Low Frequency Imaging Challenges

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Challenges

● Radio sky at low frequencies
  - Typically stronger, more complex
    • Deconvolution errors, Pixelation errors
  - Spectral index variations across the sky

● Direction dependent (DD) effects
  - Primary beam effects
    • Time and frequency dependent
    • Polarization response
  - Pointing errors
  - Long, non co-planar baselines (w-term)
  - Ionospheric phase screen
  - FPA calibration/stability

● Computing and I/O loads
Challenges

- **Strong RFI**
  - Some algorithms/schemes exist

- **Weak RFI**
  - Very difficult to detect and remove
  - Will/does affect high dynamic range imaging

- **Near field problems**
  - Remains correlated
  - Not the same at all baselines
  - Variable in time & frequency

- **Self Interference**
The Measurement Equation

- **Generic Measurement Equation:** [HBS papers]

\[
V_{ij}^{\text{Obs}}(\nu) = J_{ij}(\nu, t) W_{ij} \int J_{ij}^{S}(s, \nu, t) I(s, \nu) e^{\nu s.b_{ij}} ds
\]

- **Corruptions:**
  - Direction independent corruptions
  \[
  J_{ij} = J_{i} \otimes J_{j}^* 
  \]
  - Electronics
  \[
  J_{ij}^{s} = J_{i}^{s} \otimes J_{j}^{s*} 
  \]
  - Primary Beam errors, pointing errors,....

- **Sky:** Frequency dependent sky:

\[
I(s, \nu) = I(s, \nu_{o}) \left( \frac{\nu}{\nu_{o}} \right)^{\alpha}
\]

- **W-term:**

\[
e^{\nu s.b_{ij}} = e^{i[ul+vm+w(\sqrt{1-l^{2}-m^{2}}-1)]}
\]

: Not a FT kernel

(a.k.a. non co-planar array)
Pieces of the puzzle

- **Unknowns:**
  - $J_{ij}, J_{ij}^s$: Electronics, Primary Beams, Antenna pointing, ionosphere,...
  - $I^M$: Extended emission, spectral index variations, polarization,...

- **Need Efficient Algorithms:**
  - Correct for image plane effects
  - Decompose the sky in a more appropriate basis
    - Frequency sensitive (combine with MFS)
  - Solvers for the “unknown” direction dependent effects (pointing, PB shape, ionospheric effects,...)
    - As expensive as imaging!

- **Needs (Computing):**
  - Parallel computing & I/O
  - Scalable algorithms & software
Sky at low frequencies: Stronger/complex

- 1.4 GHz/VLA, 30 μJy/b @ 4"

(Data from: Fomolant et al.)
Sky at low frequencies: Stronger/complex

- 610MHz/GMRT 20μJy/b @ 4"
- Peak: 40mJy/b
- Errors are direction dependent
- Significant flux in the first sidelobe
- Limited by
  - PB errors
  - Pointing errors
  - Deconvolution errors

(Data from: Owen, et al.)
...sky more complex

- PB main lobe zoomed in
- Note:
  - Many resolved sources
  - Sky more filled
  - Errors are direction dependent
Sky at low frequencies: Frequency dependence

- Direction & Frequency Dependent errors
- Errors not coherent across frequency
  - Will affect spectral line signals (EoR)

More details in talks next week!
Primary Beam Effects

- EVLA full beam, full band, single feed

PB rotation, pointing errors

PB gain varies as a function of time, frequency and direction in the sky

Cross hand power pattern

PB variation across the band

EVLA: Sources move from main-lobe to side-lobes
PB errors: Full beam imaging limits

- Limits due to rotation of asymmetric PB
  - In-beam max. error @~10% point
  - DR of few $10^{3-4}$:1
  - Errors larger in the first sidelobe

- Limits due to antenna pointing errors
  - In-beam max. error at half-power points
  - DR of few $10^{3-4}$:1
  - Limits for mosaicking would be worse
    - Significant flux at half-power and side-lobes for many pointing
PB correction: A-Projection algorithm

- **Corrections in the visibility plane** (Bhatnagar, Cornwell, Kolap, Uson, A&A)
  \[ V_{ij}^{\text{Obs}} = E_{ij}(t) \ast \text{FFT}(I^M) \text{ where } E_{ij}(t) = E_i(t) \ast E_j^*(t) \]

- No assumption about the sky

- Scales well with image complexity

- Straightforward to integrate with algorithms that correct for other errors (MFS, W-Projection, MS-Clean, ASP-Clean).

× Requires a model for the PB

More details in talks next week!
Example: 1.4GHz/VLA, Stokes-I Imaging

Post-deconv. PB correction: Strong sources located at ~HP limit the dynamic range

PB correction during imaging: Limited by pointing errors? PB knowledge? (100μJy/b)

(Data from: Matthews & Uson)
During vs. Post deconvolution PB correction

- PB errors can easily limit imaging DR
- Errors are non-random
- Stable PB will be helpful
  - Dipole arrays vs. rigid structure
Extended Emission

- **Stokes-V imaging of extended emission**
  - Algorithms designed for point sources will not work
  - Need more sophisticated modeling of the extended emission
Antenna: Dipole arrays vs. Solid Steel

Simulation of LWA station beam @50MHz
(Masaya Kuniyoshi, UNM/AOC)

