The MeqTree module
working prototype for LOFAR calibration

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The LOFAR challenge

- Pathological ionosphere
- Very crowded fields (confusion, flops)
- Very bright sources (dynamic range)
- Variable (f,t,k) station beamshapes
- Instrumental polarisation (X/Y voltage beams)
- High station beam sidelobes (all-sky imaging)
- New types of instrumental effects (e.g. BSR)
- Huge data volume (Tbytes/hr)

Ionosphere movie (GMRT)

The bottom line

- The new generation of large radio telescopes (LOFAR, ALMA, SKA) needs software around a more complex Measurement Equation (M.E.) than the existing packages can offer
- A user should not depend on package builders to implement a particular M.E.
- MeqTree is an attempt to do this (the only one!)
- The existing telescopes need something also...

The Measurement Equation

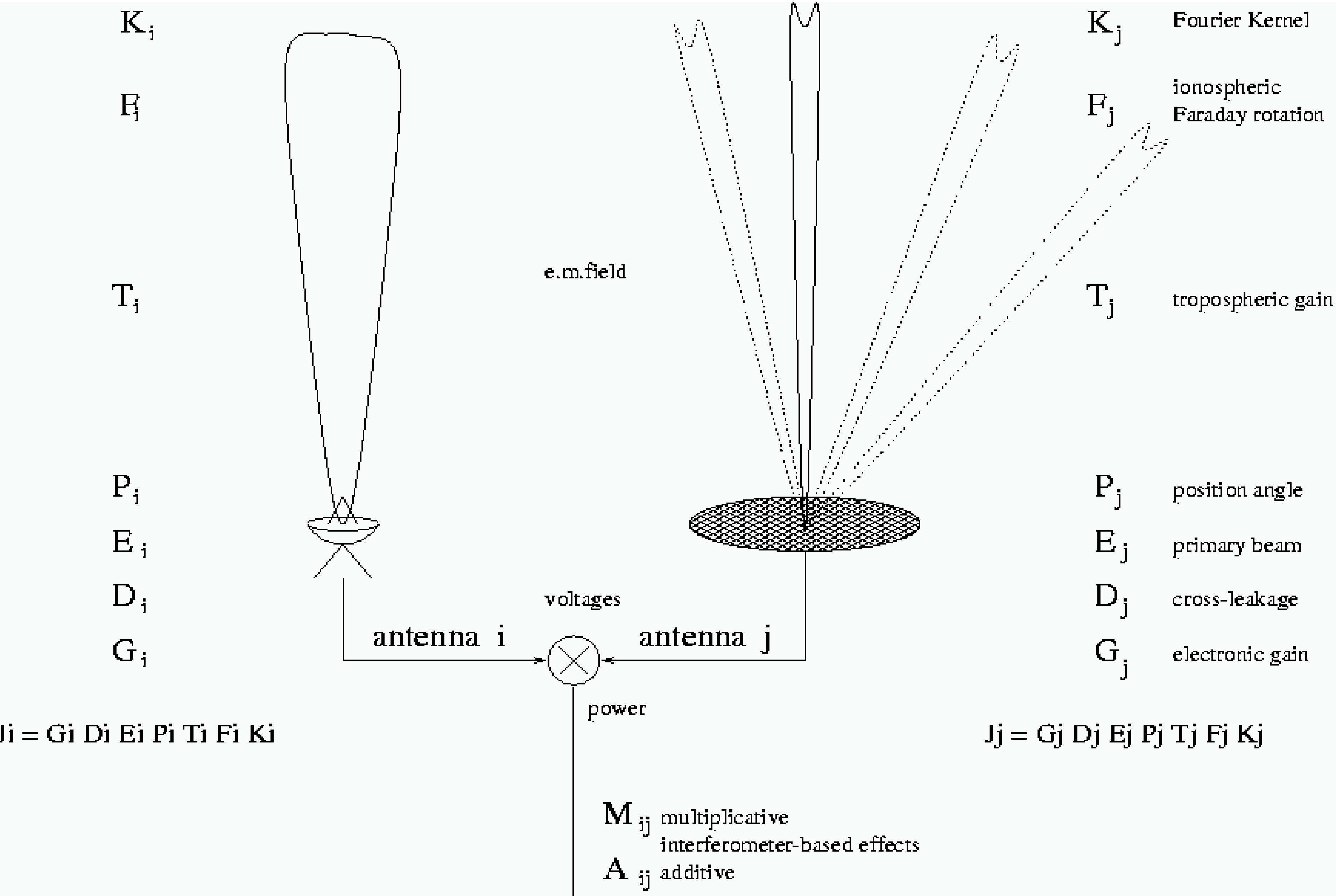
$$\vec{V}_{ij}(u,v) = \sum_k \int df \int dt \left(J_{ik} \otimes J^*_{jk} \right) S \; \vec{I}_k$$

See also:

