HOLOGRAPHIC APERTURE ARRAY STATION CALIBRATION AT LOFAR

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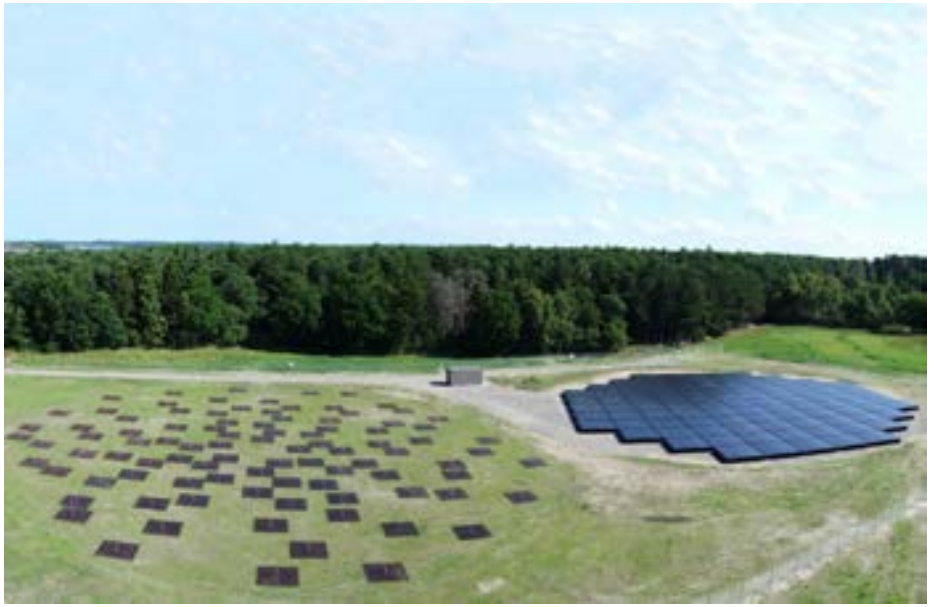
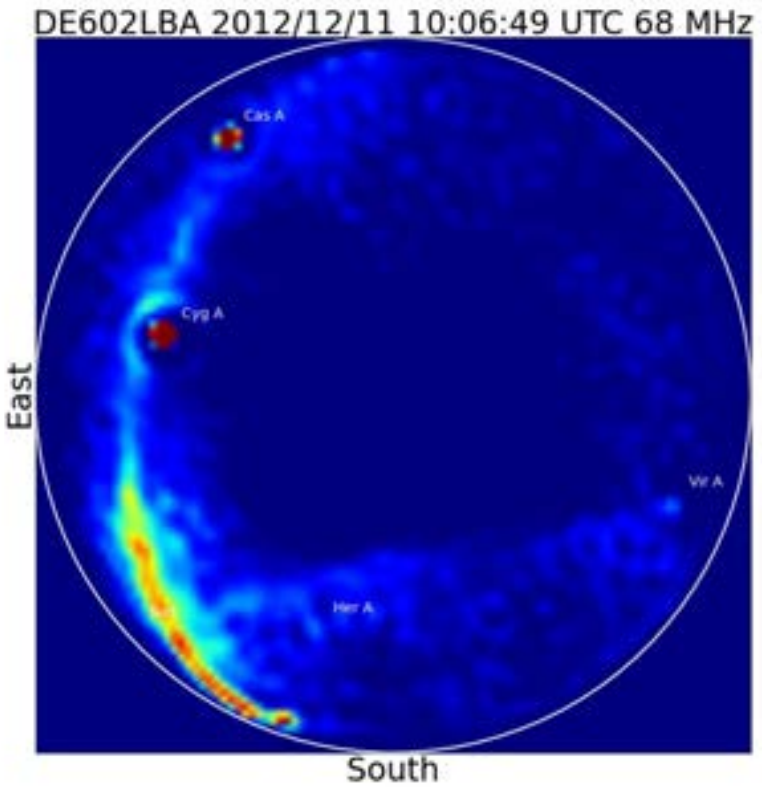
LOFAR



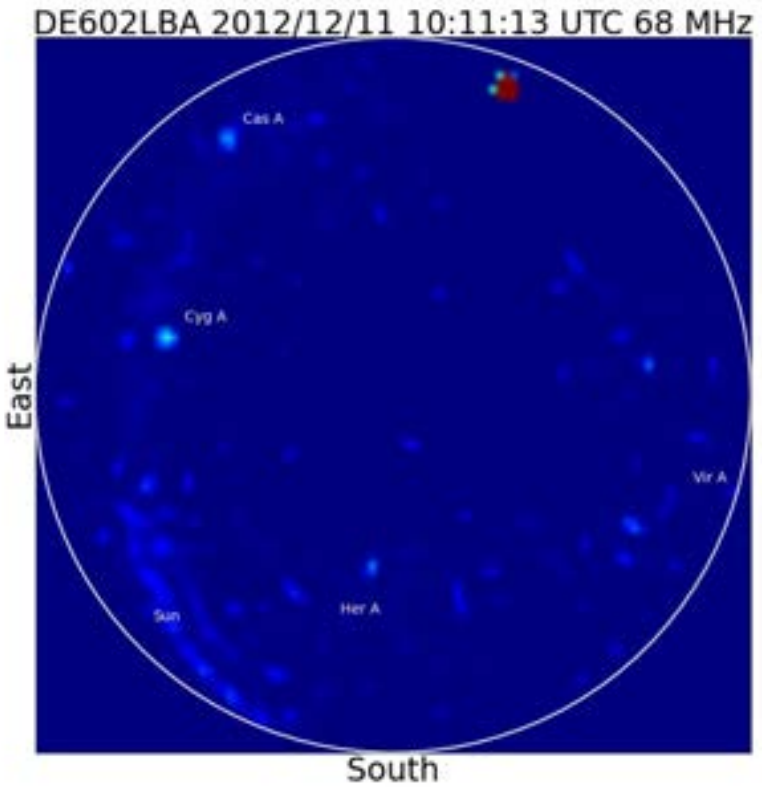
- Aperture array stations: 38 NL + 12 abroad
- Low band:
  - 10 – 90 MHz
  - Digitally beamformed droopy dipoles
- High band:
  - 110 – 250 MHz
  - Digitally beamformed tiles
  - tiles are analoguely beamformed 4×4 fat dipoles
- Up to 96 MHz bandwidth
- Resolution up to $\sim$ 200 mas.
- Sensitivity $\sim$20% SKA1 Low.

Current station calibration



- All-sky imaging/calibration
- Multi-source sky model
- Sensitive to local RFI
- Must average over model errors (24h)
- Expensive data reduction

Current station calibration



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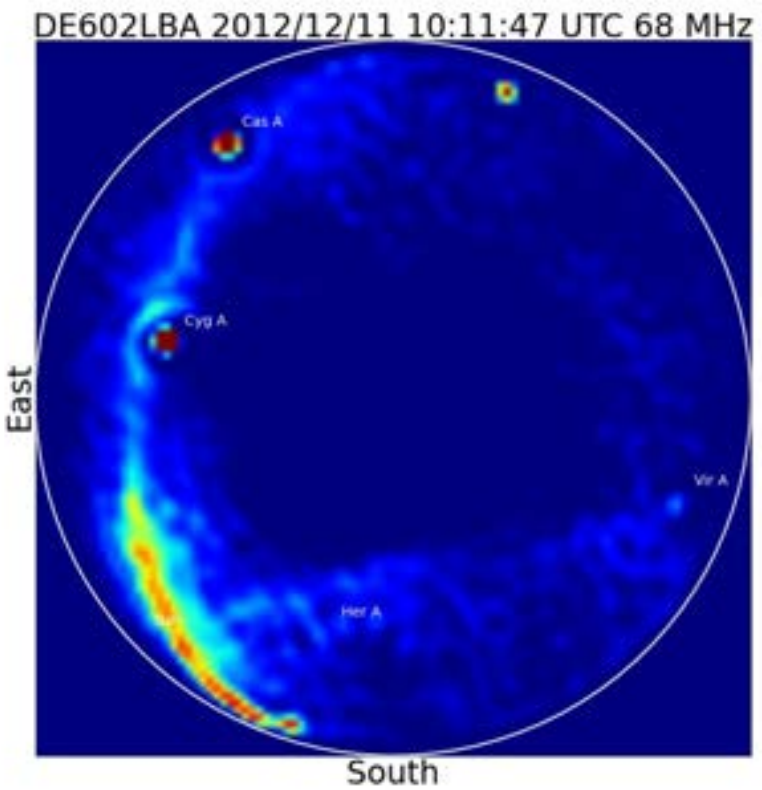
Current station calibration



