EVLA Status & Algorithms R&D

CALIM 2011, Manchester, U.K.

S. Bhatnagar, NRAO

EVLA: The Expanded VLA

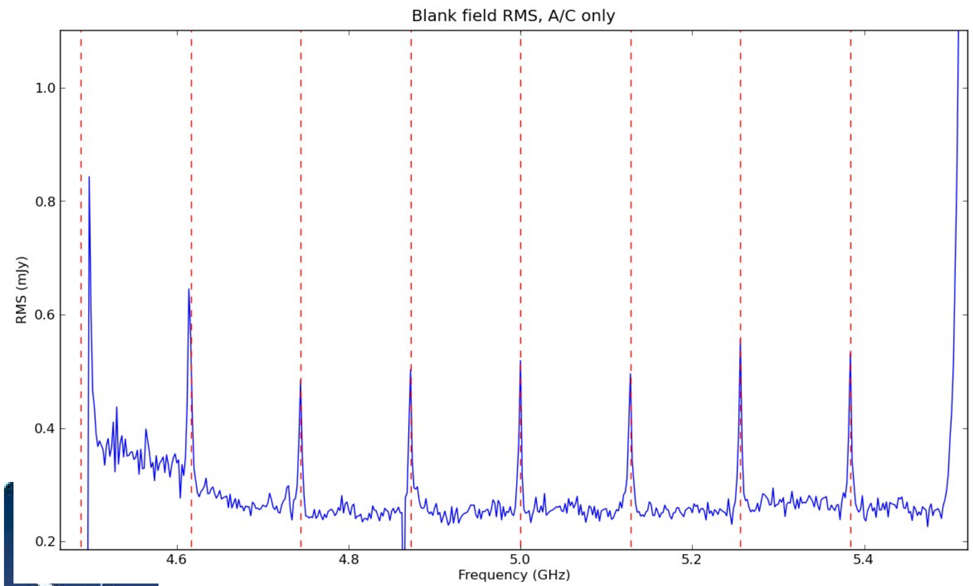
- From an observational point of view, expansion in three major areas
  - Seamless frequency coverage from 1 to 50 GHz
  - Instantaneous 2:1 band width ratio

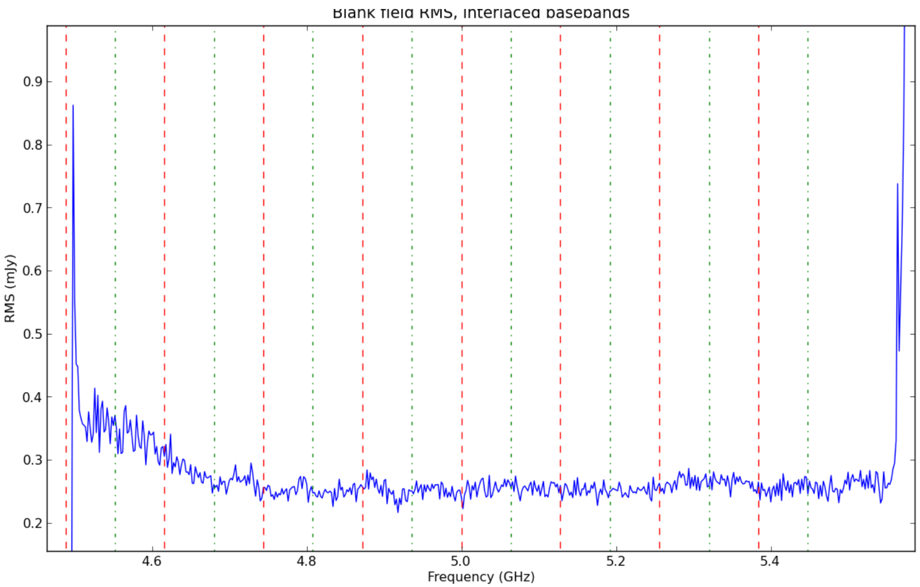
		EVLA/Interim Antennas
L-Band:	1 – 2 GHz	16/27
S-Band:	2 – 4 GHz	16/16
C-Band:	4 – 8 GHz	27/27
X-Band:	8 – 12 GHz	7/27
Ku-Band:	12 – 18 GHz	11/11
K-Band:	18 – 26.5 GHz	27/27
Ka-Band:	26.5 – 40.0 GHz	27/27
Q-Band:	40 – 50 GHz	27/27

    – Point source sensitivity (1h integration) between 1 – 6 microJy (band dependent)
    – 74/327 MHz system under test (not yet available)
  - WIDAR Correlator capabilities (high time and frequency resolution)
    – 64 independently tunable sub-bands each with full polarization capability
    – Up to 4,194,304 channels, providing frequency resolution between 1 MHz – 0.2 Hz
    – Time resolution: Possible: 0.5 millisec, currently allowed: 1 sec.

EVLA Current Capabilities

- Observing in two modes:
  - OSRO: Open Shared Risk Observing
    - https://science.nrao.edu/facilities/evla/early-science/osro
    - Two independently tunable base bands, each with 8 sub-bands each of width 128-0.03125 MHz in factors of 2
      - Total maximum band width: 2 GHz
    - Full-, dual, single-polarization modes
      - Total number of channels and channel widths scale with number of pol. Products
    - Overlapping sub-bands possible





EVLA Current Capabilities

- RSRO: Resident Shared Risk Observing
  - https://science.nrao.edu/facilities/evla/early-science/rsro
  - Early access to the growing capabilities of the EVLA as it is being commissioned, in exchange for a period of residence in Socorro to assist with the commissioning

Dates	Array config.	Max. total bandwidth per poln.	No. sub band pairs	Channels per sub band pair (4 poln products)	Max allowed data rate	Cumulative Capabilities
2010 Mar - 2010 Sep	D	2 GHz (8-bit samplers)	16	64	15 MB/s	- Sub-bands identical - Sub-bands indep. tunable with restrictions - Can trade polarization products for channels
2010 Oct - 2011 Jan	C	2 GHz	**more than 16**	64	15 MB/s	- Can trade sub-bands for channels
2011 Feb - 2011 Apr	B	2 GHz	**64**	64	15 MB/s	- 64 Sub-band pairs available
2011 May - 2011 Aug	A	2 GHz	64	**up to 16,384**	**25MB/s**	- Recirculation enabled - Fewer restrictions on Sub-band tuning - N_chan * N_pol restricted by max data rate
2011 Sep - 2011 Dec	D	2 GHz	64	up to 16,384	25 MB/s	- Sub-bands can be independently tuned
2012 Jan - 2012 Apr	C	2 GHz	64	up to 16,384	**50 MB/s**	- Sub-bands may have different BW & N_chan
2012 May - 2013 Jan	B, A	**2/8 GHz (3-bit or 8-bit samplers)**	64	up to 16,384	**75 MB/s**	- Basebands either 1 GHz or 4 GHz BW

EVLA Current Capabilities

- RSRO: Resident Shared Risk Observing
  - Modes driven by RSRO science proposals and availability of expert users for commissioning

(Even) more flexibility in the allocation of correlator resources	**Multiple subarrays**
Phased array and single-dish VLBI	**Solar mode**
Planetary mode	**Burst mode**
Radar mode	**Pulsar binning**
On-the-fly mosiacing	**7-bit correlation**
Fast switching between correlator set-ups	**Very fast dumps**
Mixing of 3-bit and 8-bit samplers	**More processing by the correlator back-end**
Enable more channels for single-polarization observations	**Online RFI flagging**
Multiple phase/delay tracking centers	**Output to user instruments**

EVLA Current Capabilities

- The telescope is still under construction
  - Completion by end of 2012
- All 27 antennas are available
  - Some receivers in 'interim' mode (old OMTs, new receivers)