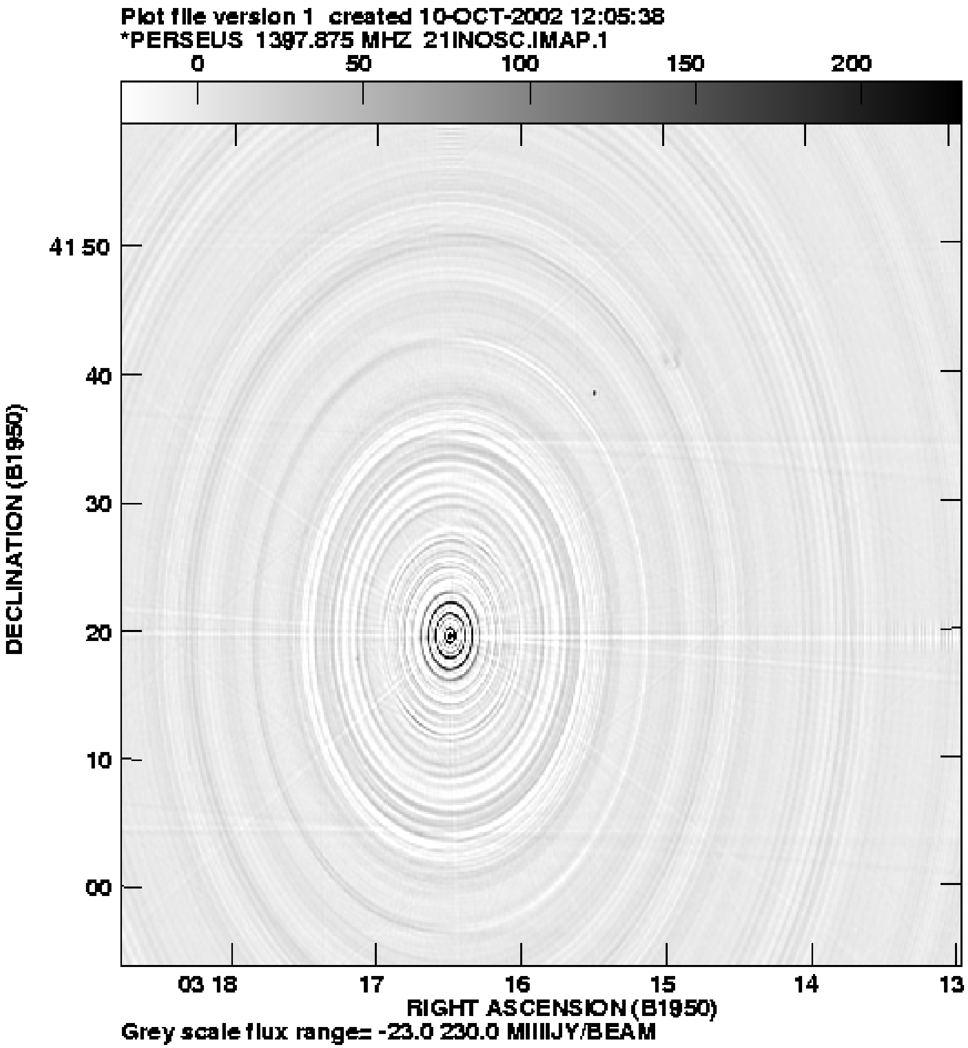
AIPS++ note 185

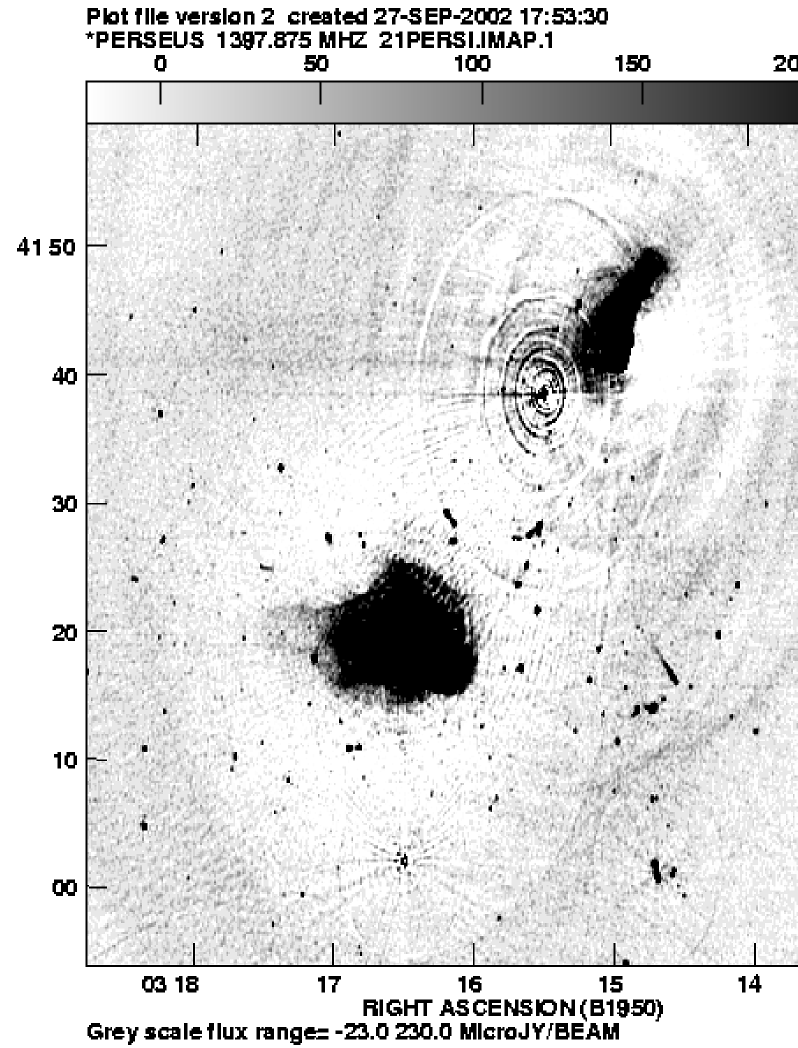
Hamaker-Bregman-Sault formalism
Station-pair (i,j): Vector of 4 ‘correlations’
Matrix equation: full polarization
Instrumental Jones matrices J (2x2)
Stokes matrix S (4x4)
Sum over sources (k): Flux [I,Q,U,V]
Integral over time-freq domain

M.E. instrumental effects



3C84, WSRT, 21cm





Dynamic range: 100 : 1

Dynamic range: 500.000

The big issues

- Image-plane effects
  - Extra processing
  - Apply to extended sources
- Minimise the number of parameters
  - Minimum Ionospheric Model (MIM)
  - Beamshapes
- Data volume (performance)

Path to LOFAR calibration software

- Two separate teams:
  - Development: MeqTree module and AIPS++
  - Implementation: Black Board Selfcal (BBS)
- MeqTree is a tool for M.E. development
  - Reduce the number of parameters
  - Low threshold
  - Exercise on real data (WSRT/WHAT, VLA74 HMz …)
- Involve lots of people (especially next generation)
- Continue with MeqTree module afterwards