- All-sky imaging/calibration
- Multi-source sky model
- Sensitive to local RFI
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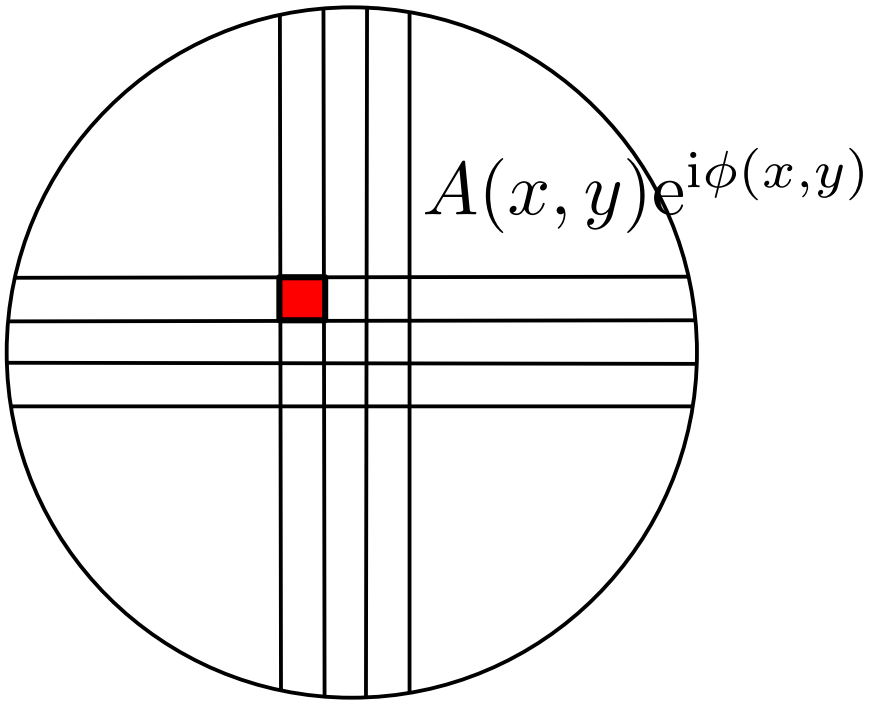
Beams / aperture illumination

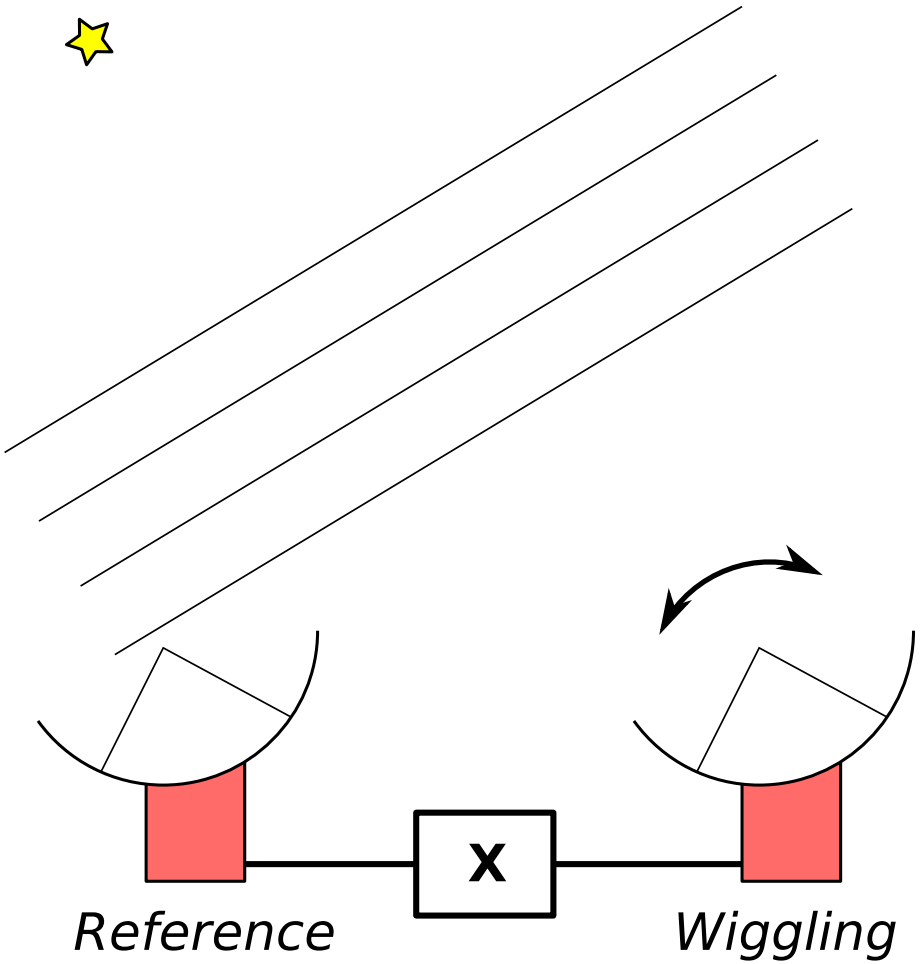


- Each element reflects radiation to focus
- All paths same length
- Add in phase at focus

$$G(l,m) = \int_{xy} a(x,y)e^{2\pi i(xl+ym)\nu/c}$$

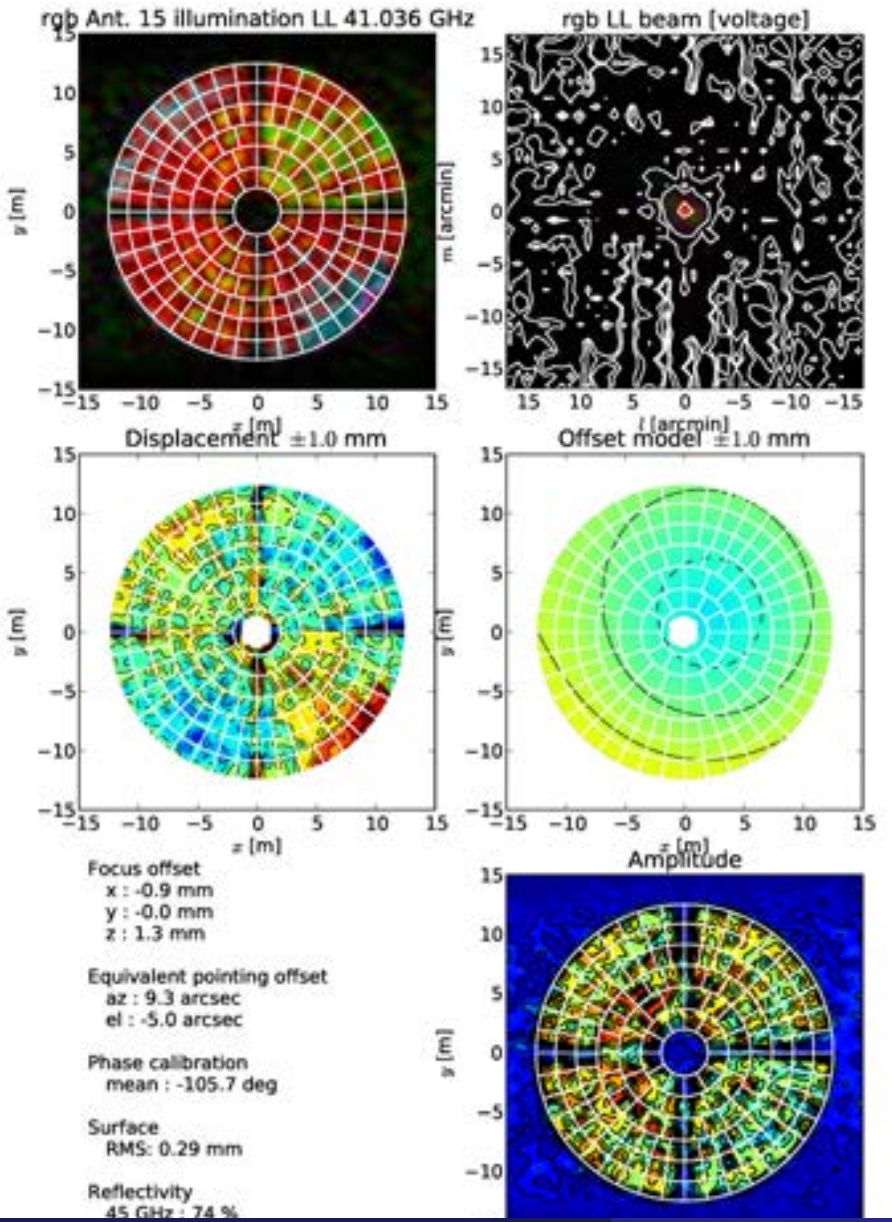
$$a(x,y) = A(x,y)e^{i\phi(x,y)}$$

Holography



- Measure voltage beam pattern
- Dishes: scan target dish across cal source
- Dishes: correlate with reference station pointing at cal source
- Visibility: $g_{\text{wiggling}} V g^*_{\text{ref}}$
- Aperture arrays: use simultaneous multi-beaming
- Fourier transform voltage beam: aperture map!

