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Recent developments in LOFAR calibration & imaging

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Reminder: imaging

- The *visibility* y for antennas i, j, channel q, time t given by:

$$y_{ijqr} = \iint_{lm} e^{-j2\pi\left(u_{ijr}l + v_{ijr}m + w_{ijr}n\right)/\lambda_q} g_{iqr}(l,m) g^{*}_{jqr}(l,m) I(l,m)\, dl\, dm$$

- I(l,m) is the image we're interested in.
- Direct inversion impossible:
  - number of l,m pixels ~ 10^9, number of visibilities ~ 10^9
- Use FFT!

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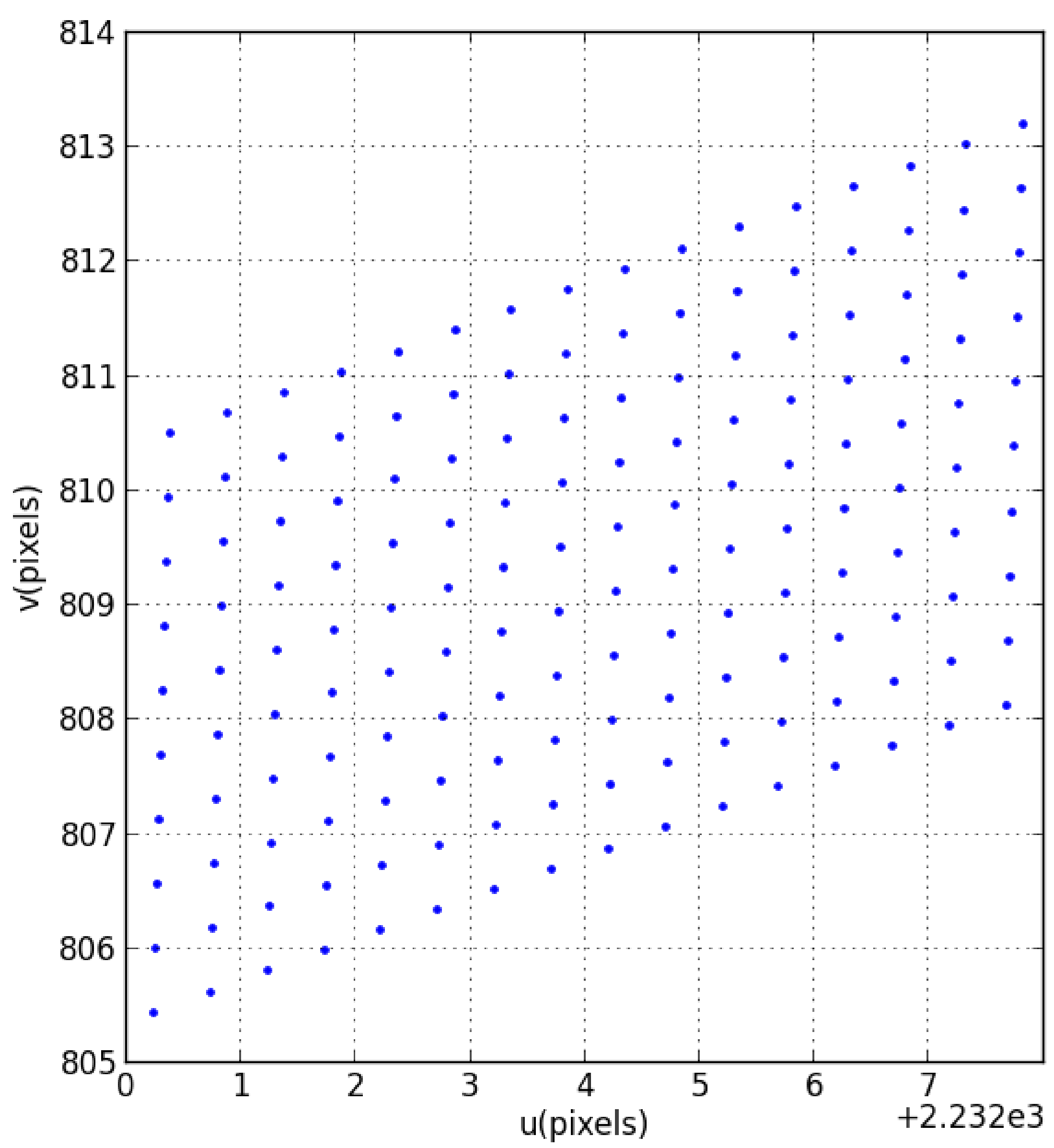
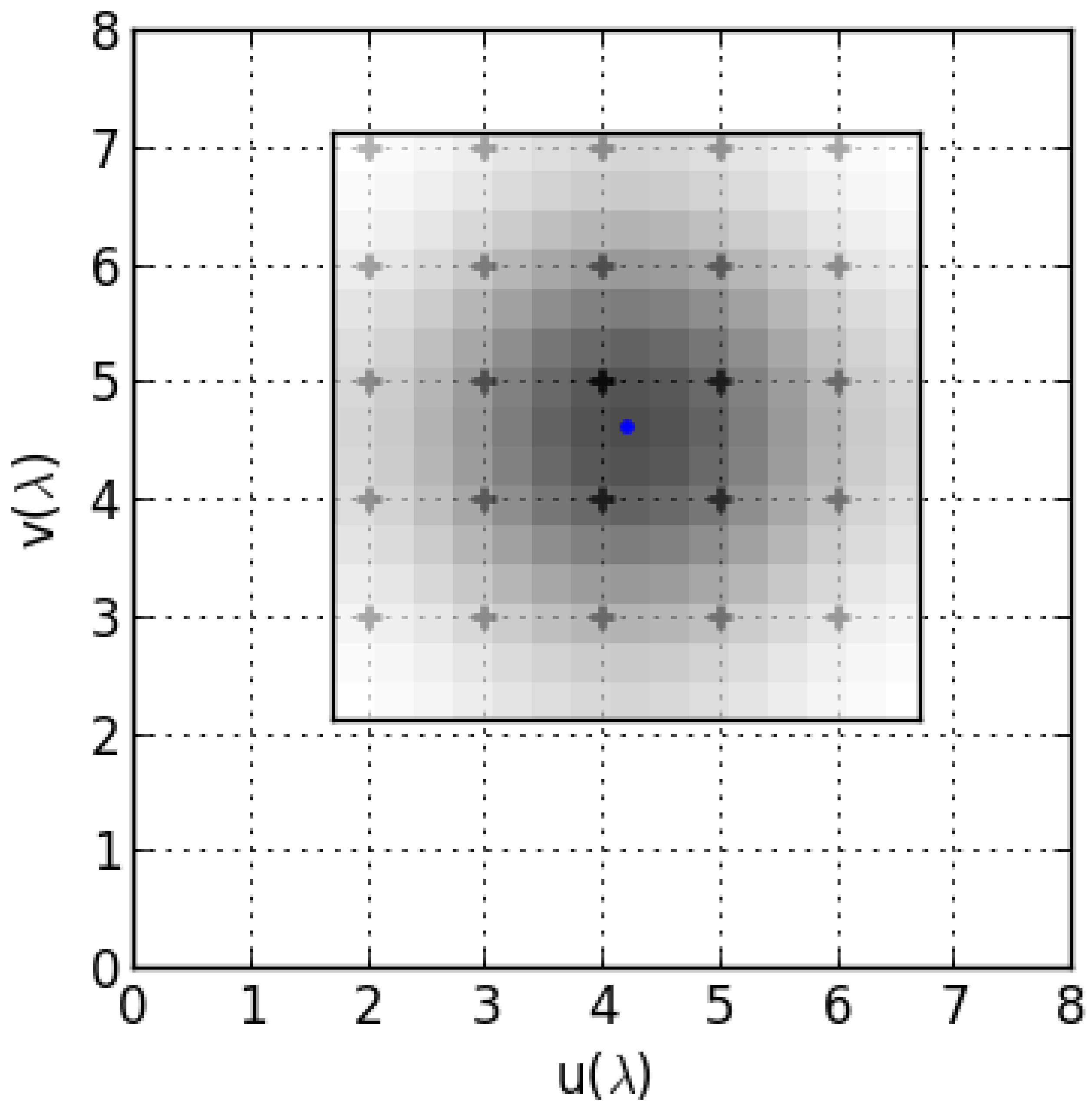
Convolutional resampling