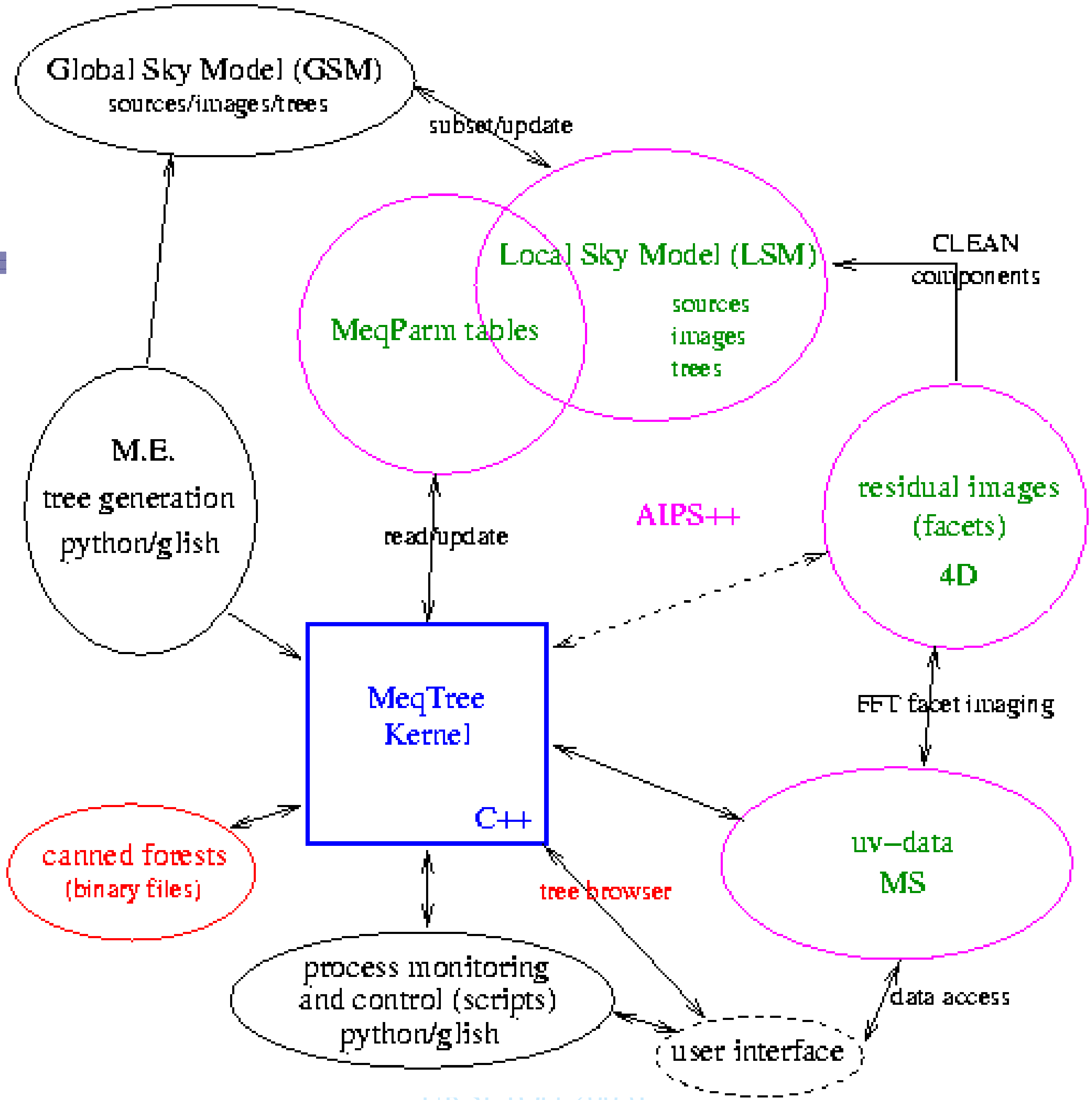
Alternate between two domains

- Instrumental errors are in Fourier domain
  - They vary in time and frequency
  - They vary over the Field of View (!)
- Bright sources are subtracted in Fourier domain
- Faint sources are found in image plane
  - But subtracted in Fourier plane (PSF)
- Residual images must be deconvolved