JVLA ANT 15



- Extreme precision
- “Big” distortion on lower right side
- Distortion can be removed by moving panels
- Moving panels = station calibration

LOFAR holography observing

- Only calibrates *digital* beam former gains
- Two station sets: target & reference
- Reference: point at source
- Target: multi-beam at and around source (436 beams)
- Correlator tracks source for all stations and beams
- Swap target and reference sets & repeat
- Select next sub band & repeat
- LBA: 2 min scans, HBA: 30 sec scans

LOFAR holography reduction

Calibration

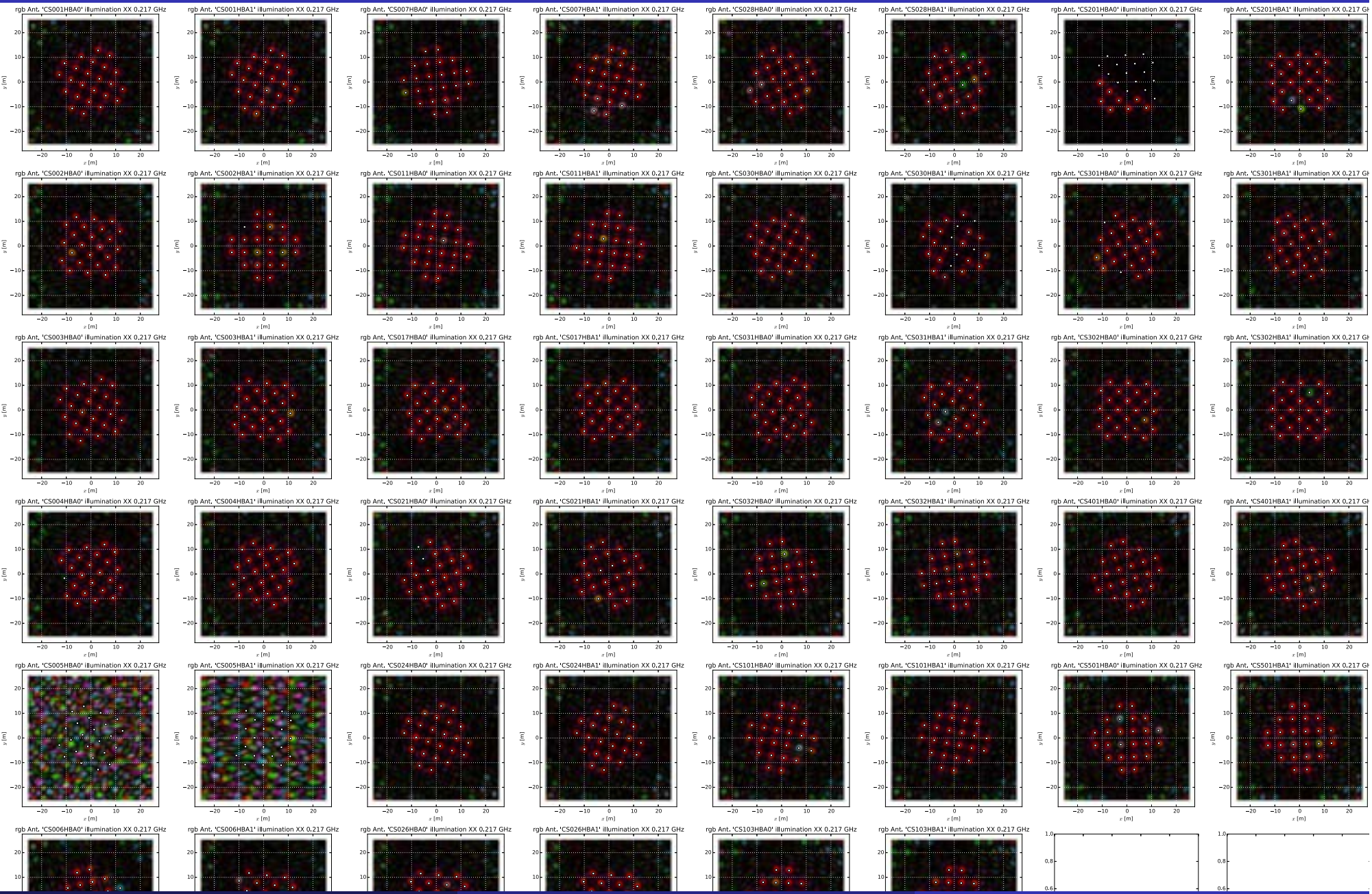
$$
\begin{aligned}
\mathbf{V}_c &= \mathbf{J}_{ic}\mathbf{E}_{ij}\mathbf{J}_{jc}^{\dagger} \\
\mathbf{V}_k &= \mathbf{J}_{ik}\mathbf{E}_{ij}\mathbf{J}_{jc}^{\dagger} \\
\tilde{\mathbf{V}}_k &= \mathbf{V}_k\mathbf{V}_c^{-1} \\
\tilde{\mathbf{V}}_k &= \mathbf{J}_{ik}\mathbf{E}_{ij}\mathbf{J}_{jc}^{\dagger}\left(\mathbf{J}_{ic}\mathbf{E}_{ij}\mathbf{J}_{jc}^{\dagger}\right)^{-1} \\
\tilde{\mathbf{V}}_k &= \mathbf{J}_{ik}\mathbf{E}_{ij}\mathbf{J}_{jc}^{\dagger}\mathbf{J}_{jc}^{\dagger\,-1}\mathbf{E}_{ij}^{-1}\mathbf{J}_{ic}^{-1}
\end{aligned}
$$

$$\tilde{\mathbf{V}}_k = \mathbf{J}_{ik}\mathbf{J}_{ic}^{-1}$$

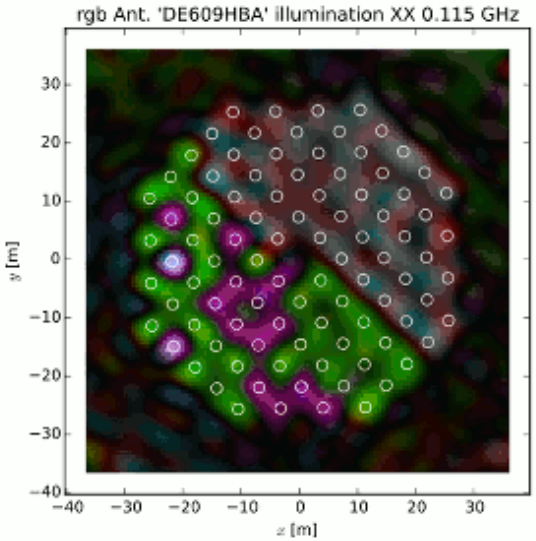
Gain fitting

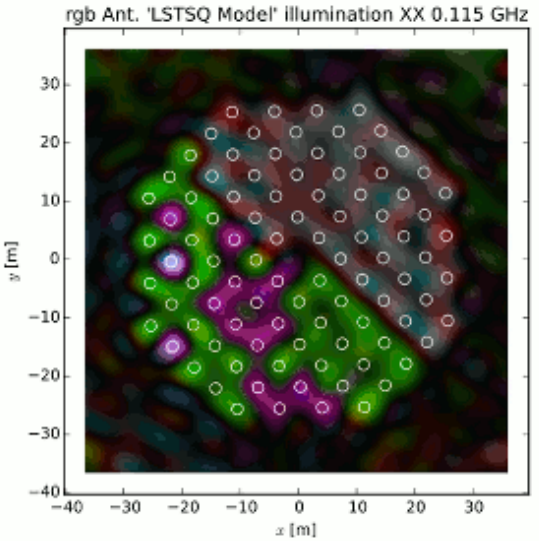
- Average per reference station (and determine σ_{m})
- Weighted avg over reference stations
- $$\mathbf{WB} = \mathbf{WFa}$$
- Simple weighted linear problem
- Allows determination of (co)variances of parameters