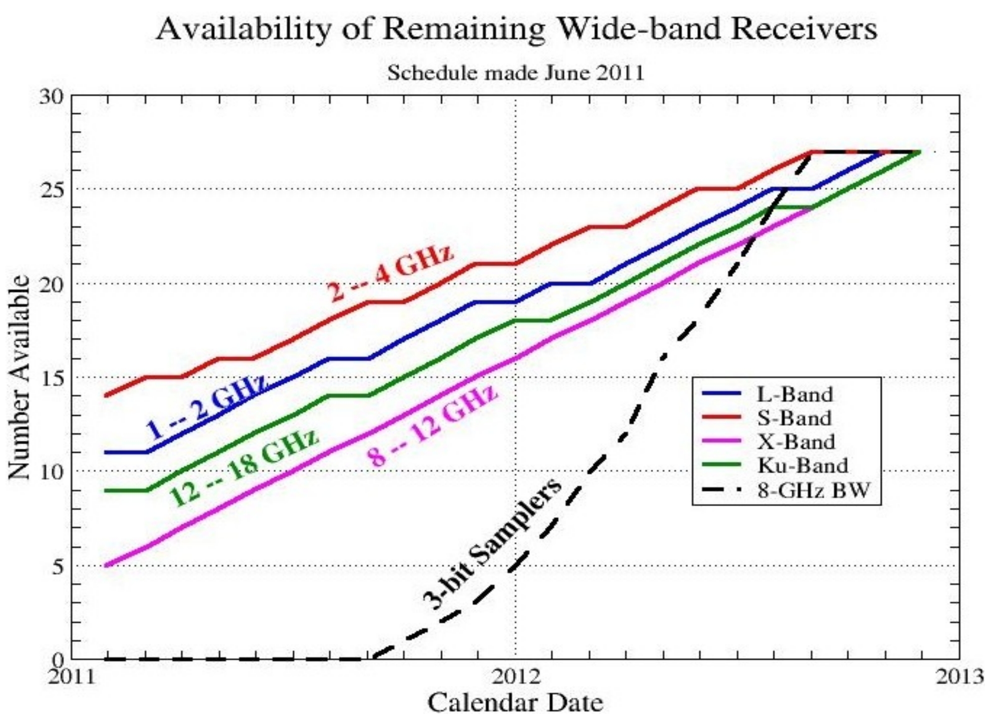


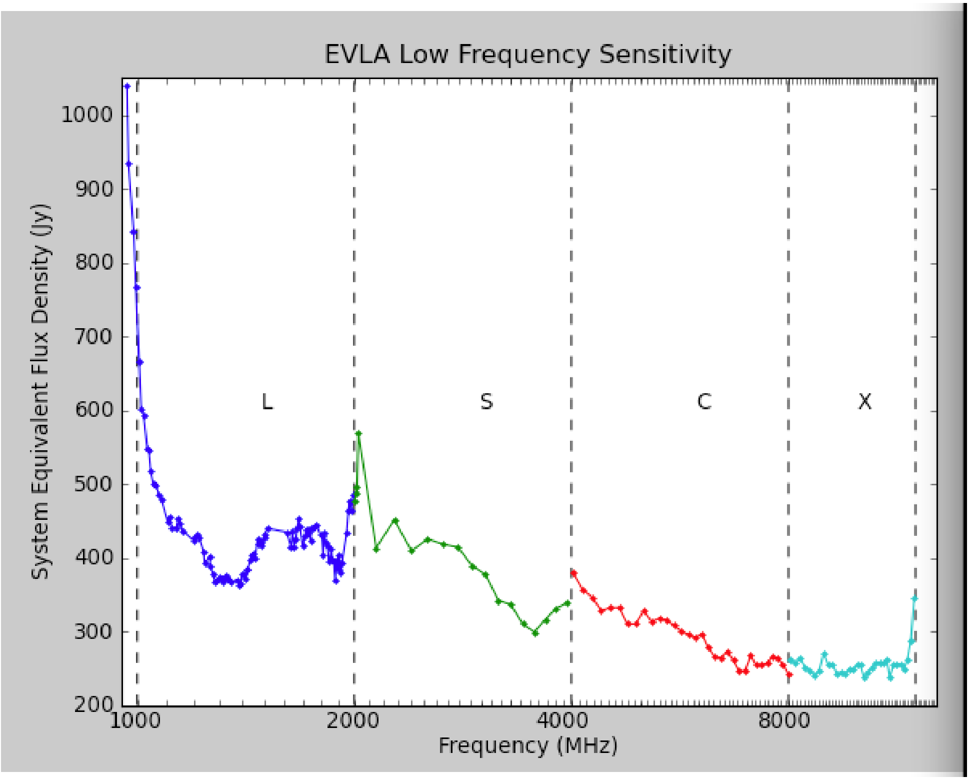
Table 1: Correlator capabilities per sub-band for full-polarization

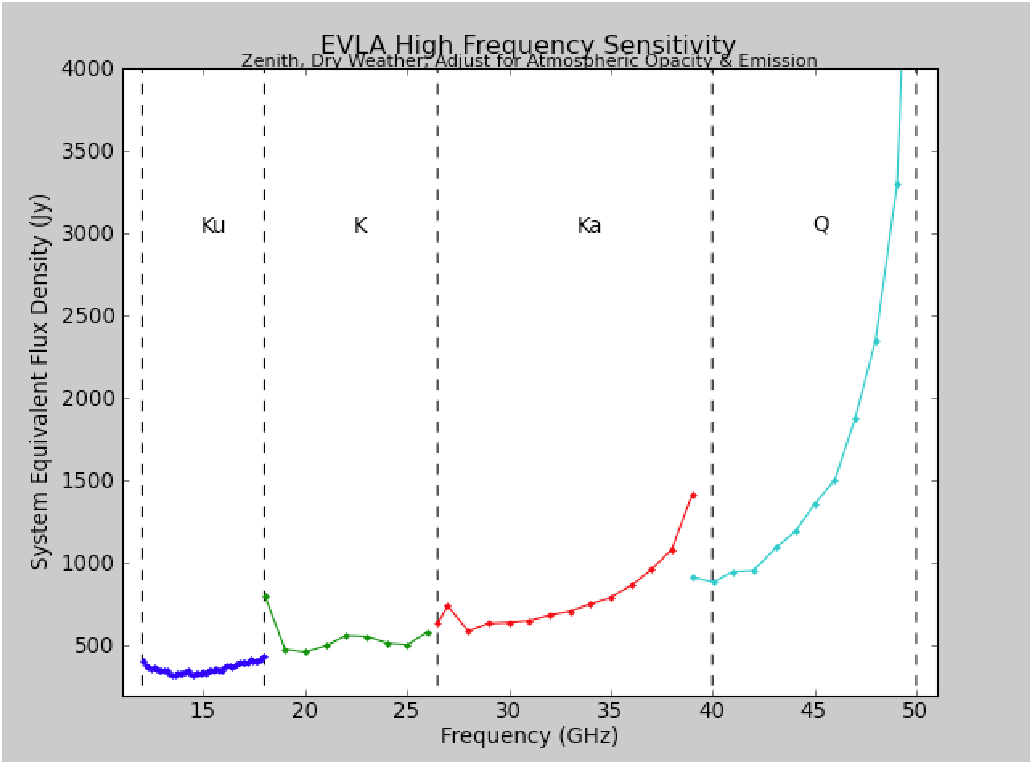
Sub-band BW (MHz)	Number of channels/poln product	Channel width (kHz)	Channel width (km/s at 1 GHz)	Total velocity coverage per sub-band (km/s at 1 GHz)
128	64	2000	600/ν(GHz)	38,400/ν(GHz)
64	64	1000	300	19,200
32	64	500	150	9,600
16	64	250	75	4,800
8	64	125	37.5	2,400
4	64	62.5	19	1,200
2	64	31.25	9.4	600
1	64	15.625	4.7	300
0.5	64	7.813	2.3	150
0.25	64	3.906	1.2	75
0.125	64	1.953	0.59	37.5
0.0625	64	0.977	0.29	18.75
0.03125	64	0.488	0.15	9.375