The result of successful calibration

Part II: MeqTree Module Overview

MeqTree Environment

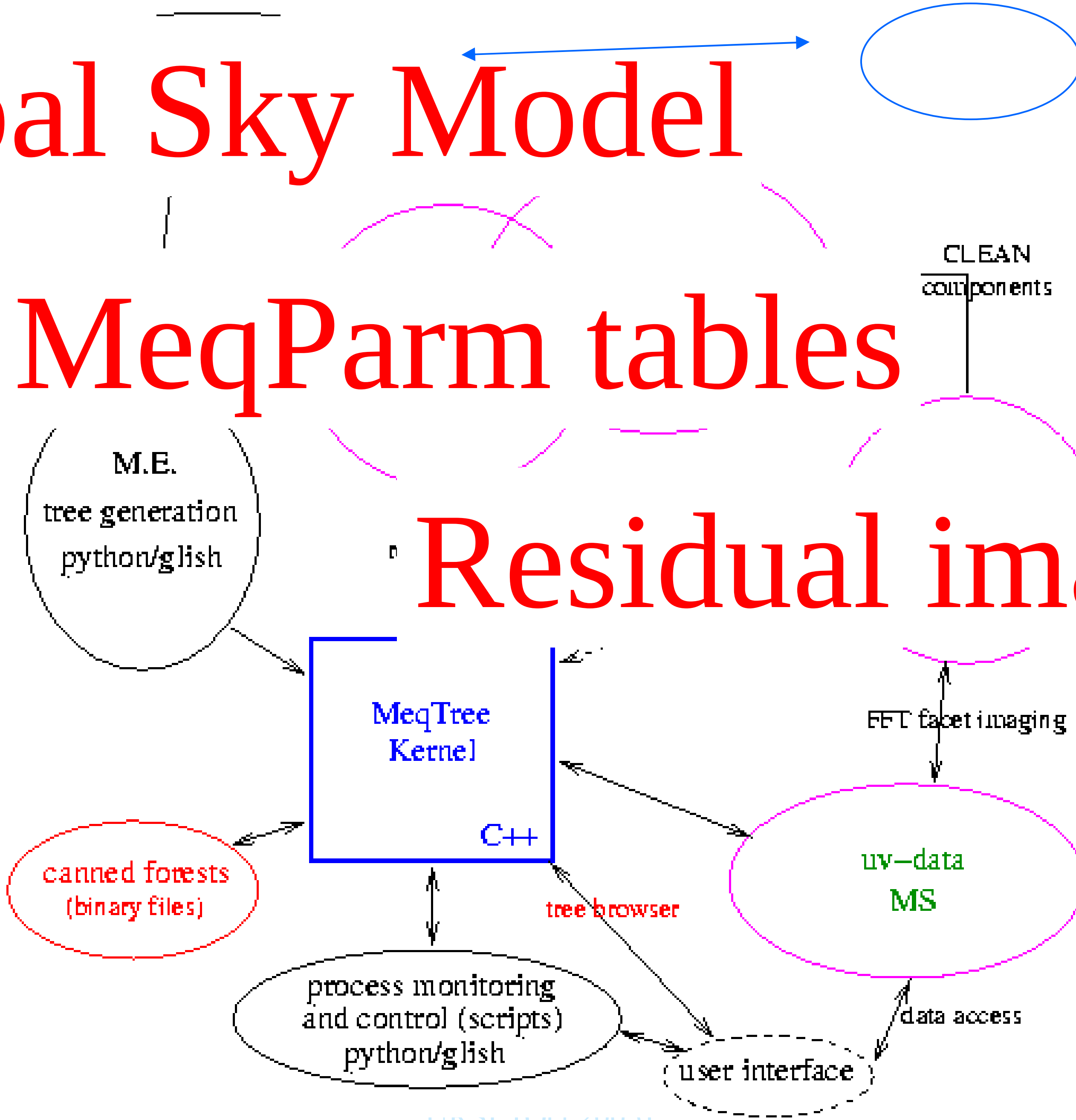


LOFAR deliverables

Global Sky Model

MeqParm tables

Residual images



LOFAR

The MeqTree Team

Tom Oosterloo

Michiel Brentjens

Sarod Yatawatta

Maaijke Mevius

Jan Noordam

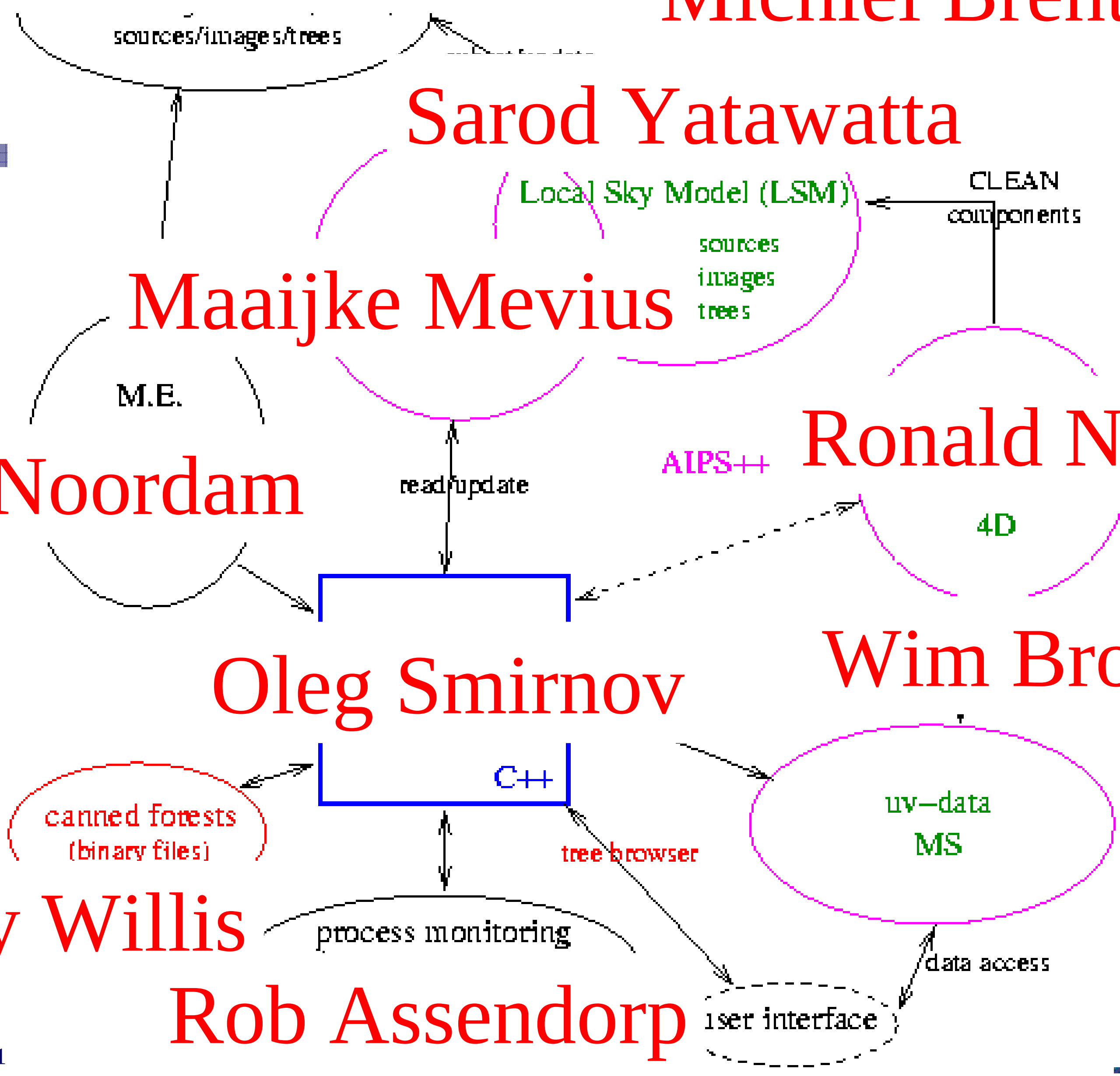
Ronald Nijboer

Oleg Smirnov

Wim Brouw

Tony Willis