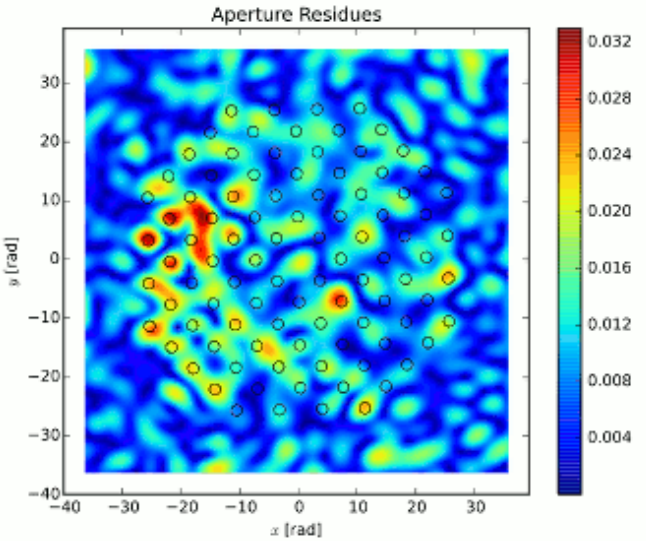
The Core!

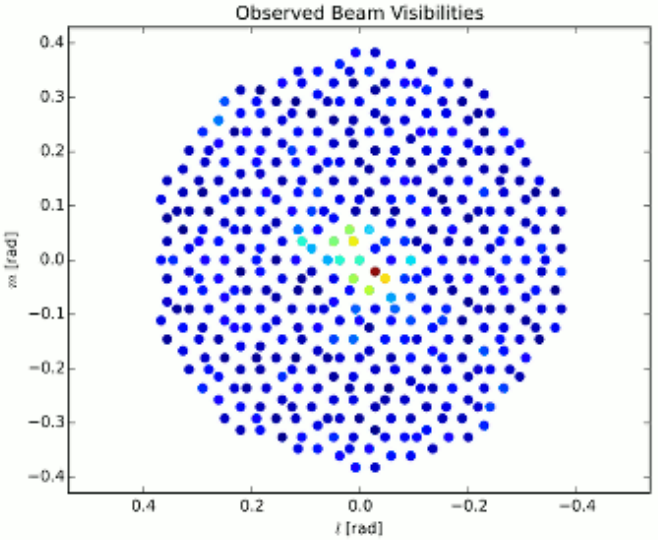

rgb Ant. 'CS001HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS001HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS007HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS007HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS028HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS028HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS201HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS201HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS002HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS002HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS011HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS011HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS030HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS030HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS301HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS301HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS003HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS003HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS017HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS017HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS031HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS031HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS302HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS302HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS004HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS004HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS021HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS021HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS032HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS032HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS401HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS401HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS005HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS005HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS024HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS024HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS101HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS101HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS501HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS501HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS006HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS006HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS026HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS026HBA1' illumination XX 0.217 GHz
rgb Ant. 'CS103HBA0' illumination XX 0.217 GHz
rgb Ant. 'CS103HBA1' illumination XX 0.217 GHz
x [m]
y [m]

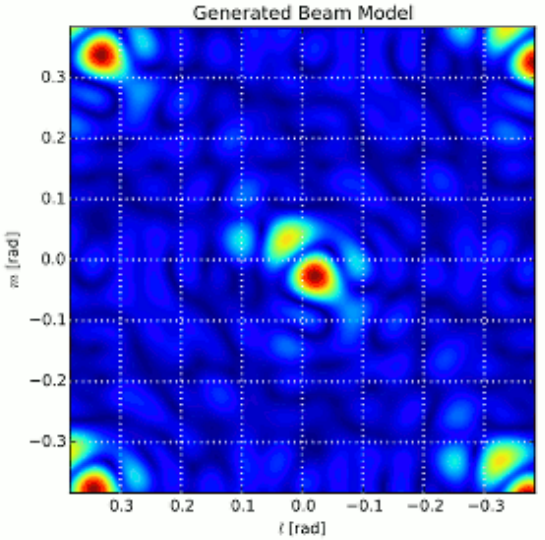
DE609HBA

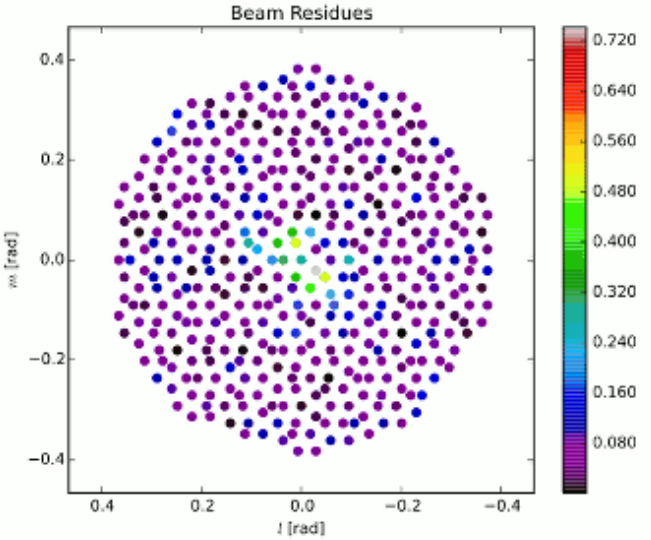

rgb Ant. 'DE609HBA' illumination XX 0.115 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.115 GHz
y [m]
x [m]

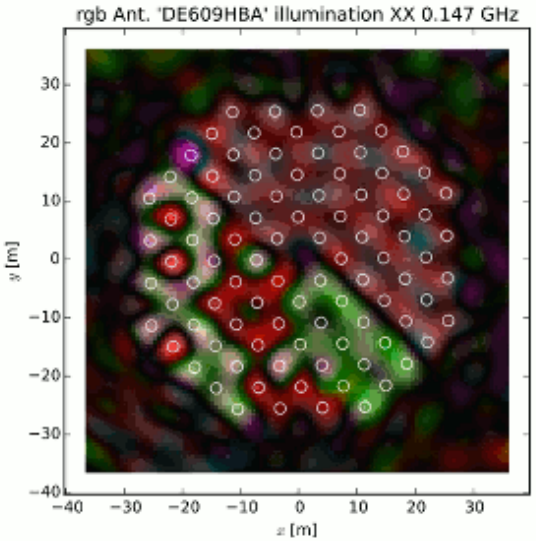

Aperture Residues
y [rad]
x [rad]
0.032
0.028
0.024
0.020
0.016
0.012
0.008
0.004

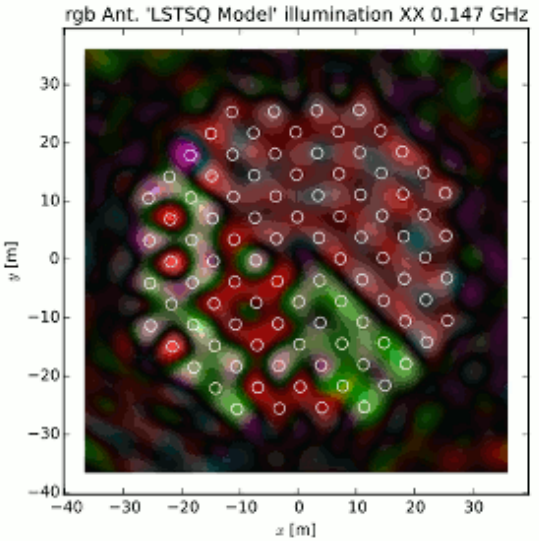

Observed Beam Visibilities
m [rad]
l [rad]