Wide band Sensitivity

- Sensitivity

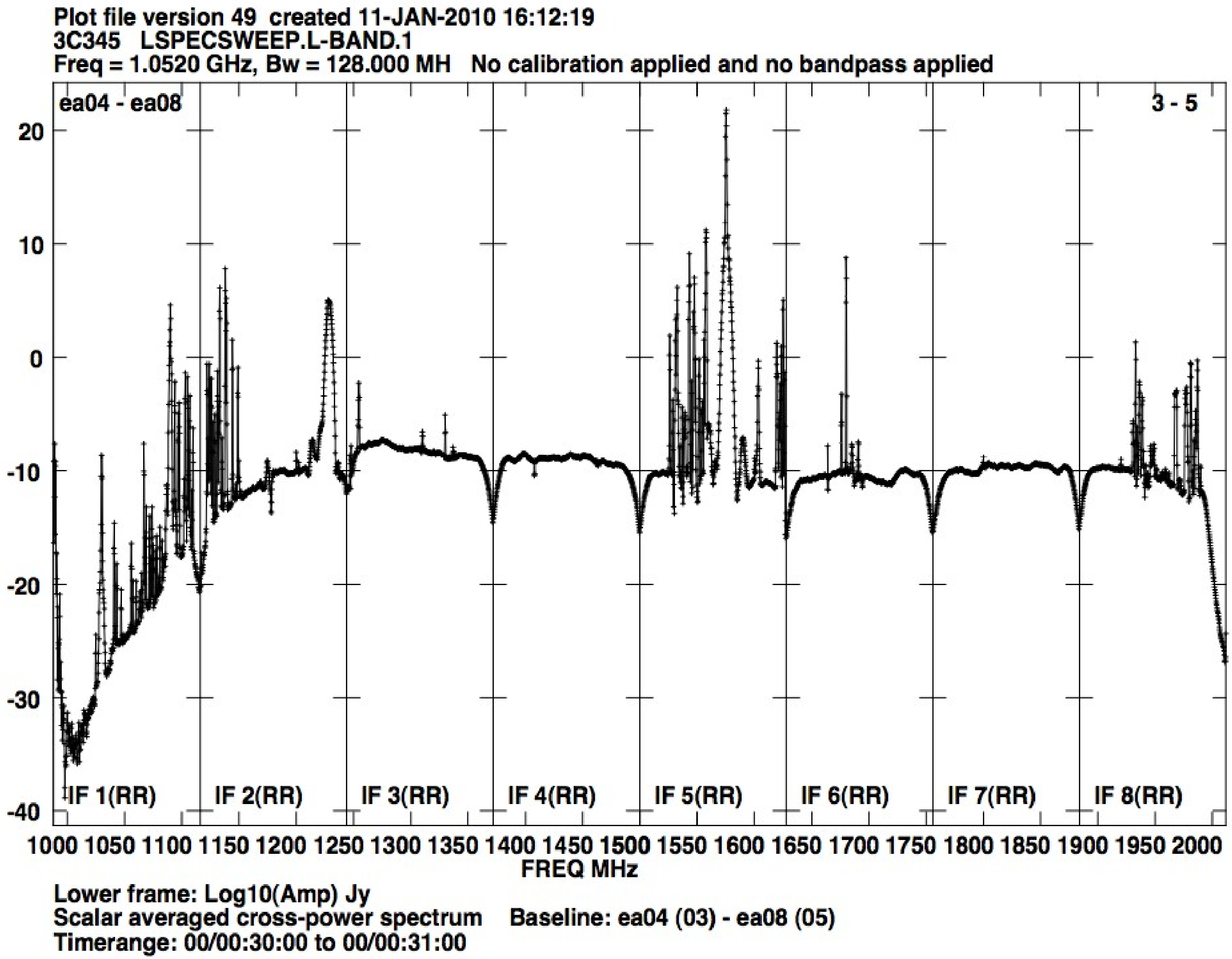
$$\frac{SEFD}{\eta_c \sqrt{n_{pol} N_a (N_a - 1) \tau\, BW}} = \frac{5.62\, T_{sys}}{\eta_a \eta_c \sqrt{n_{pol} N_a (N_a - 1) \tau\, BW}}$$