Rob Assendorp

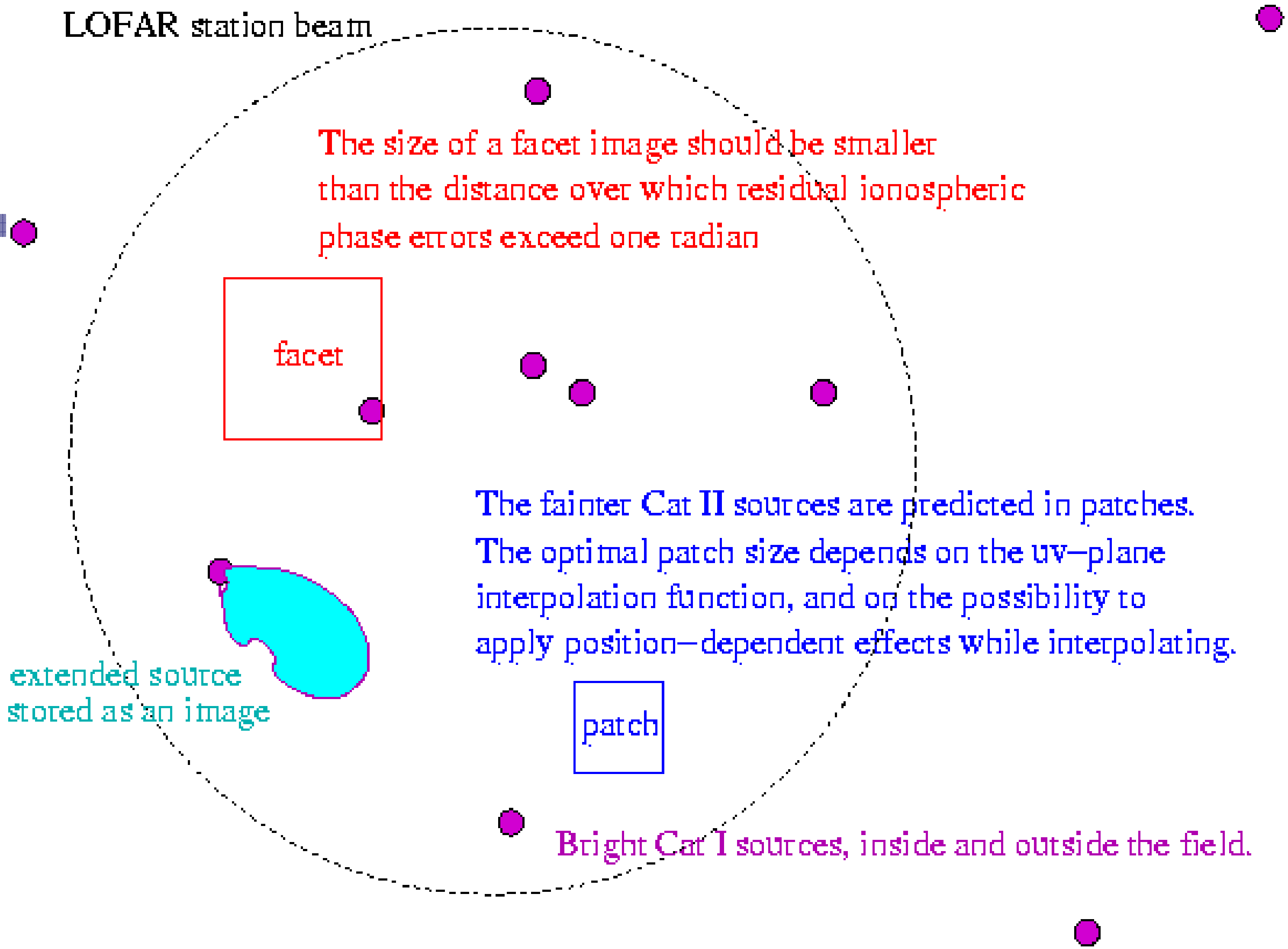


The MeqTree Kernel

- Implements arbitrary M.E.
- Solves for subsets of M.E. parameters
- Policy Free (!)
  - Will be applied to other areas
- Data interface (MS)
- MeqParm interface (AIPS++ tables)
- Tree Definition Language (TDL)
- User interaction via the MeqBrowser

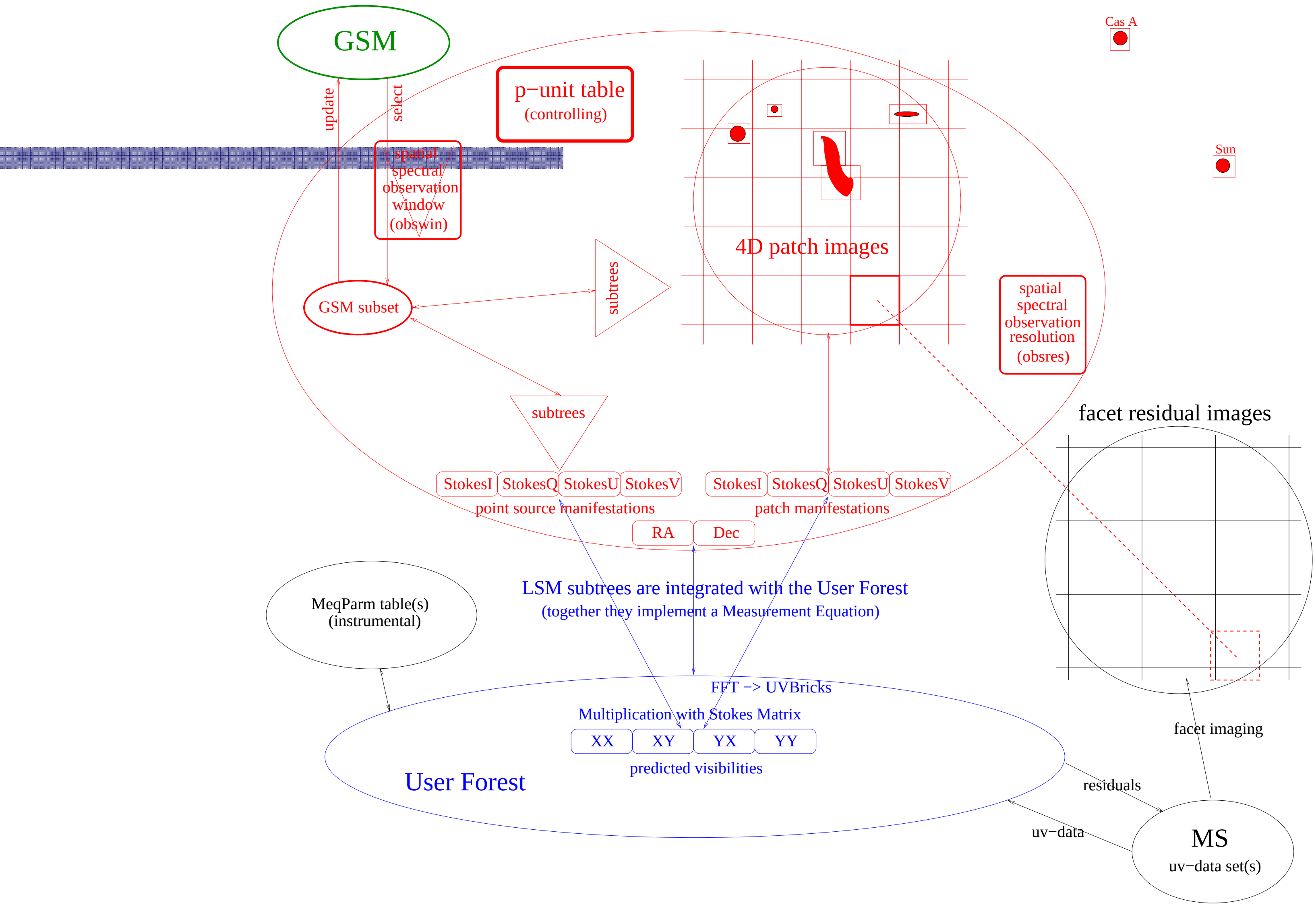
LOFAR

Local Sky Model (LSM)