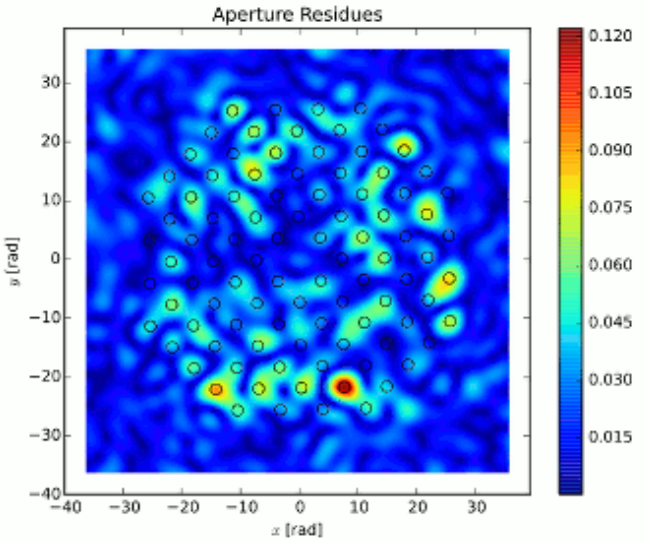

Generated Beam Model
m [rad]
l [rad]

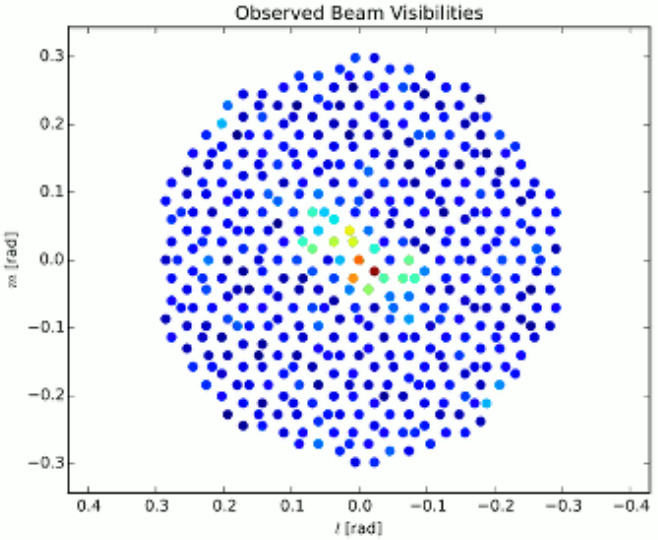

Beam Residues
m [rad]
l [rad]
0.720
0.640
0.560
0.480
0.400
0.320
0.240
0.160
0.080

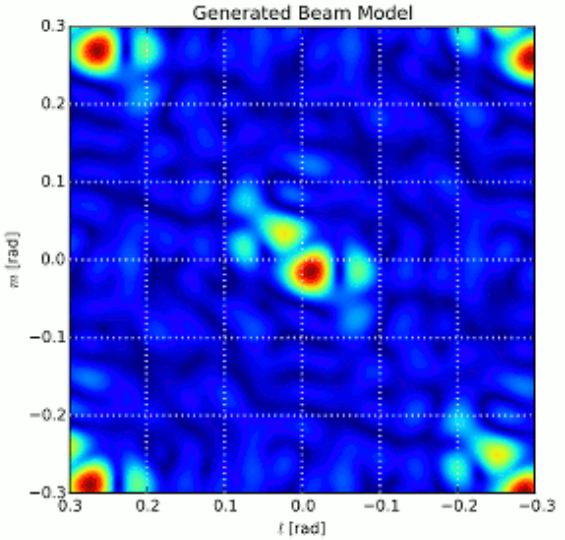
DE609HBA

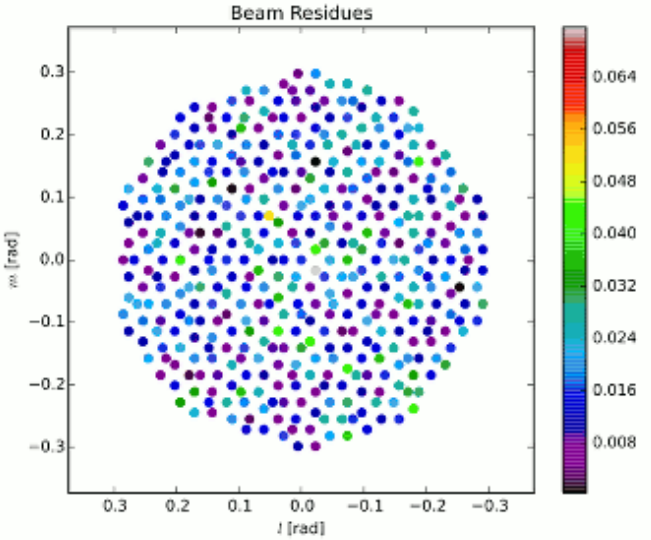

rgb Ant. 'DE609HBA' illumination XX 0.147 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.147 GHz
y [m]
x [m]

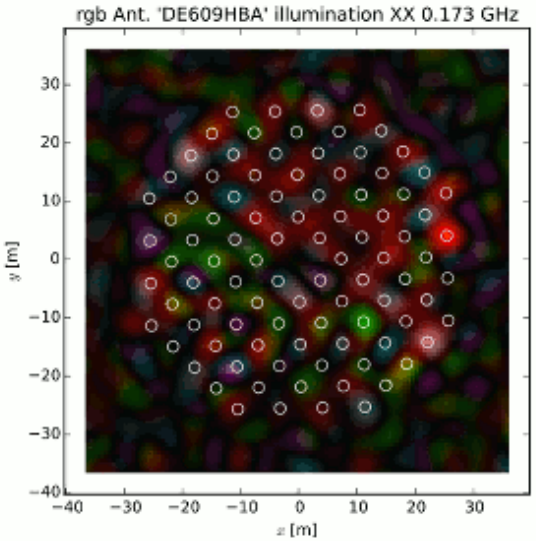

Aperture Residues
y [rad]
x [rad]
0.120
0.105
0.090
0.075
0.060
0.045
0.030
0.015

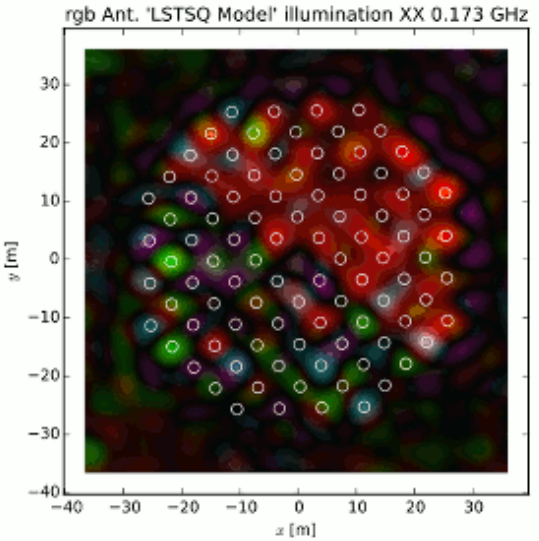

Observed Beam Visibilities
m [rad]
l [rad]

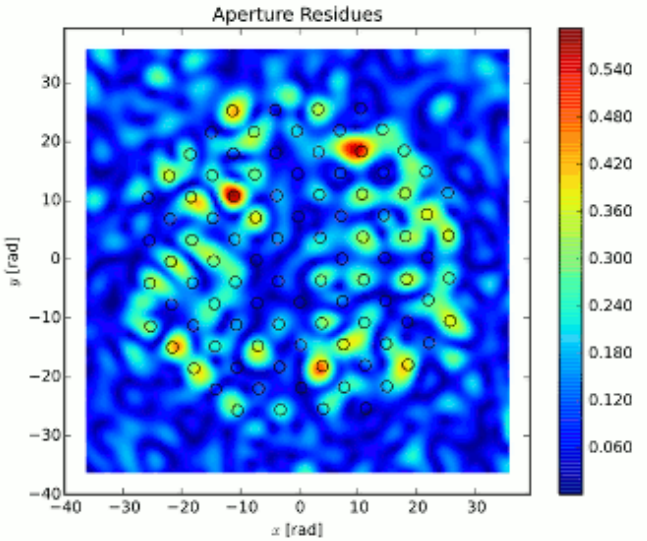

Generated Beam Model
m [rad]
l [rad]