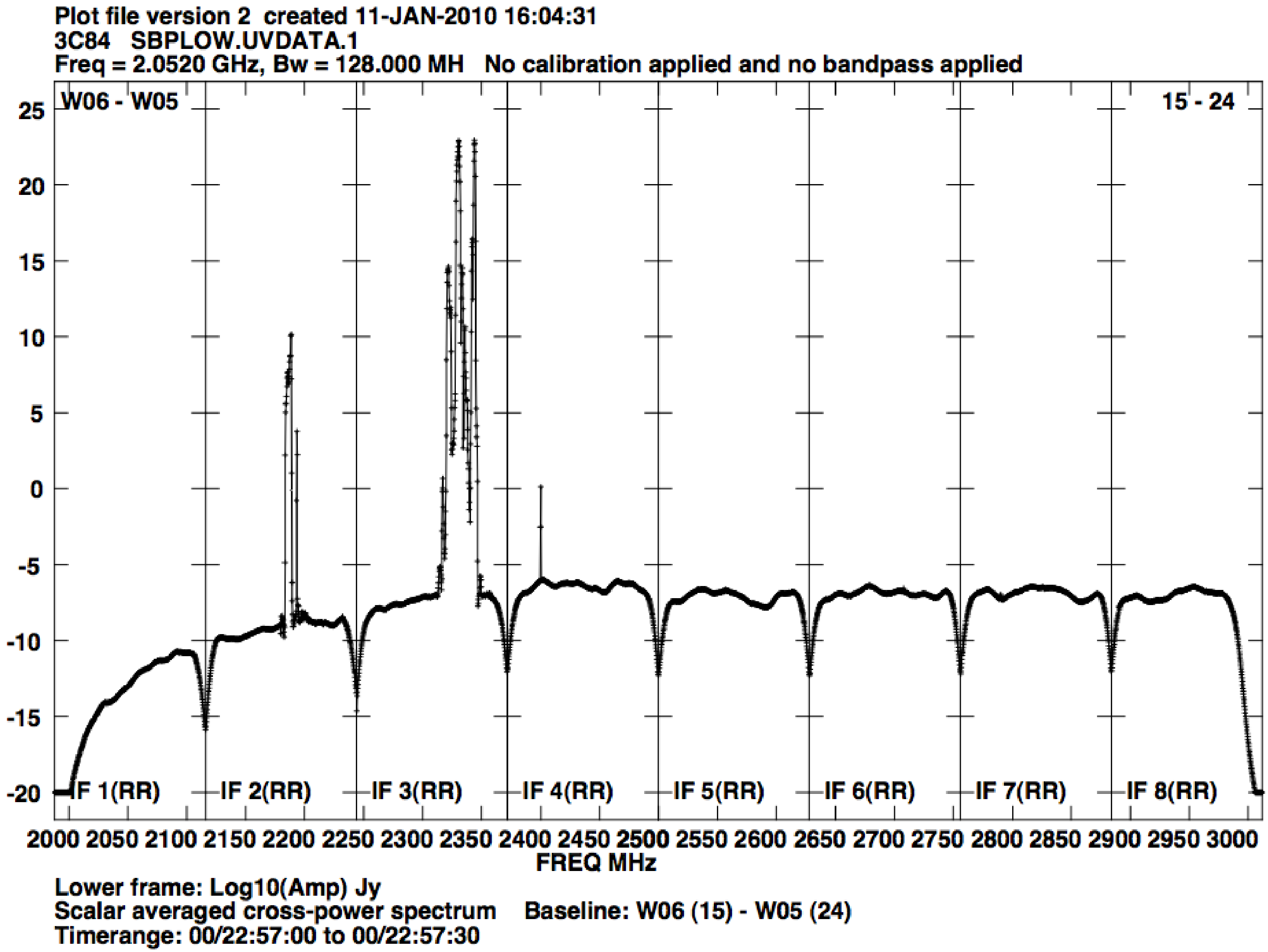
Wide band RFI

- L-Band Sweep



Wide band RFI

- S-Band Sweep



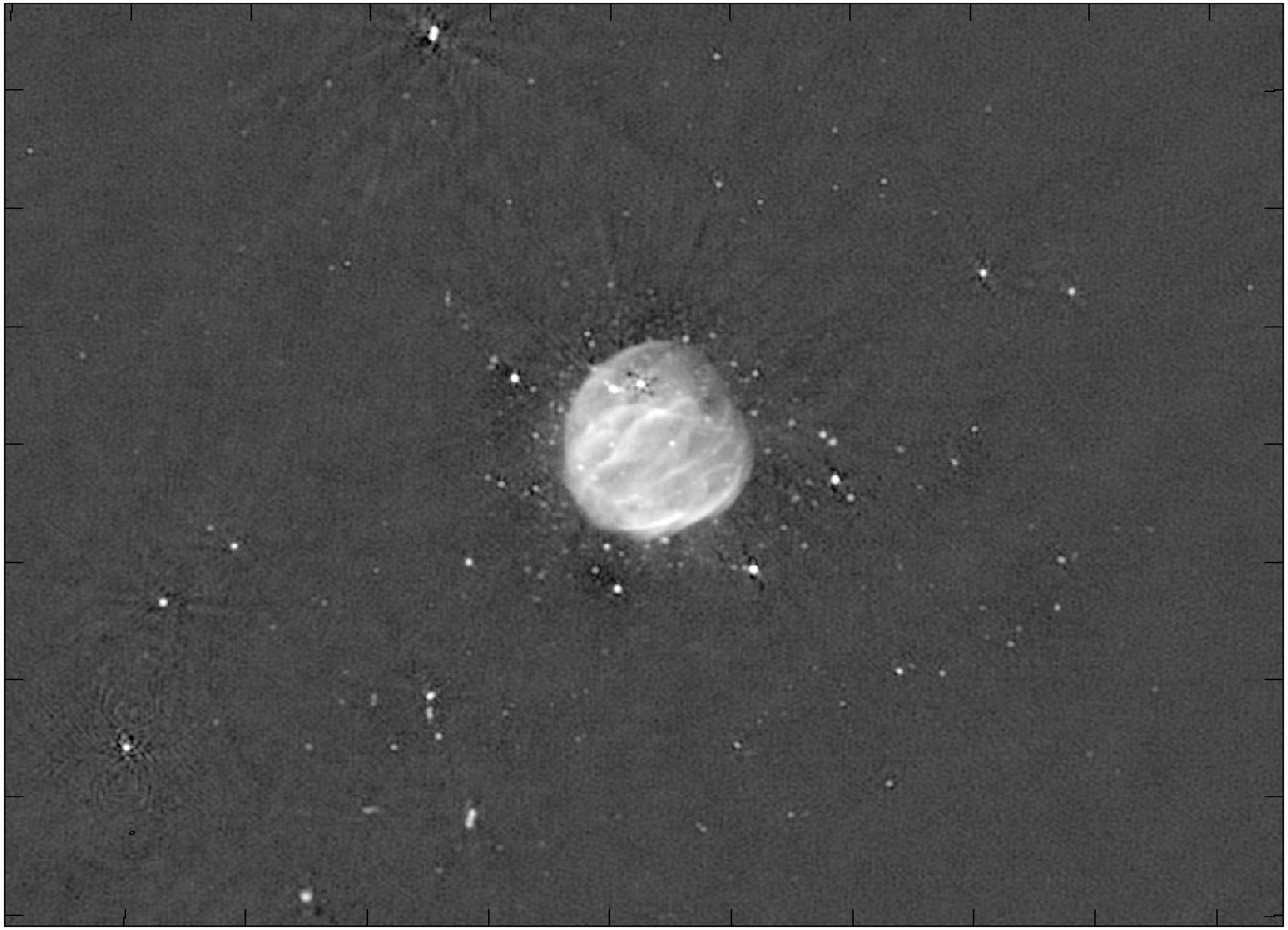
Early Science Results

- Wide-band imaging
    - Also need wide-field imaging
    - Array is non-coplanar in all configurations at low frequencies

- **L-Band using BW ~ 400MHz**
- **D-array**
- **4 hr. synthesis**
- **~2x2 deg. FoV**
- **RMS noise ~10 microJy/b**

- **RSRO Project AB1345**
    - **Pilot GP Survey**
    - **Spectral Index mapping**

  (ApJL EVLA Special Issue, Bhatnagar, Rau, Green & Rupen, in press)



Early Science Results

- Check out the ApJL EVLA Special Issue – ~Sept. 2011

- Results include
  - Wide-band continuum and spectral index mapping capabilities
  - Wide-band polarimetric imaging
  - Simultaneous multiple spectral line observations
  - Deep imaging of simple fields
  - Demo-science: L-Band Mosaicking

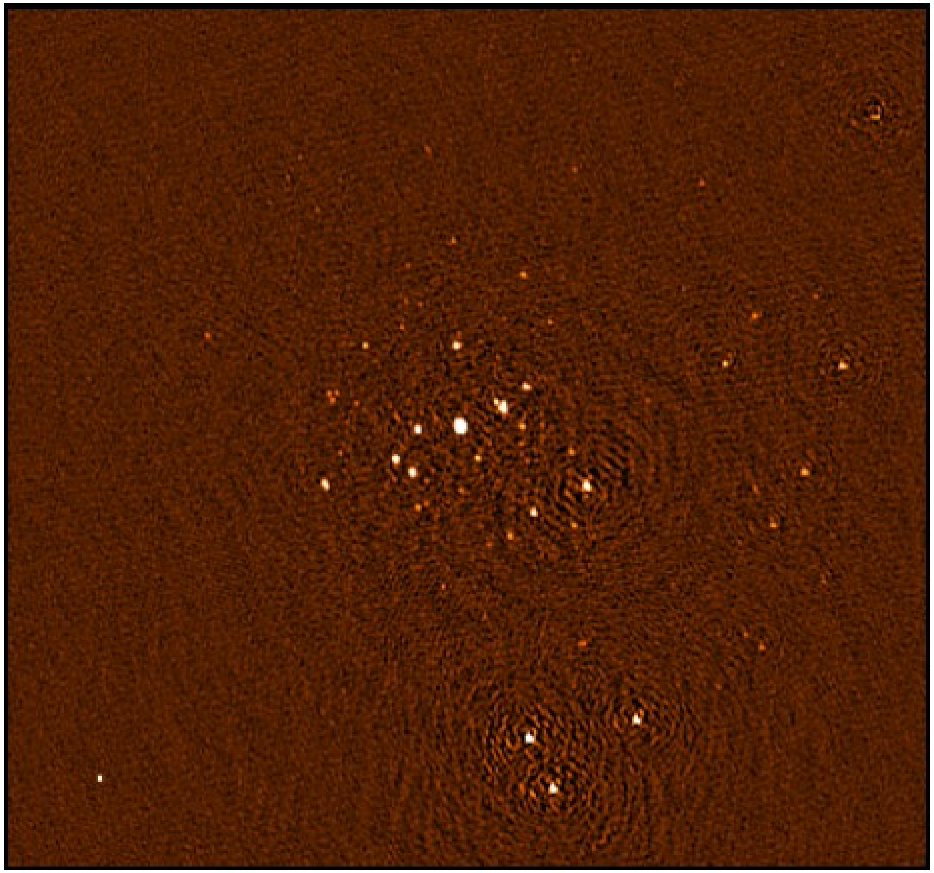
- All project details, capabilities and Early Science related info. Available from
  - https://science.nrao.edu/facilities/evla

Algorithms R&D drivers

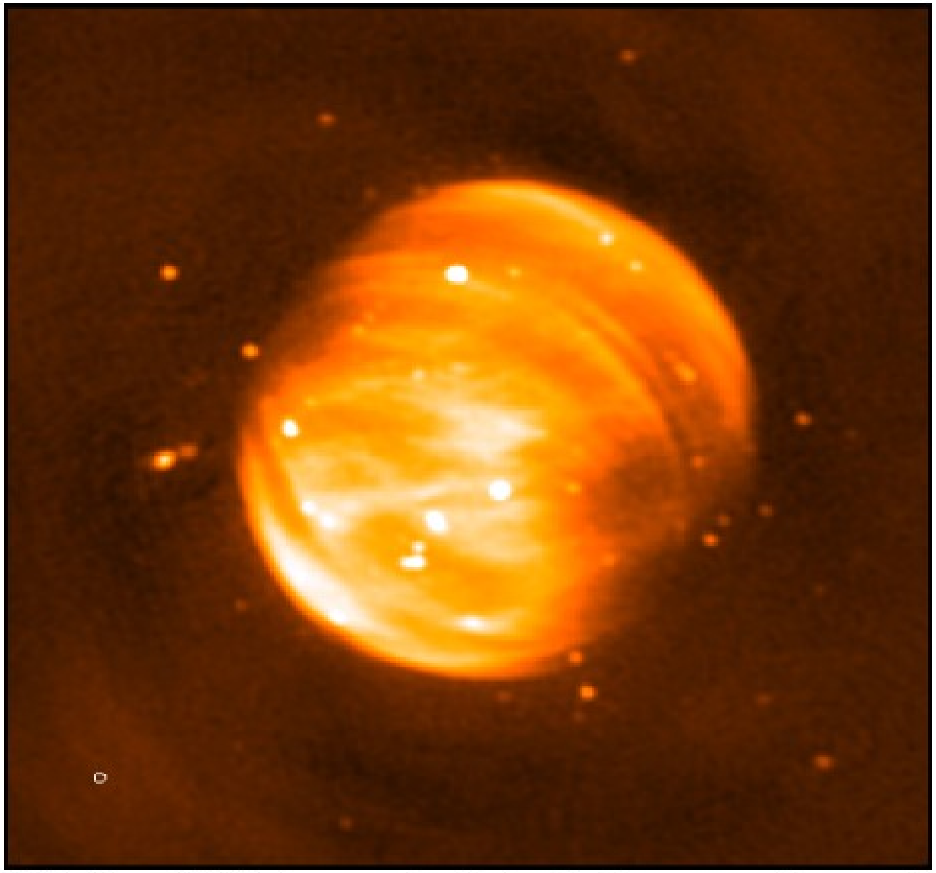
- The “highest nails”
  - Wide-band wide-field imaging (even single pointing with EVLA)
    - Instantaneous 2:1 band-width ratio of the EVLA (wide-band imaging)
  - Heterogeneous array – ALMA
    - Three different kind of antennas
  - WIDAR correlator capabilities – high time and frequency resolution
    - Large data volume to realize full scientific potential