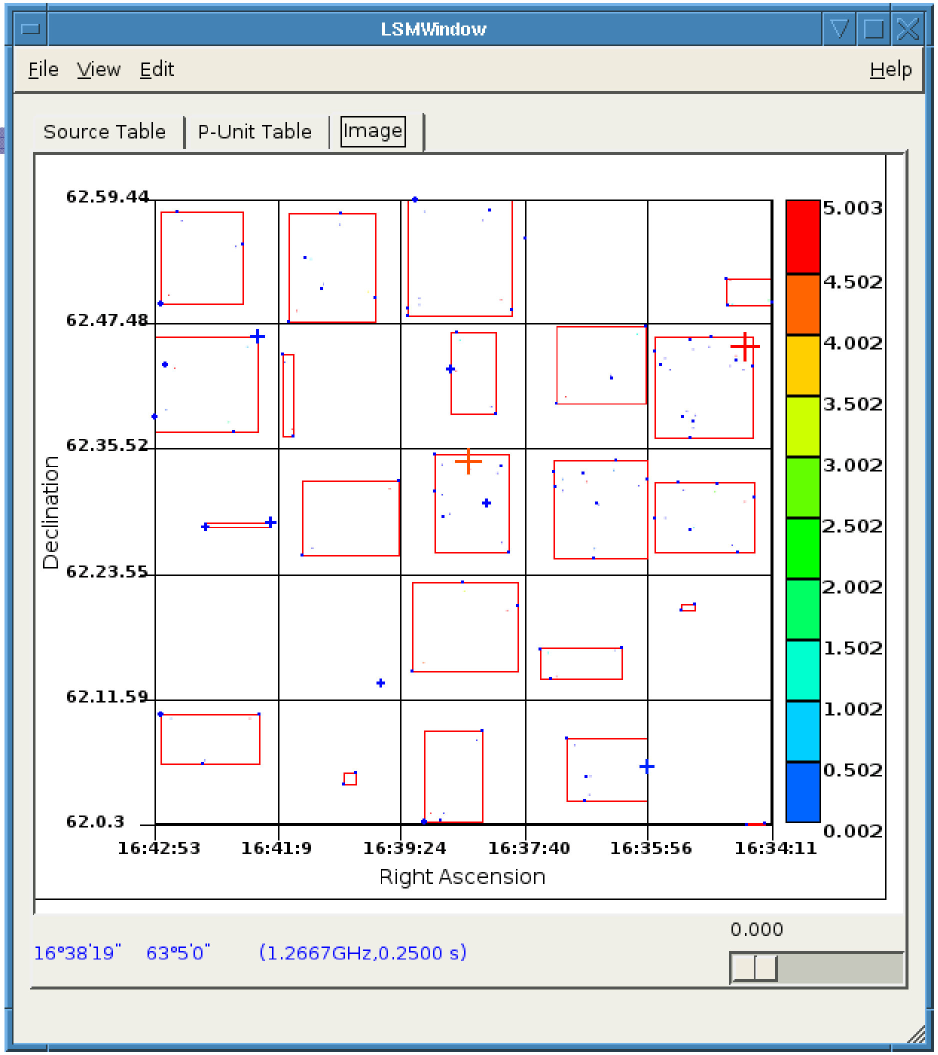
Contents of a Local Sky Model

Local Sky Model (red) and user tree (blue)



URSI (Oct 2005)

LSM Interface GUI



URSI (Oct 2005)

Three categories of sources

- Cat I: Bright enough to be used for Selfcal
  - Subtracted individually from the uv-data
- Cat II: Bright enough to be identified in a residual image, and put into the LSM
  - Subtracted in groups (patches) from the uv-data
- Too faint to be in the LSM, so not subtracted in the uv-plane
  - Imperfectly imaged…

Peeling

- Deal with sources/patches sequentially
  - Large potential saving in processing
- Selfcal: Solve for instrumental parameters in the direction of bright sources, in order of brightness
  - Potential problem: contamination of fainter sources
- Subtraction: All LSM sources (Cat I and Cat II)
- Each time, the phase centre is shifted to the position of the peeling source or patch

Bottleneck: Source subtraction

- All LSM sources are subtracted from the uv-data
- Requires uv-model derived from LSM
- But: We are not interested in the details (flux, position) of individual foreground sources
- Are there ways to 'filter' them out?
- The PAST team may have the beginning of such an algorithm…

field of view

Residual (facet) imaging

facet

- Split the field-of-view up in facets
- Correct residual uv-data for facet centre
  - Errors increase towards the edge
- Integrate (f,t) to decrease field-of-view
- FFT: Make a residual image of each facet
- Analyse residual images:
  - Find/update Cat II GSM sources
  - Deconvolve Cat III sources (if possible)
- Combine with GSM: LOFAR deliverables

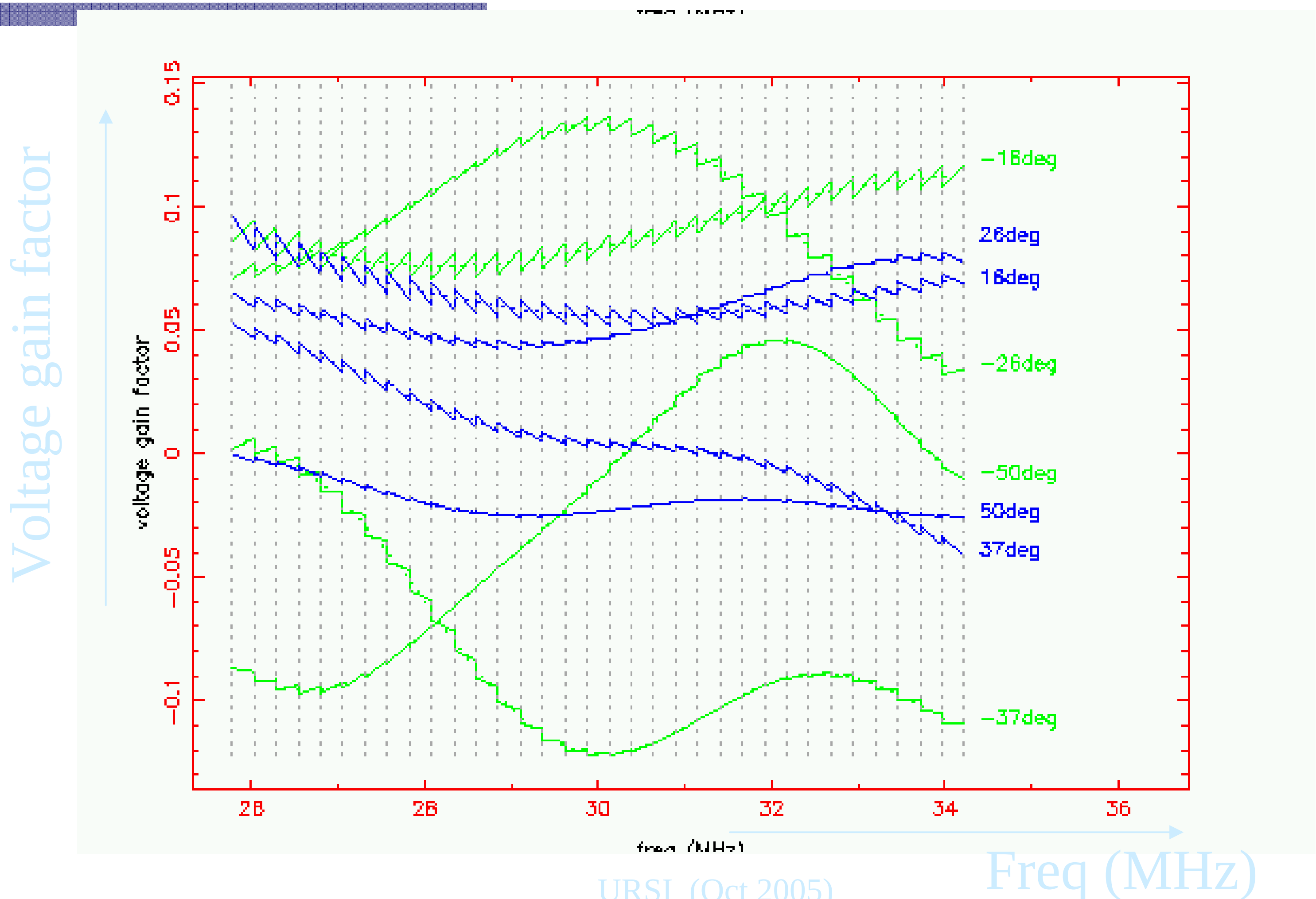
Source extraction from residual images

- Need a PSF
  - Strictly valid for centre of field only
  - But may degrade benignly towards the edge
- First check positions where Cat II sources have been subtracted: update LSM source parameters
- Then look for new (Cat III) sources for LSM
- Iterate until diminishing returns
- Ultimately, use the LSM to update the GSM