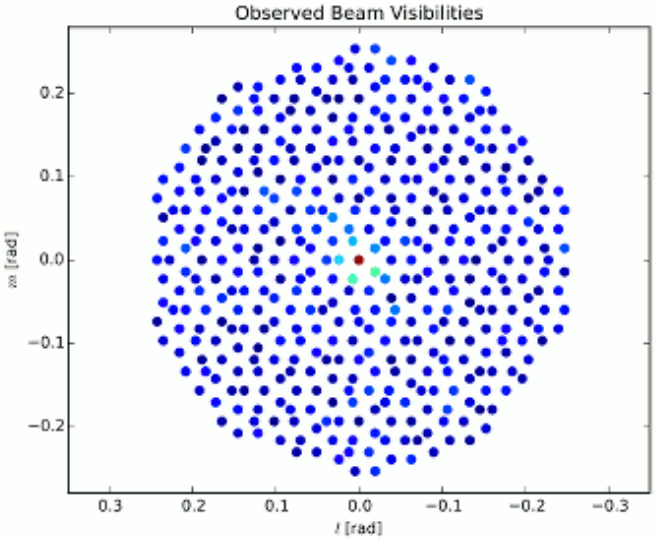

Beam Residues
m [rad]
l [rad]
0.064
0.056
0.048
0.040
0.032
0.024
0.016
0.008

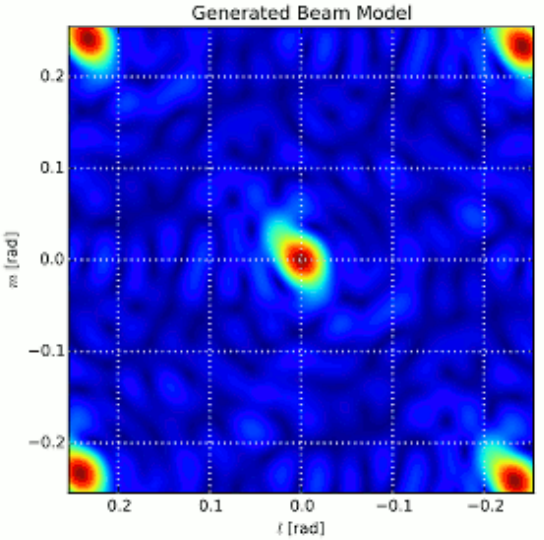
DE609HBA

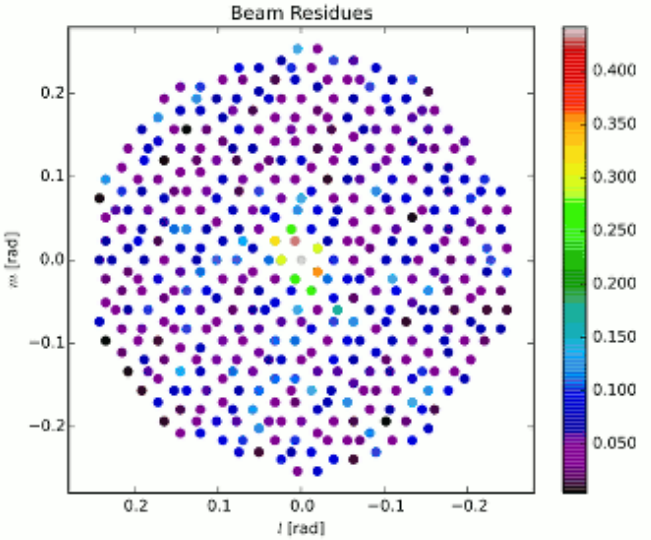

rgb Ant. 'DE609HBA' illumination XX 0.173 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.173 GHz
y [m]
x [m]

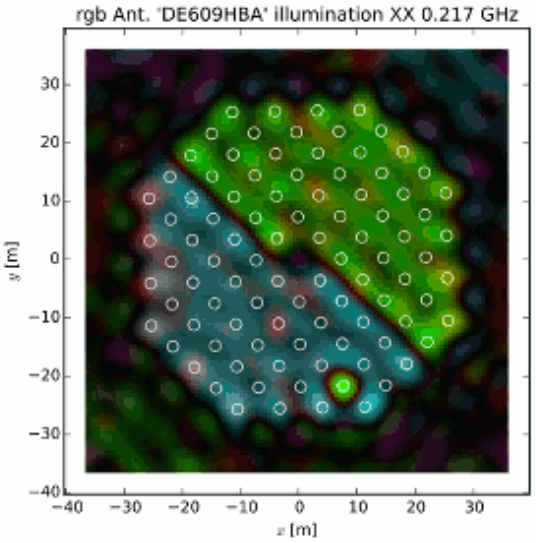

Aperture Residues
y [rad]
x [rad]
0.540
0.480
0.420
0.360
0.300
0.240
0.180
0.120
0.060

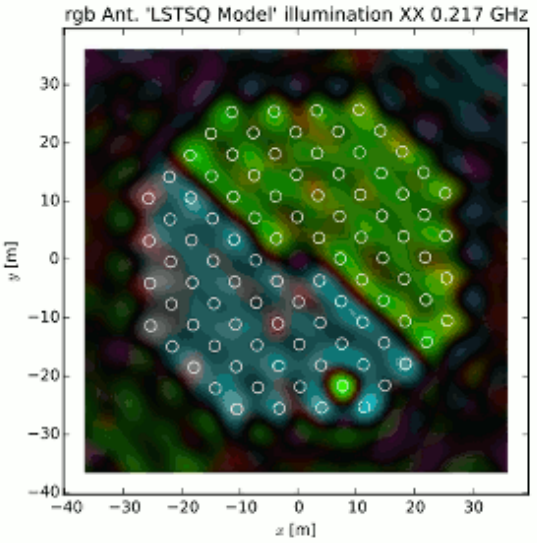

Observed Beam Visibilities
m [rad]
l [rad]

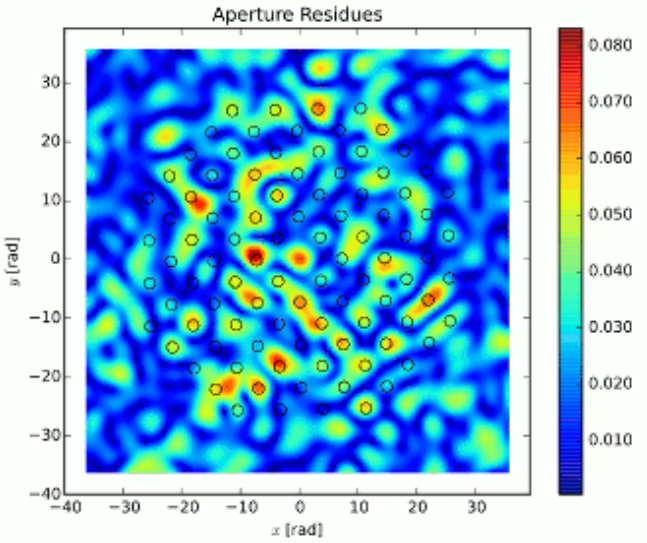

Generated Beam Model
m [rad]
l [rad]

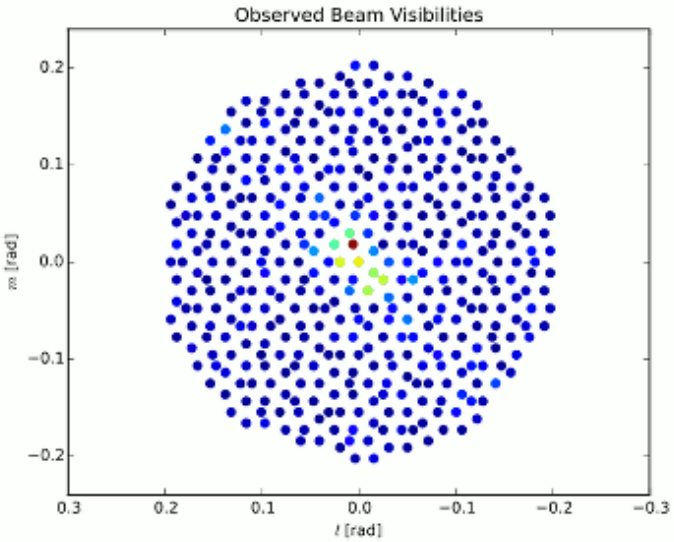

Beam Residues
m [rad]
l [rad]
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050