- Algorithms for post-processing
  - For W-Term, PB effects and sky spectral index variations
    - Simultaneously for wide-band full polarization case
    - All of the above to work in mosaic-imaging mode too
  - For in-beam instrumental polarization correction
  - RFI flagging
  - Pipeline processing using all of the above on HPC platforms

Range of imaging challenges



Deep EVLA Image of the 3C147 field in the 1-GHz band



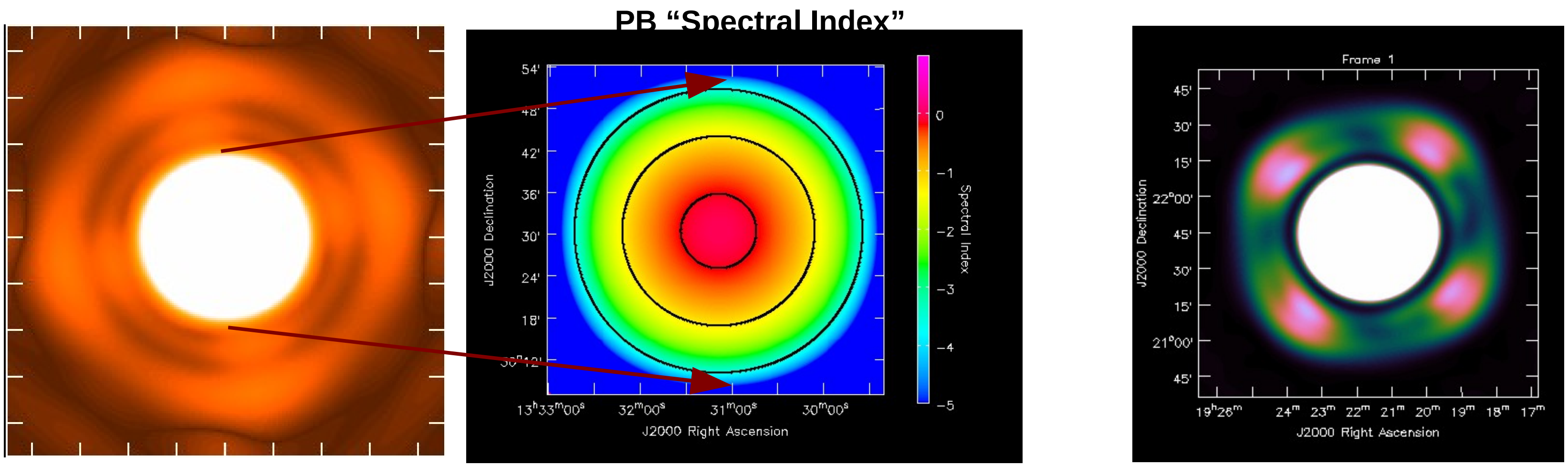
Wide-band EVLA image of a Galactic Supernova Remnant

- Relatively "narrow band width" (~128 MHz; OSRO mode, old data)
- Dynamic range: 900,000: 1

Wide-band Issues

- $I_{Continuum} = \int I_o PB(\nu)(\nu/\nu_o)^{\alpha(\nu)} d\nu\, dt = \int I_o (\nu/\nu_o)^{\alpha_{pb}(\nu,t)+\alpha(\nu)} d\nu\, dt$

- PB “spectral index” due to frequency dependence of the PB
  - Varies with time for rotationally asymmetric PBs



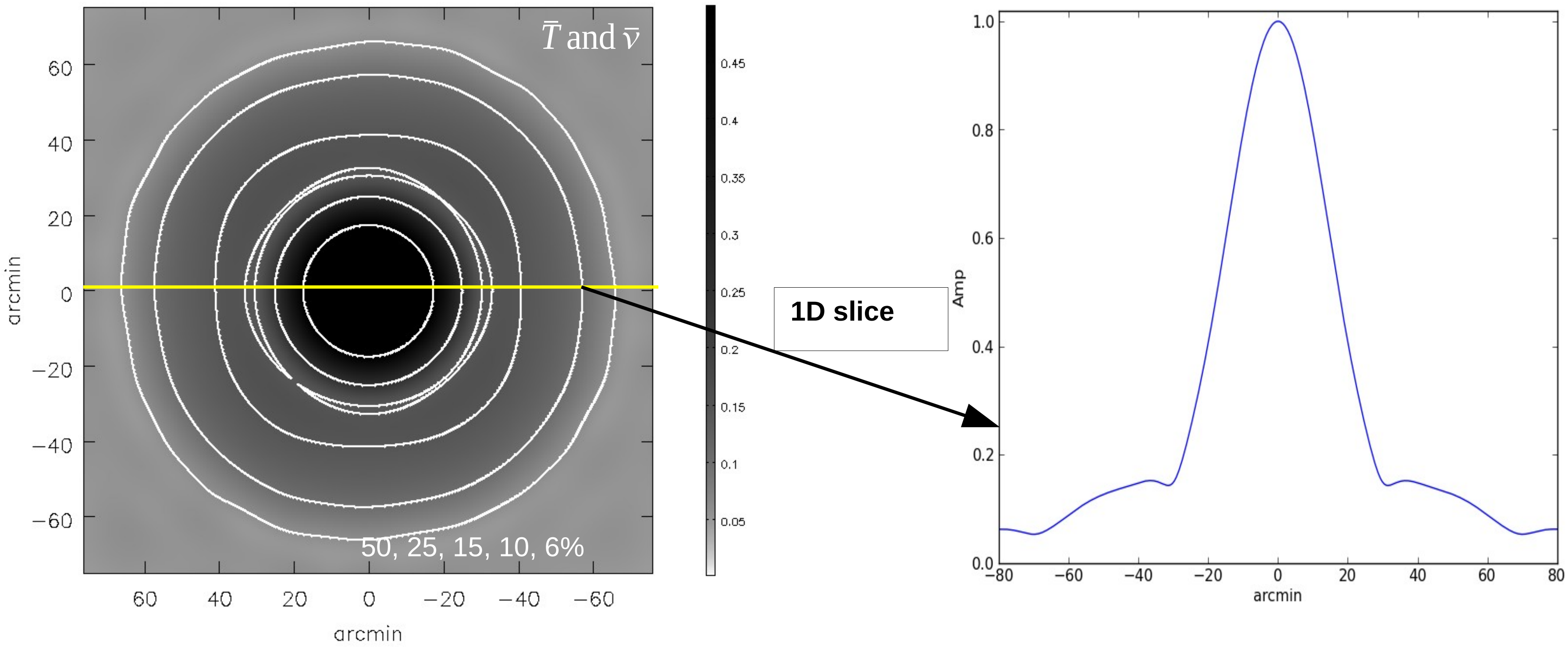
- Sky spectral index varies with direction
  - Varies with frequency over EVLA bandwidths

Wide-field Issues

- Large bandwidth provides high instantaneous sensitivity

$$\propto \frac{T_{sys}}{\sqrt{T_{\mathrm{Int}} \Delta \nu}} \qquad \Delta \nu = 1-2 GHz \qquad (\text{up to 8 GHz for wide-band imaging})$$

- For the same integration time, EVLA is sensitive to emission farther out



Wide-field Imaging: Scientific motivation

- Noise limited imaging: At the center of the field requires wide-field imaging
  - Noise contribution from a 1-Jy source, 1 deg away: 100-20x $RMS_{Thermal}$
- Survey Speed: In the EVLA sensitivity pattern, the VLA-sensitivity is achieved at the point of VLA-null!

