fewer unknowns than selfcal (2 vs N)
- RSC is supposed to be sky-model-independent
  - Which makes it fast and “safe”
  - But RSC does still need a model to align time-slots
    - i.e. to equalise their position and total flux
    - We tried to use the centre-of-flux of the entire field for that
- RSC may be seen as an extra constraint on selfcal
Problems with RSC

• Different antennas “see” a different sky
  – More so for more ambitious (macho) imaging

• RSC can't deal with Direction Dependent Effects (DDE)
  – E.g. station beam-shapes, or the ionosphere

• Redundant baselines reduce the uv-coverage
  – Only a problem for arrays with few elements
The Known Unknowns
(for a single time-slot)

** RedunPlot "GerFest":

![Graph showing the known unknowns for linear and logarithmic scales.](image)
The Unknown Knowns
(for an entire observation)

** RedunPlot "GerFeest":

- instr. parameters
- skymodel parameters

nr of instrumental unknowns vs nr of stations (N)

nr of skymodel unknowns (nvits-huk instr) vs nr of stations (N)
A second youth for Redundant Spacing Calibration?
LOFAR superterp redundancy
LOFAR HBA station redundancy
(used for HBA station calibration)

2D array of 144 antennas that share only 2 unknown phases!
Redundancy for SKA?
(advocated by the Man Himself)

- Easily achieved for the central 3 km or so
- Stations (and even antennas) on single flat grid
  - Fully filled grid: sensitivity
  - Fully sampled uv-plane: imaging
- Powerful diagnostic tool
- Rapid initial calibration
- The idea of an “FFT telescope” (Tegmark and friends)
  - No gridding needed (except to apply DDE's...?)

GerFest, Dwingeloo, 8 nov 2013
GerFest, Dwingeloo, 8 nov 2013

Rectangular Array

** RectangularArray "test": nant=49 nifr=1176 nbasel=84

![Graphs showing ant positions and redundancy solution]
** RectangularArray "test": nant=25 nifr=300 nbasel=81

Optimised
Stations and Antennas
all on the same grid

** Monster "monster": nant=180 nifr=16110 nbase1=1309

![Graph showing stations and antennas on a grid]
Enjoy...