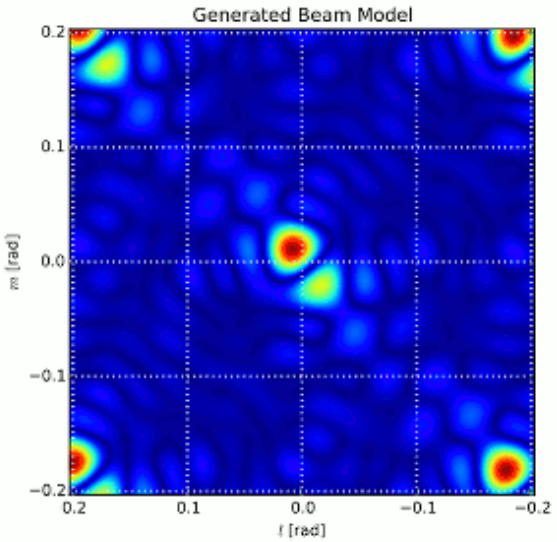
DE609HBA

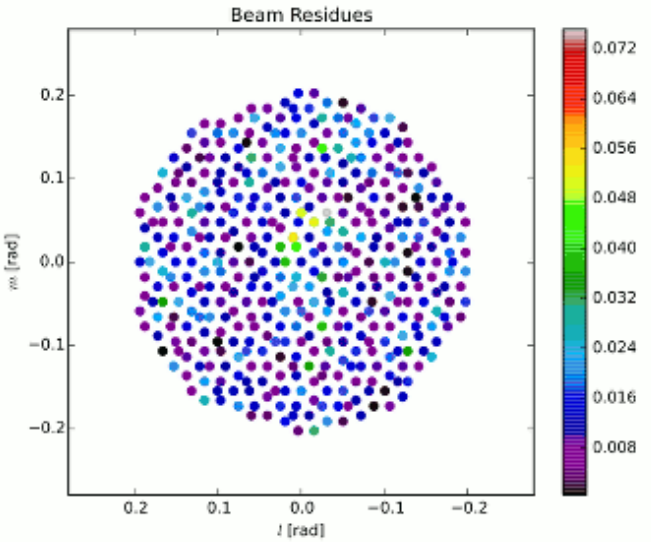

rgb Ant. 'DE609HBA' illumination XX 0.217 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.217 GHz
y [m]
x [m]

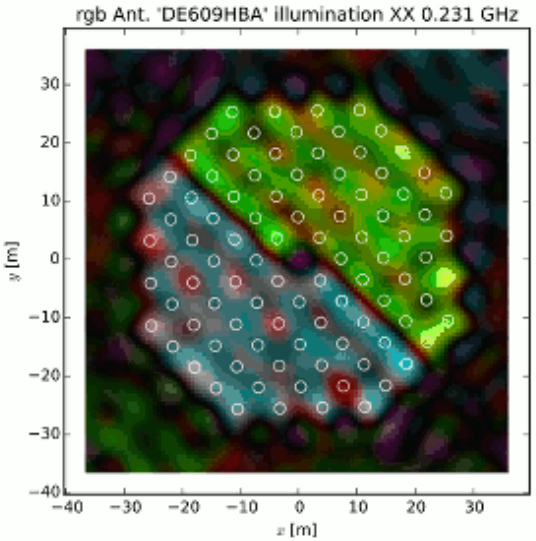

Aperture Residues
y [rad]
x [rad]

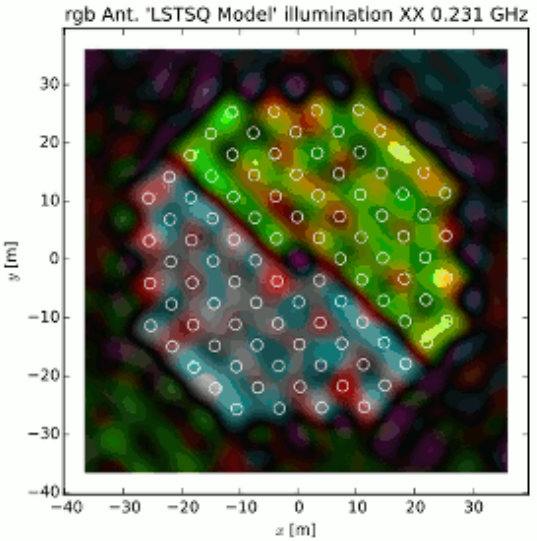

Observed Beam Visibilities
m [rad]
l [rad]

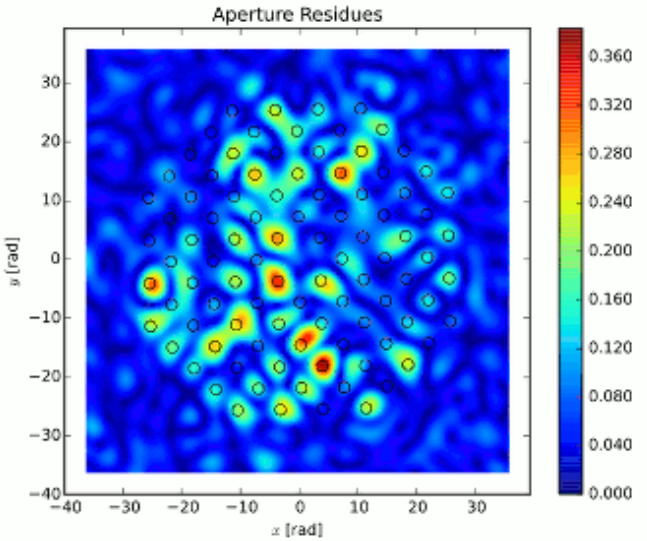

Generated Beam Model
m [rad]
l [rad]

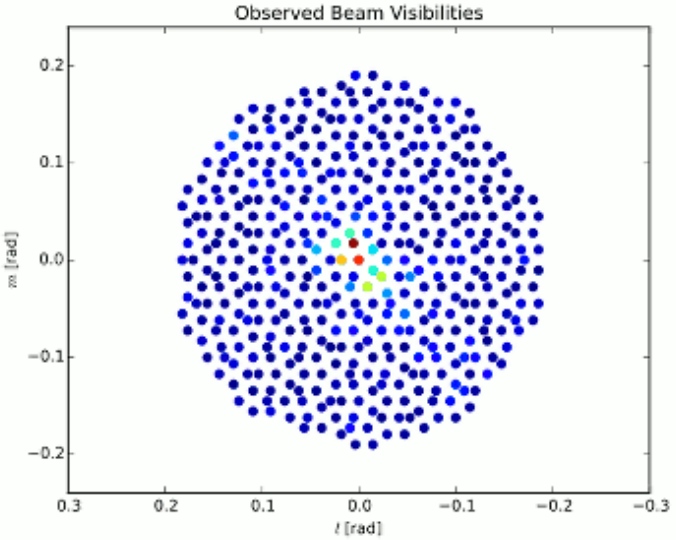

Beam Residues
m [rad]
l [rad]

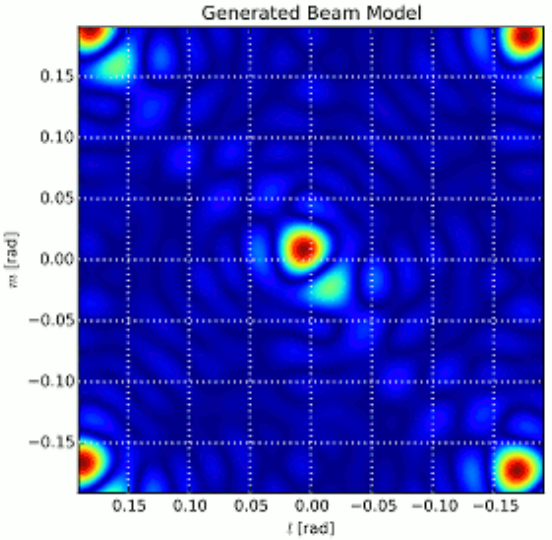
DE609HBA

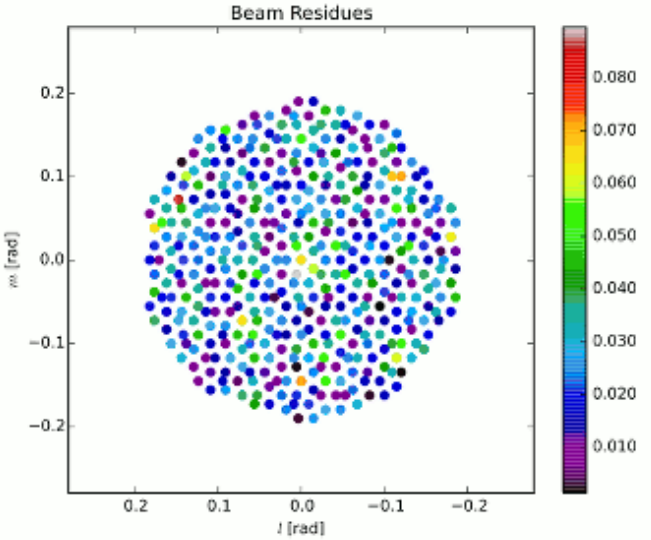

rgb Ant. 'DE609HBA' illumination XX 0.231 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.231 GHz
y [m]
x [m]