Some imaging artefacts

- Remnants of Cat I subtraction (peeling)
- Remnants of Radio Frequency Interference
- BSR effect (far from bright sources…?)
- Pattern of facet edges (cat III imaging)
- Sidelobe confusion (PSF sidelobe level)
- Pattern of *p-unit* edges (cat II subtraction)
- Etc, etc

Bandpass Sawtooth Ripple (BSR effect)

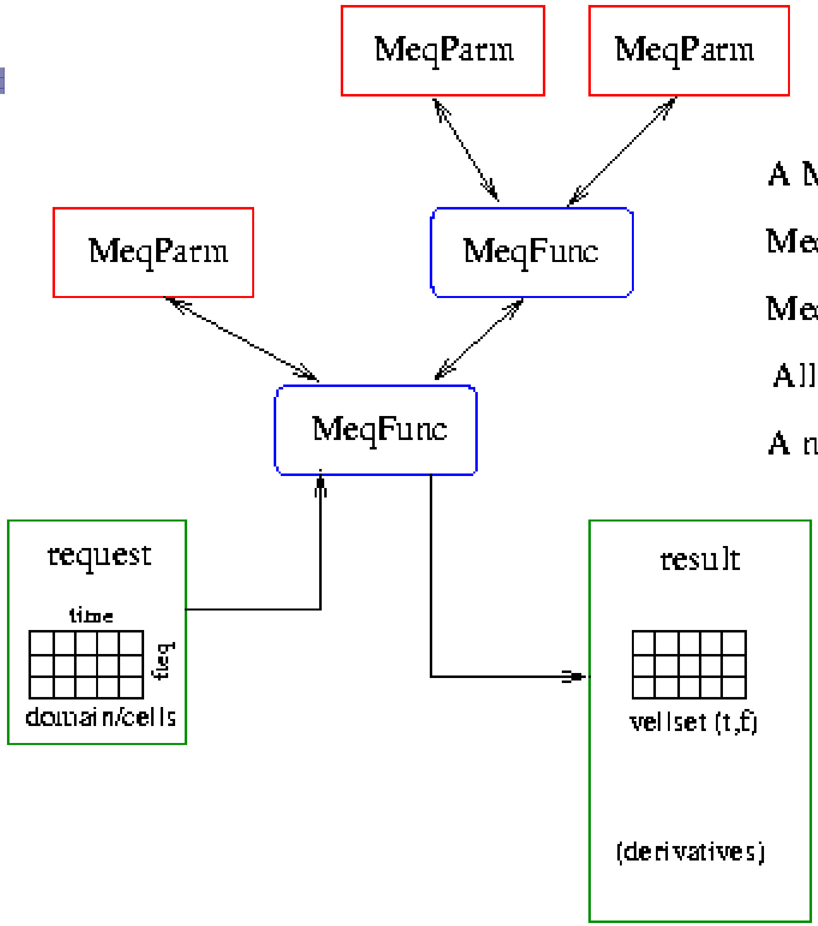


Global Sky Model (GSM)

- Very large number of LOFAR sources
- Inhomogeneous parametrisation
  - Includes shapelets, pixons and actual images
  - Use MeqTrees in GSM/LSM
- Freq/time dependencies
  - Use funklets in GSM/LSM
- Should be compatible with Virtual Observatory

PART III: MeqTree details

My first MeqTree



A MeqTree implements a (part of) a M.E.

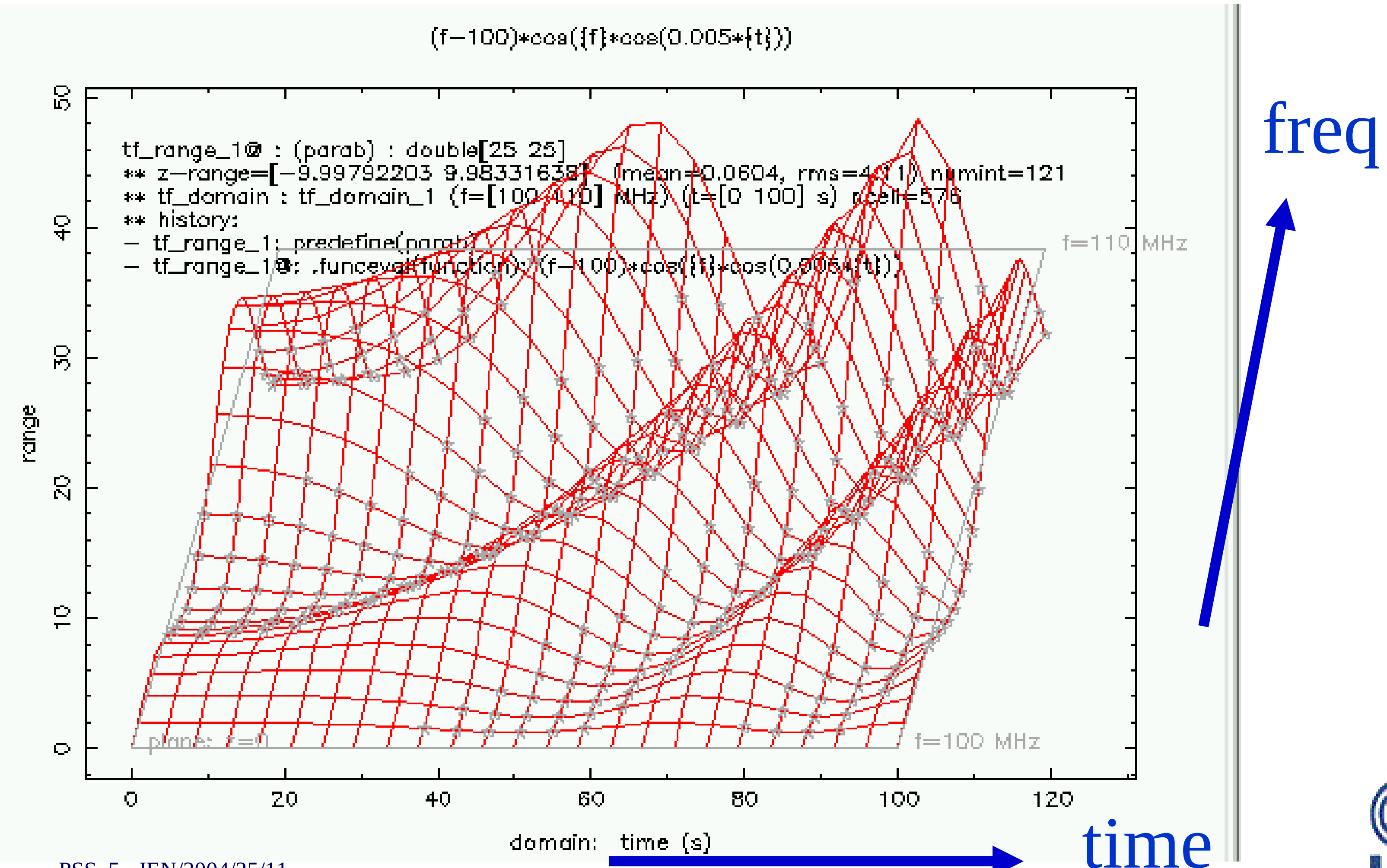
MeqParm nodes represent M.E. parameters

MeqFunc nodes combine child results

All nodes have the same interface

A node deals with its direct family only

A node result contains vells, i.e. an array of values for the cells of a given domain (t,f):