Telescope	BW (MHz)	FoV (deg^2)	D (m)	N	Eff.	T_{sys} (K)	Survey Speed
EVLA+	512*	0.5*	25	27	0.5	26	1.0
ASKAP	300	30	12	36	0.8(!)	50	2.3
MeerKAT	512	1.0	13.5	64	0.7	30	1.4

+ All numbers from measurements/experience with real data
*** Conservative limits**

$$FoM : FoV\ BW \left(\frac{A_{eff}}{T_{sys}} \right)^2$$

Real difference is time commitment, not capability.
- D. Frail

Data volume

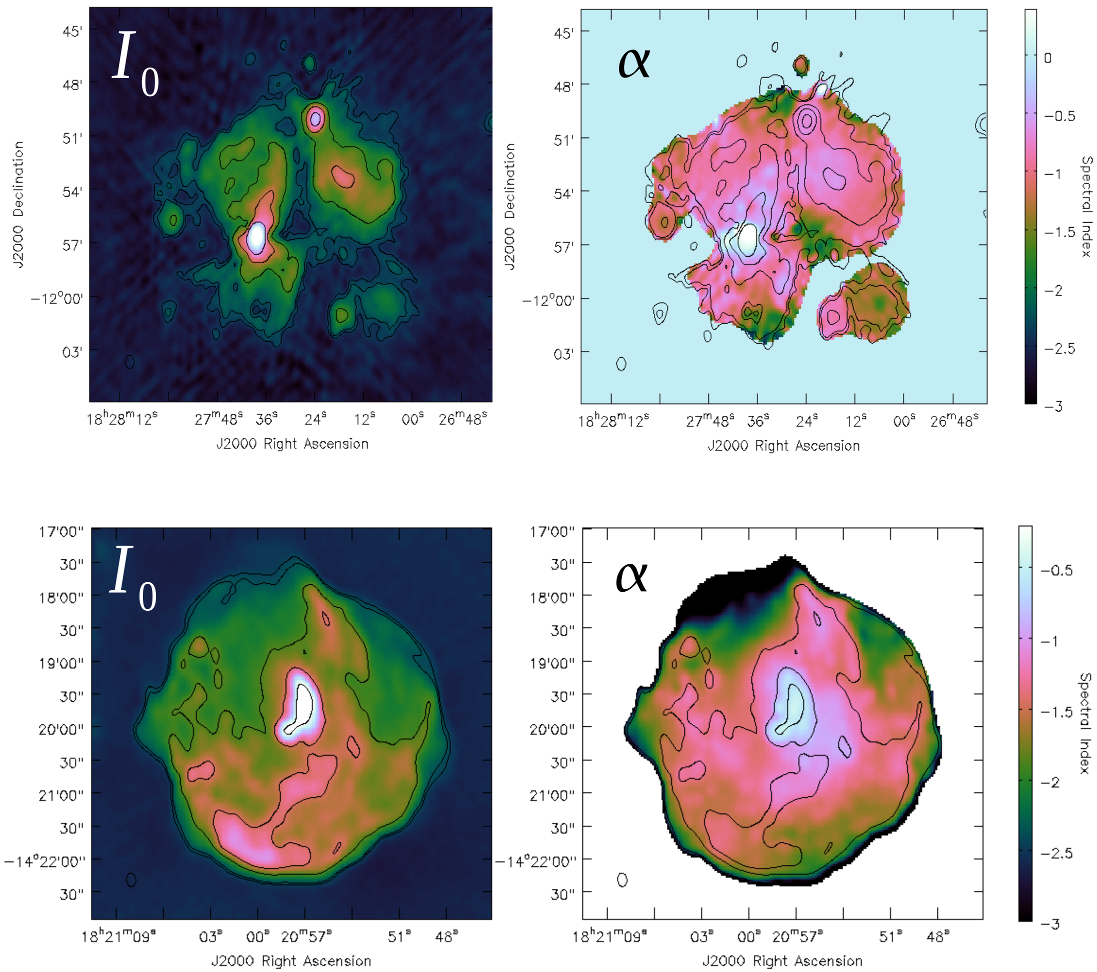
- Bandwidth smearing limit for continuum imaging

$$\Delta \nu = \frac{\nu_o \eta D}{N_{PBSidelobes} B_{max}}$$

- Required channel width $\Delta \nu = 1\,MHz$
- No. of channels needed ~ 1000 (BW: 1 GHz)
- Integration time = 1-5 sec due to RFI and time-smearing limits
- Bottom line
  - Large data volume is an inevitable consequence of improved sensitivity
  - More computing cycles using large data is also an inevitable consequence of increased instantaneous sensitivity

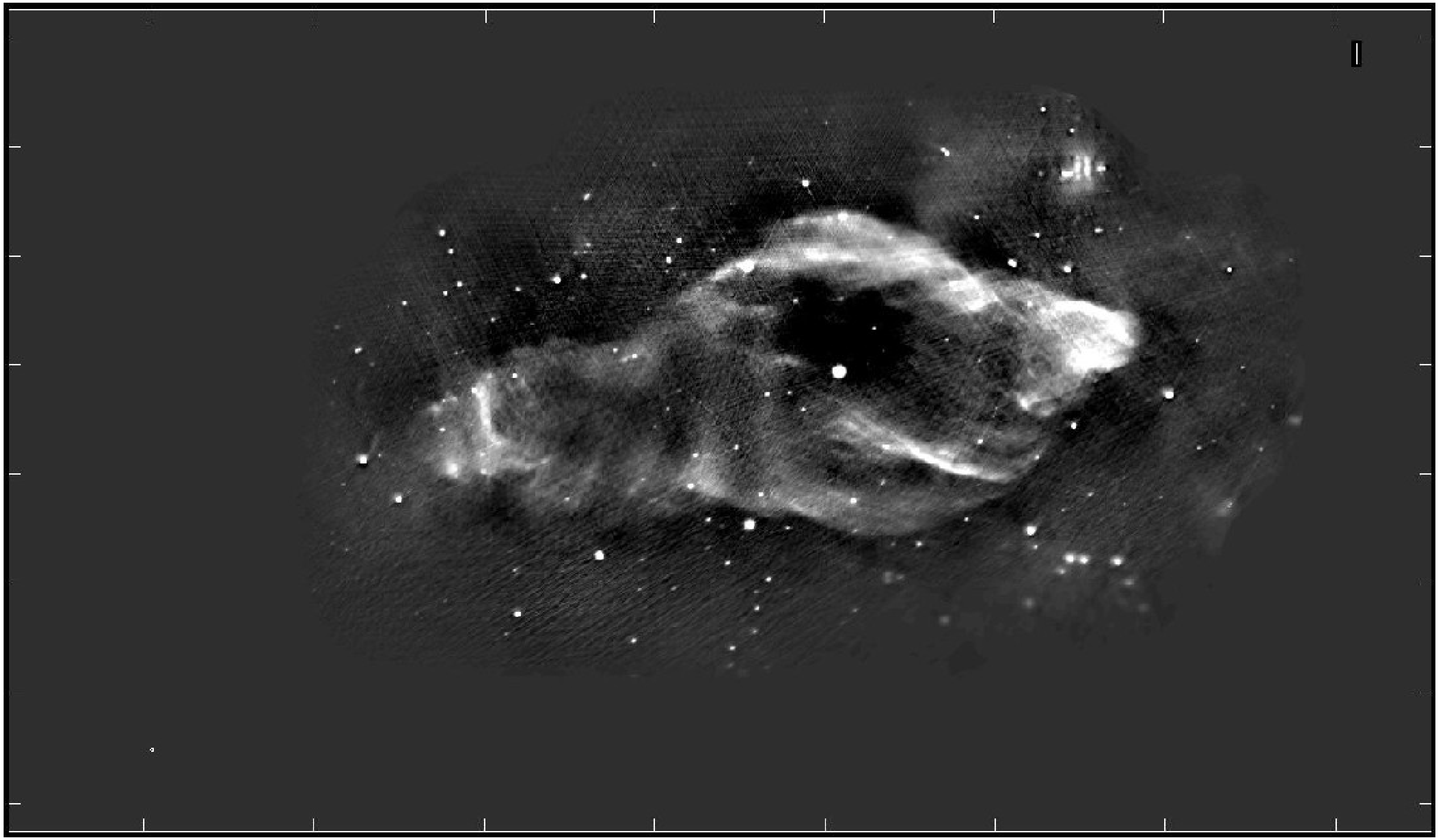
Algorithms: Status

- Wide-band imaging using Multi-term MFS released in CASA
  (Rau&Cornwell, A&A, 2011)



Algorithms: Status

- Mosaicking: Demo-science observations of W50 field @ L-Band
  - Image courtesy: K. Golap et al.
  - Work in progress: More data coming



Algorithms: Work in progress

- Strong overlap between EVLA, ALMA, MeerKAT. LOFAR is the union of all these!