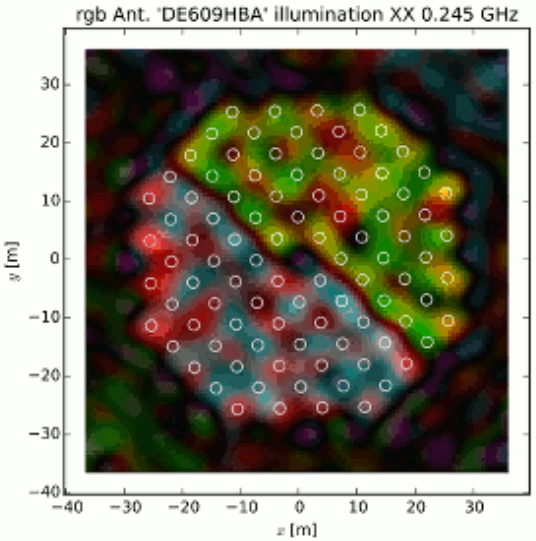

Aperture Residues
y [rad]
x [rad]

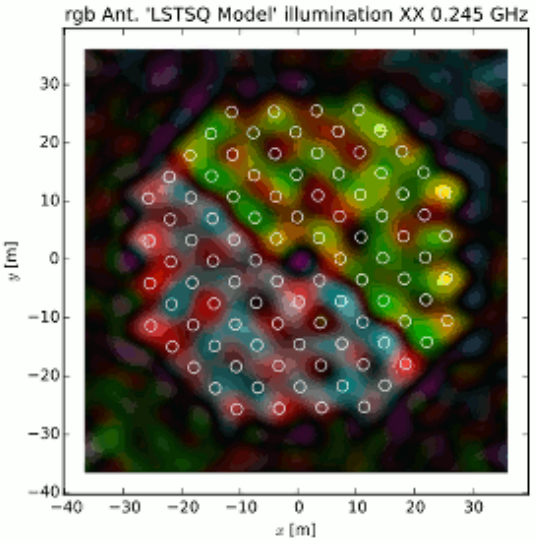

Observed Beam Visibilities
m [rad]
l [rad]

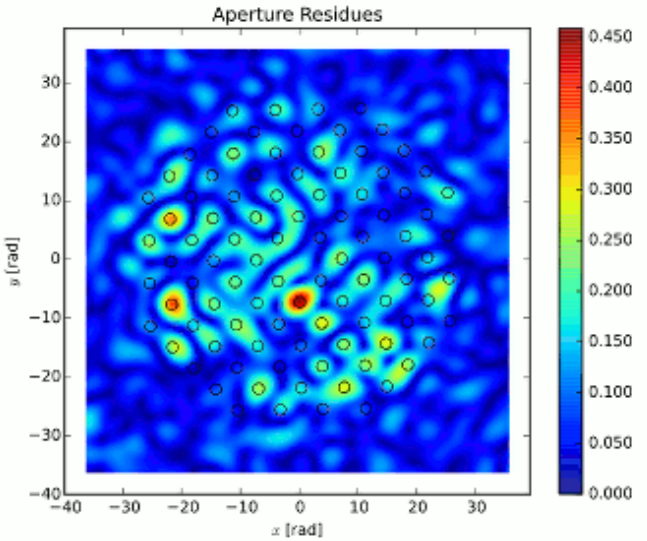

Generated Beam Model
m [rad]
l [rad]

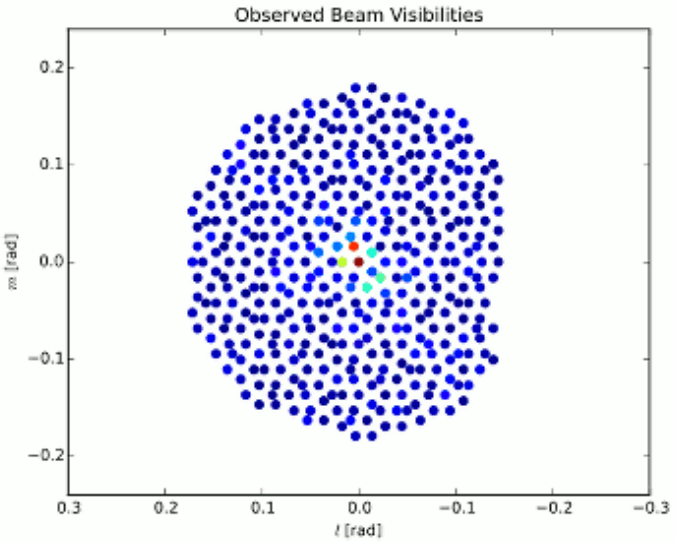

Beam Residues
m [rad]
l [rad]

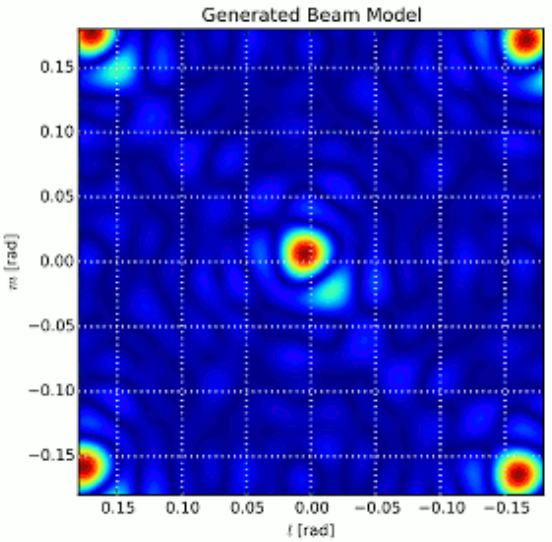
DE609HBA

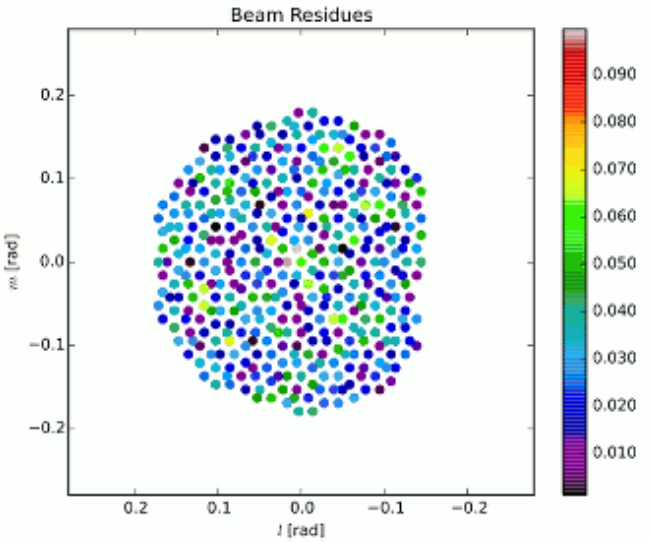

rgb Ant. 'DE609HBA' illumination XX 0.245 GHz
y [m]
x [m]


rgb Ant. 'LSTSQ Model' illumination XX 0.245 GHz
y [m]
x [m]


Aperture Residues
y [rad]
x [rad]


Observed Beam Visibilities
m [rad]
l [rad]


Generated Beam Model
m [rad]
l [rad]


Beam Residues
m [rad]
l [rad]

Conclusions

- Fast
- Accurate
- Easy data reduction
- Less sensitive to local RFI
- Only calibrates *digital* beam former gains
- Requires massive multibeaming ($n_{\text{beams}} \gg n_{\text{ant/station}}$)
- But...not yet operational (will be this year).