EVLA antenna PB rotation with Parallactic Angle

More details in talks next week!
Number of sources @ 1.4GHz

- Assuming max. PSF side-lobe at 1% level, need to deconvolve sources >100μJy to get RMS(1σ) = 1μJy/beam

- $10^{4-5}$ sources per deg$^2$ >10μJy @1.4GHz
  - Brighter at lower frequencies ($\alpha \sim -0.8$)
  - Source size distribution important at resolution < ~2"

- High precision, efficient algorithms for imaging required!
Pointing SelfCal: Example

Model image: 59 sources from NVSS.
Flux range ~2-200 mJy/beam

Red: Typical antenna pointing offsets for VLA as a function of time
Blue: Solved antenna pointing errors
Pointing SelfCal: Test performance

- No pointing correction:
  - RMS ~ 15μJy/b

- After pointing correction:
  - RMS ~ 1μJy/b

(Bhatnagar, Cornwell & Kolap, EVLA Memo #84/paper in prep.)
Imaging extended emission: Asp-Clean

- Pixel-to-pixel noise in the image is correlated

- *Keep the DoF in control!*
  - Sub-space discovery

  - Search for local scale, amplitude and position
Non coplanar baselines

- \( V(u, v, w) = G(u, v, w) \ast V(u, v, w = 0) \)

where \( G(l, m, w) = e^{2\pi i \left\{w/\sqrt{1-l^2-m^2}\right\}} \)

- \( E_1 = E'_1(u, v, w) \) propagated using Fresnel diffraction theory.

- Away from the phase center, sources are distorted

- Problem for long baselines
  - \( N = 2 \frac{B_{\text{max}}}{f D^2} \)
    - \( N \): No. of W-planes
    - \( B_{\text{max}} \): Max. Baseline
    - \( D \): Antenna diameter
    - \( f < 1.0 \) for high DR (\( \geq 10^4 \))
Confusion limit vs. resolution

- \( \sigma_{\text{confusion}} \propto \left( \nu^{-2.7}/B_{\text{max}}^2 \right) \)

- \( B_{\text{max}} \sim 100 \text{ Km at 200MHz for } \sigma_{\text{confusion}} \sim 1\mu\text{Jy/beam} \)

- \textbf{Challenges:}
  - \( W \)-term an issue for \( B_{\text{max}} > 2\text{-}3\text{Km} \) & \( DR > 10^4 \)
  - Ionospheric calibration: Even field based calibration fails for \( B_{\text{max}} > 3\text{Km} \)
W-projection algorithm: Scaling laws

W-projection: \[ (N_{wproj}^2 + N_{GCF}^2) N_{vis} \]

UV-facet: \[ N_{facets}^2 N_{GCF}^2 N_{vis} \]

(Cornwell, Kolap & Bhatnagar, paper submitted)
W-Projection: Example

- Coma cluster at 74 Mhz/VLA
- 30 arcsec resolution, RMS ~30mJy/beam
- Imaged using the W-projection algorithm (Golap)
Ionospheric phase screen

- Ionospheric phase varies across the FoV
- For short baselines (1-3Km) at 74MHz/VLA, field based calibration helps (Cotton et al. 2004)
  - Corrects of phase gradients only
- De-focusing significant at baselines >3Km.
  - No known algorithm for this
  - Solutions will probably be computationally expensive
- Imaging DR limits not reliably known
  - Simulation work with realistic ionosphere in progress

Non-isoplantic ionospheric effects (by Cotton).
Note: Differential source wandering + de-focusing.
Ionosphere: Field Based Calibration

- Find shifts of strong sources from snapshot images
- Fit 2\(^{nd}\) order Zernike polynomials to get phase screen model
- Correct for the phase screen during imaging
  - De-focusing not handled
  - Limited to snapshot imaging sensitivity \textit{(Cohen et al., AJ, 2007)}
Computing & I/O costs

• Higher sensitivity ==> more data + correction of more error terms
  – Needs more sophisticated parameterization
  – Significant increase in computing and I/O loads

• Imaging:
  – Correction for PB variations, Pointing errors, ionosphere
  – Better modeling of extended emission

• Calibration: solve for direction dependent effects
  – As expensive as imaging
  – PB shape, pointing, ionosphere

• Processing cost dominated by forward and backward transforms (gridding)
  – I/O time comparable to computing time
Development challenges

- **Software development costs will be significant**
  - Need (many) more, highly skilled FTEs

- **Investment in research**
  - Basic algorithms research
  - Development of scalable algorithms
    - Scaling with computing & DR

- **Software**
  - Design and implement scalable software (non trivial)
  - Large teams in space-time

- **Management**
  - Expect attrition: Design and implement accordingly
  - Attract new talent: Algorithms & software development mainstream RA!
Summary

- Improvements in algorithms for imaging & calibration required for high dynamic range
- High DR ==> longer baselines ==> challenges
- Many effects are direction dependent
  - Need efficient algorithms which correct for these
- Good progress in some areas
  - W-Projection (W-stacking), A-Projection, Pointing selfcal, MS-Clean/Asp-Clean, Wide field imaging, Ionosphere
- Need “system” integration and tests
- Ionospheric calibration and correction at high resolution/DR a difficult, largely unsolved problem (some works in progress)
- Need to change how we work (software development)
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Yes We Can! Message of Hope (Obama et al. 2008; www.barakobama.org)