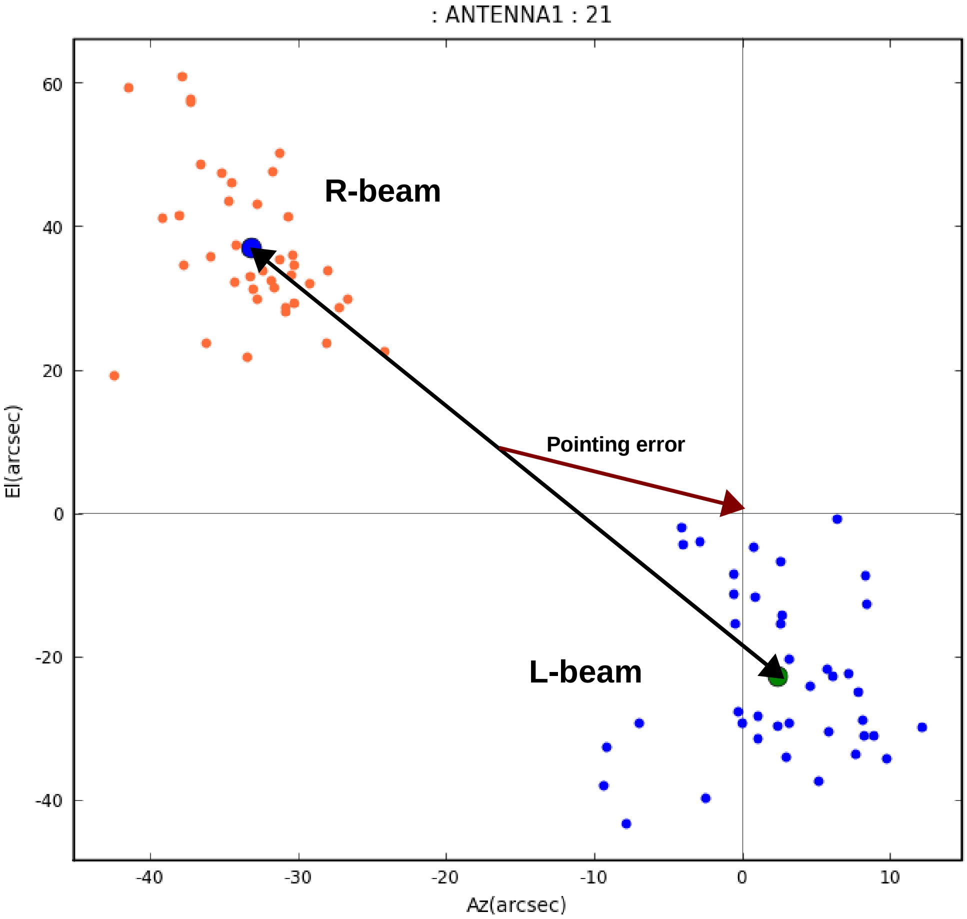
$$\begin{bmatrix} V^o_{pp} \\ V^o_{pq} \\ V^o_{qp} \\ V^o_{qq} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} V_{pp} \\ V_{pq} \\ V_{qp} \\ V_{qq} \end{bmatrix}$$

- Software framework for the general problem: wide-band, full-pol. Imaging with DD-corrections
  - Collaboration with LOFAR and MeerKAT teams
  - Integrating MT-MFS with wide-field imaging algorithms
  - Integrating with DD-solvers
  - Initial tests with data from EVLA (soon from ALMA)

- Eventually release as a scientific library of “standard” RA algorithms
  - Share-n-enjoy!

Algorithms: DD-solvers

- EVLA antenna pointing errors using wide-band data
- Demonstrates optimal use of available SNR
- Combining PB measurements + solvers

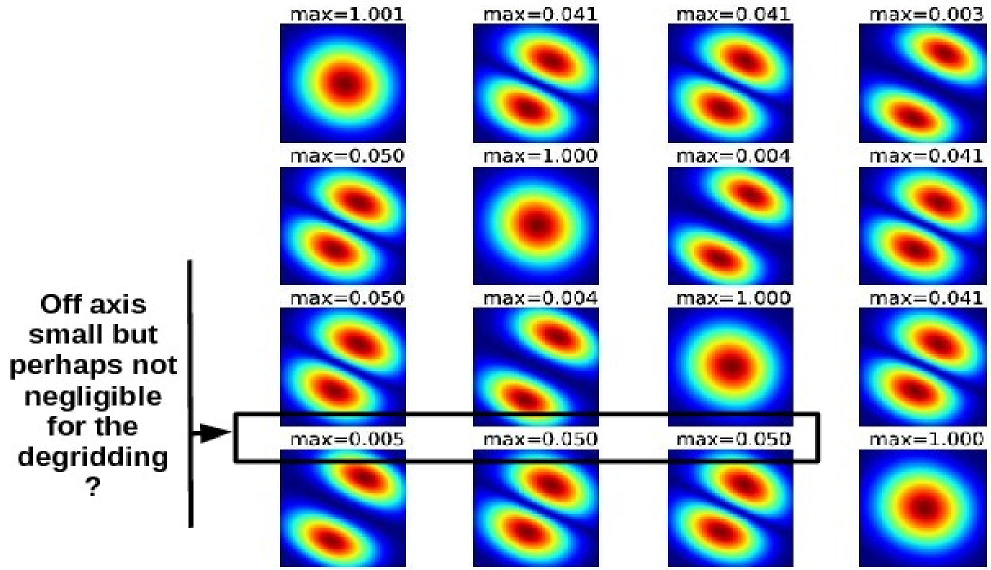


Algorithms: Work in progress

- LOFAR Imager using CASASynthesis framework
  - LOFAR team: C.Tasse, Bas van der Tol, Joris van Zwieten, Ger van Diepen
  - NRAO: S. Bhatnagar, K. Golap, U. Rau

LOFAR Beam: The Mueller Matrix in the image plane

Beam bormalized by Beam Jones matrix at the center of the field (we correct the visibilities accordingly before the imaging)



!!! Color bar is adapted to the image here otherwise you don't see anything!!!