- FFT needs data on regular grid





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Instrumental effects

- Convolution applies a multiplication in the image domain. The same convolution can be used for applying instrumental or atmospheric effects.

- Can become very expensive for fast varying effects.

$$y_{ijqr} = \iint_{lm} e^{-j2\pi\left(u_{ijr}l + v_{ijr}m + w_{ijr}n\right)/\lambda_q} g_{iqr}(l,m) g^*_{jqr}(l,m) I(l,m)\, dl\, dm$$

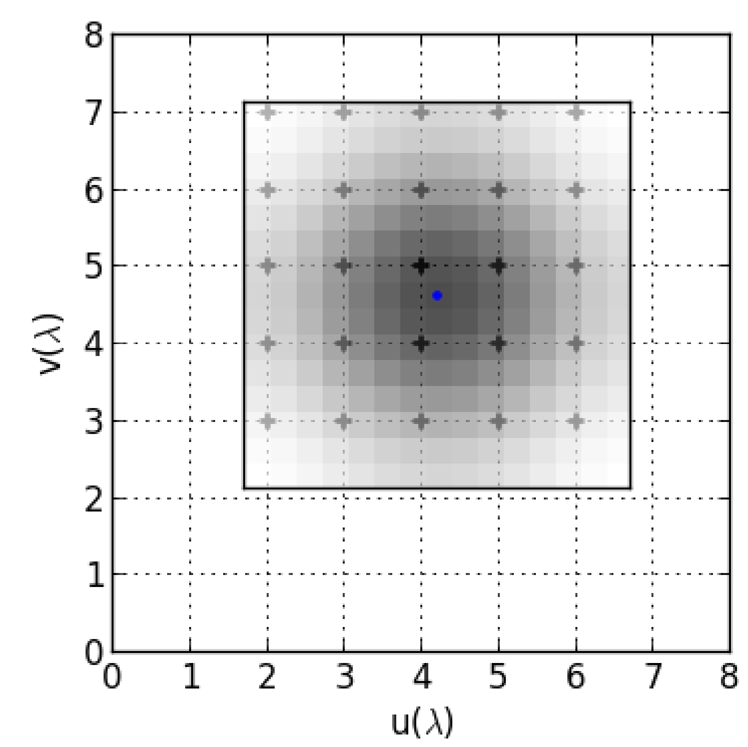

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Image domain gridding (IDG)

- Image domain gridding applies kernel in image domain. Needs going back and forth to image domain, costs a lot more computation.

- Operations in IDG are much more effective in memory, fit very well on GPUs.

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Image domain gridding: status

- Optimized implementations for many platforms (by Sebastiaan van der Tol & Bram Veenboer)
  - CPU: Intel Haswell, Xeon Phi
  - GPU: Nvidia & AMD
  - FPGA (ongoing)
- Integrated in wsclean (established imager), code available at https://gitlab.com/astron-idg/idg
- Algorithm published: A&A 616, A27 (2018)
- Implementation papers forthcoming.
- Shown working on LOFAR, MWA & ASKAP data.

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Calibration

- The *visibility* y for antennas i, j, channel q, time t given b

$$y_{ijqr} = \iint_{lm} e^{-j2\pi\left(u_{ijr}l + v_{ijr}m + w_{ijr}n\right)/\lambda_q} g_{iqr}(l,m)\, g^{*}_{jqr}(l,m)\, I(l,m)\, dl\, dm$$

- Direction independent calibration: $g_{iqr}(l,m) = g_{iqr}$
- Can be found from model visibilities.
- Risk: overfitting.

Direction-independent calibration

- Find $\hat{G} = \text{argmin}_G \|V - GMG^H\|^2_{\text{frob}}$.
  - V is a matrix of observed visibilities.
    V_{pq} is correlation between signal from station p and q.
  - M is a matrix of model visibilities.
  - $G = \text{diag}(g)$ is unknown matrix of gains, $g_p = e^{i \cdot \varphi_p}$

- G contains corrections for effects such as wrong cable lengths, drifting clocks, electronic gains, and delays due to the ionosphere.
- Challenge: parametrize G with few parameters.

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Calibration: stefcal (ADI)

- Goal: find $\hat{G} = \operatorname{argmin}_G \|V - G M G^H\|_{frob}^2$
- Idea:
  - Fix G, solve for G
  - Fix G, solve for G (same computation)
  - Average: $G^{(i)} = \frac{1}{2}(G + G)$
  - Iterate
- Given G, $G = \operatorname{diag}(g_p)$ simply $g_p^{\leftarrow} = \dfrac{(GM)_{:,p} \cdot V_{:,p}}{(GM)_{:,p} \cdot (GM)_{:,p}^H}$

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Constrained calibration

- Iterations in stefcal can be interleaved with constraining operations, that restrict solutions to satisfy e.g. a given frequency dependency (physical).
- Limits number of free parameters, overfitting.
- Still converges (if constraint is linear).

Calibration forms

Calibration: f nd $\{G_p\}$ to minimize

measured model

$$\| G_p V_{pq} G_q^H - M_{pq} \|$$

station p

G_p can be restricted to:

		# unknowns per station
• Full Jones	$G_p = \begin{pmatrix} A_{xx}^{(p)} e^{\varphi_{xx}^{(p)}} & A_{xy}^{(p)} e^{\varphi_{xy}^{(p)}} \\ A_{yx}^{(p)} e^{\varphi_{yx}^{(p)}} & A_{yy}^{(p)} e^{\varphi_{yy}^{(p)}} \end{pmatrix}$	8
• Diagonal	$G_p = \begin{pmatrix} A_{xx}^{(p)} e^{\varphi_{xx}^{(p)}} & 0 \\ 0 & A_{yy}^{(p)} e^{\varphi_{yy}^{(p)}} \end{pmatrix}$	4
• Phase only	$G_p = \begin{pmatrix} e^{\varphi_{xx}^{(p)}} & 0 \\ 0 & e^{\varphi_{yy}^{(p)}} \end{pmatrix}$	2
• Common phase	$G_p = \begin{pmatrix} e^{\varphi^{(p)}} & 0 \\ 0 & e^{\varphi^{(p)}} \end{pmatrix}$	1

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Calibration: status

- Stefcal extended to include direction dependent effects (Smirnov & Tasse 2015).
- Constrained calibration part of DPPP, joint work with André Offringa
  Diepen, G., & Dijkema, T.J. 2018, Astrophysics Source Code Library, ascl:1804.003
- Code available at https://github.com/lofar-astron/DP3
- Used in prefactor, the default LOFAR calibration pipeline.

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