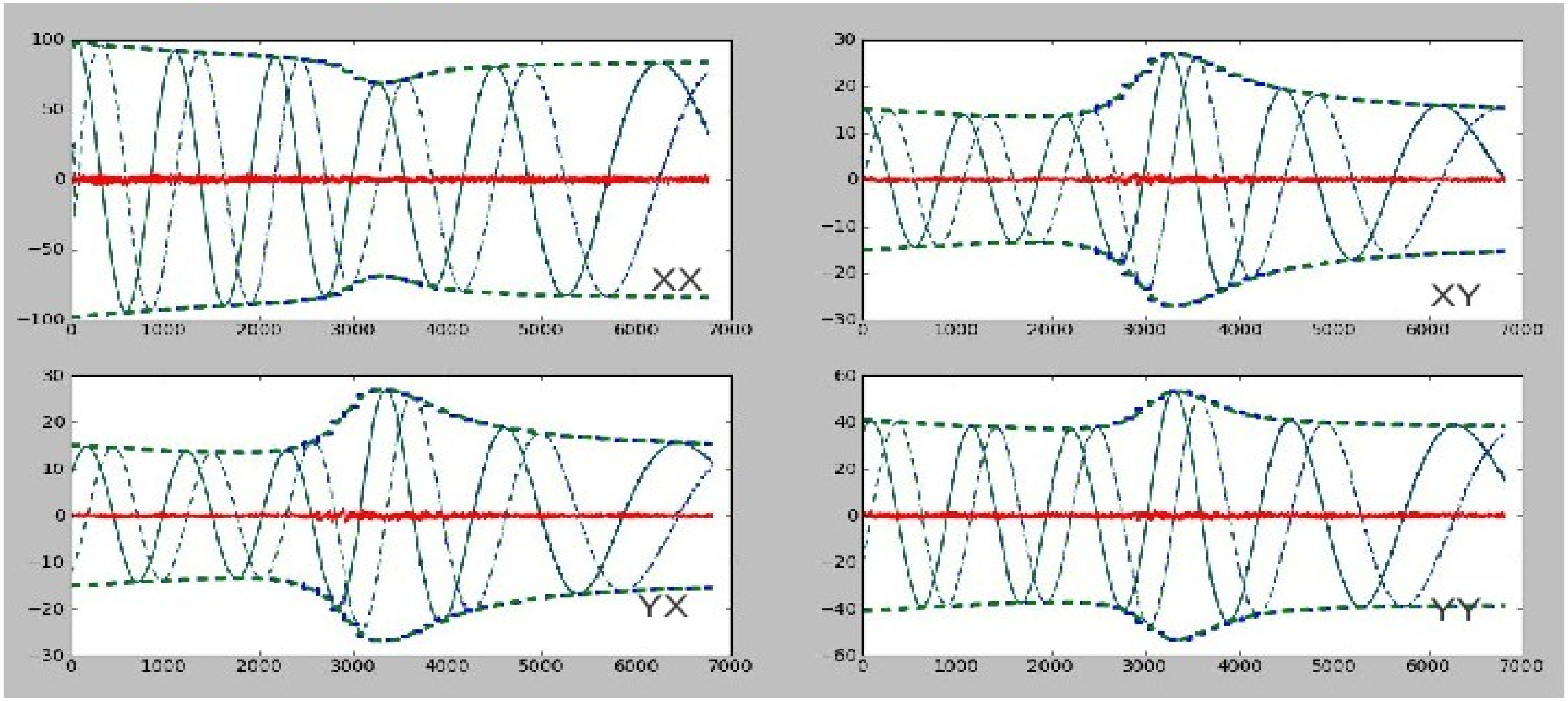
Slides courtesy: C. Tasse

Algorithms: Full-'Mueller' treatment

JAWS: mathematical framework-works

BBS predict (DFT)

AW degridding (clean component put by hand)



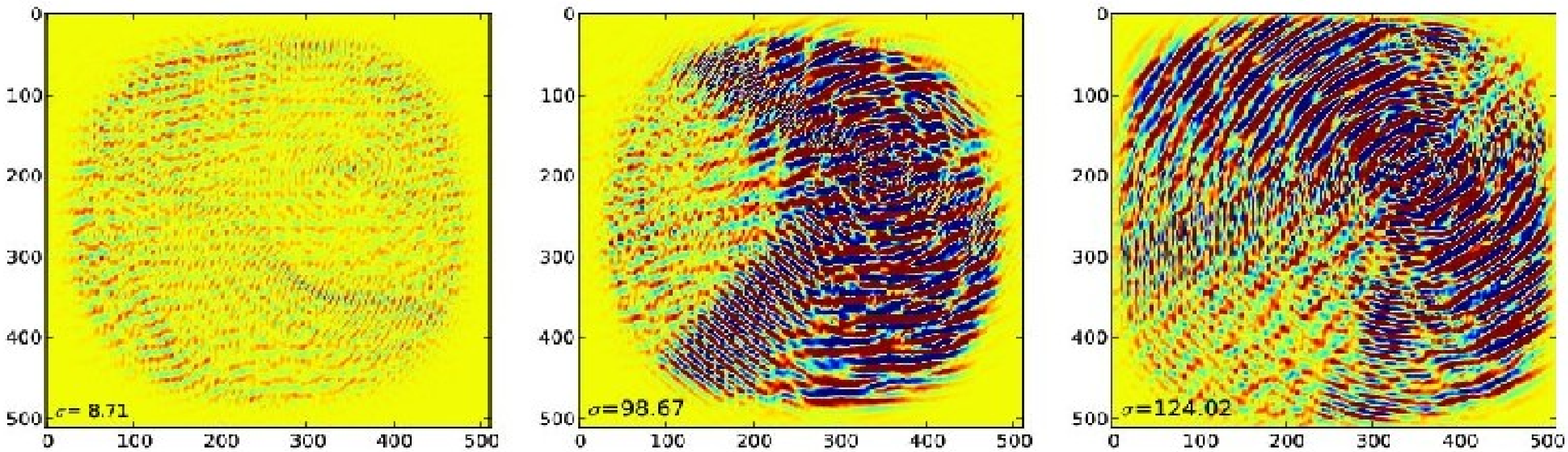
Slides courtesy: C. Tasse

Algorithms: Full-'Mueller' treatment

JAWS: mathematical framework-works

Same simulated dataset with one off-axis source and the beam (IQUV=100,40,20,10)

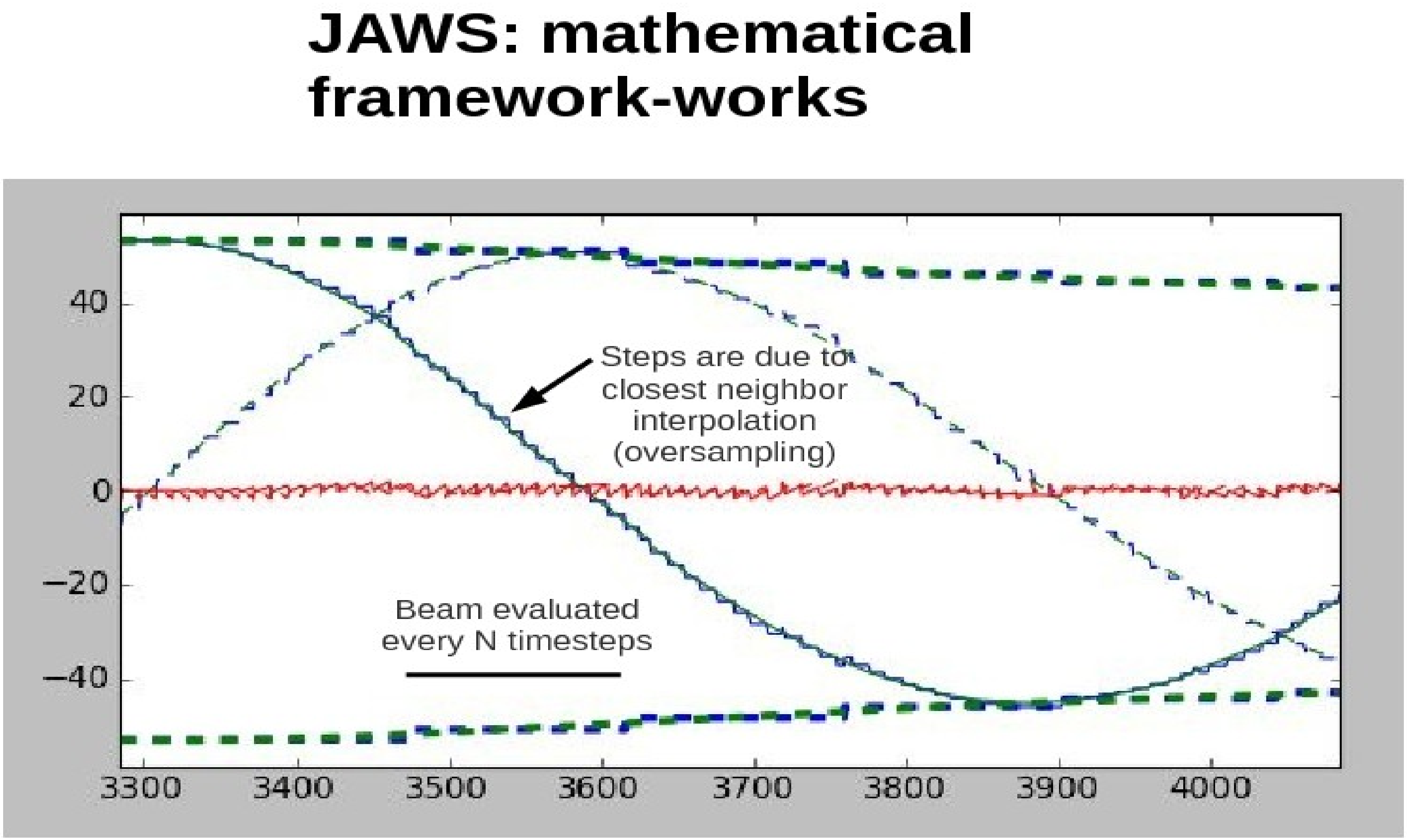
Residual images, Stokes I



AW projection | **AW, only diag terms** | **W projection only**

Slides courtesy: C. Tasse

Algorithms: Full-'Mueller' treatment



Slides courtesy: C. Tasse

High Performance Computing

- Lead by: K. Golap, J. Kern, J. Robnett
  - Collaborations with LOFAR and MeerKAT groups

- Cluster of multi-CPU, multi-core nodes connect with a Lustre file system via high bandwidth network
- Multi-threaded I/O
- Combination of multi-process and multi-threaded computing at nodes
- Algorithmic development in progress (some in advanced stages) to improve I/O through-put and memory foot print
- Low-level code sharing with collaborators possible via the common imaging framework
  - Collaborations in an active (and healthy) state