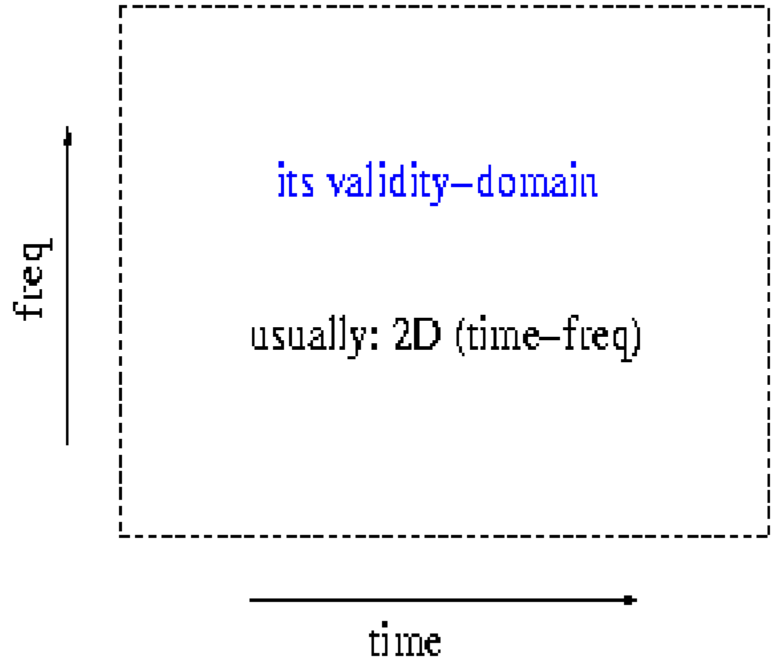


MeqParm values are 'funklets'

c00	c10	c20	c30
c01	c11	c21	...
c02	c12	...	...

A pole: an N-dim array of polynomial coefficients

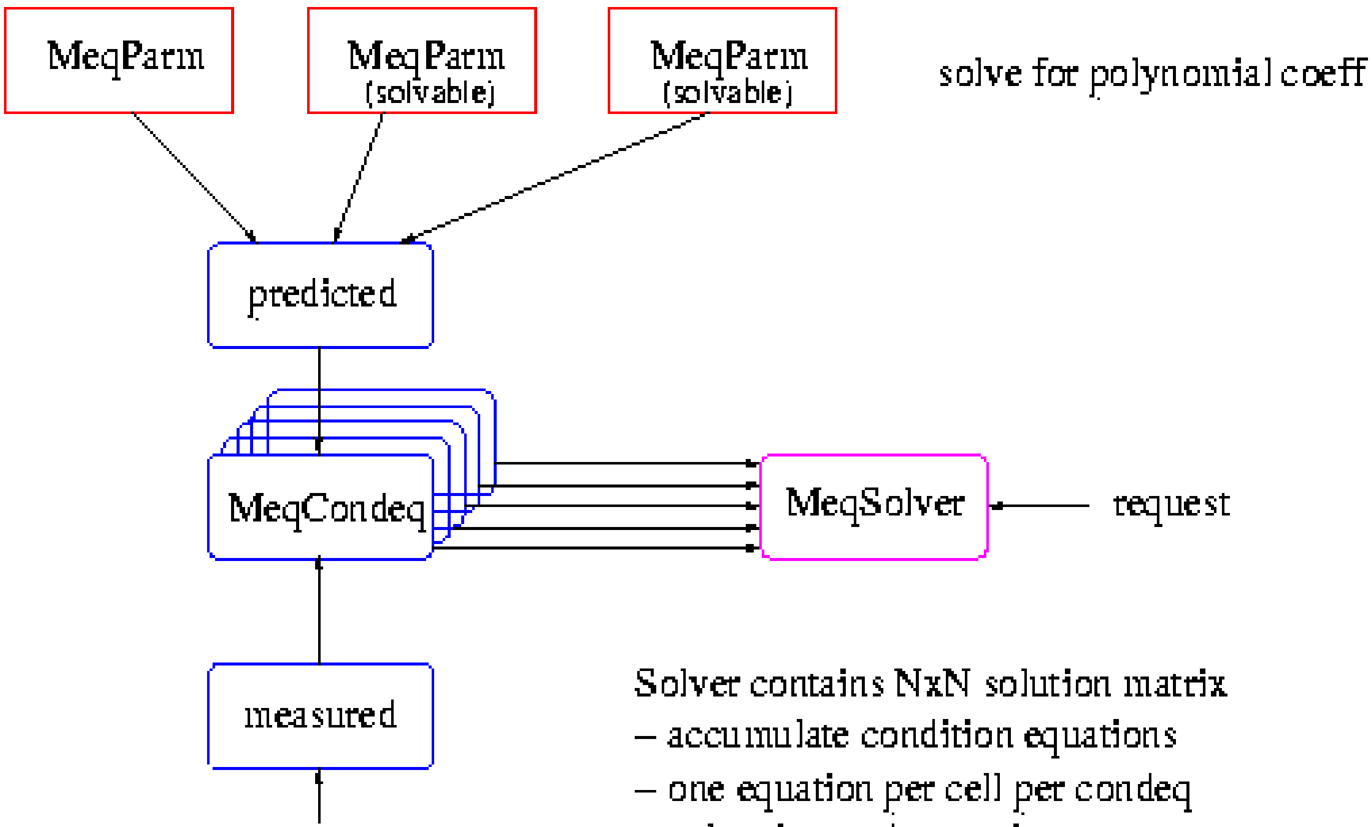
(or coeff of any other smooth function)



Funklets (cont'd)

- Most M.E. paramaters have 2D (f,t) polynomial funklets
- But: funklets an have any number of dimensions, with different base 'functionals' along each axis
- Examples of complex funklets:
  - The Minimum Ionospheric Model (MIM)
  - Station voltage beam shapes

A solving tree



Solver contains NxN solution matrix
- accumulate condition equations
- one equation per cell per condeq
- solve: invert the matrix
- update the MeqParm values (via the tree)

MeqSolver issues

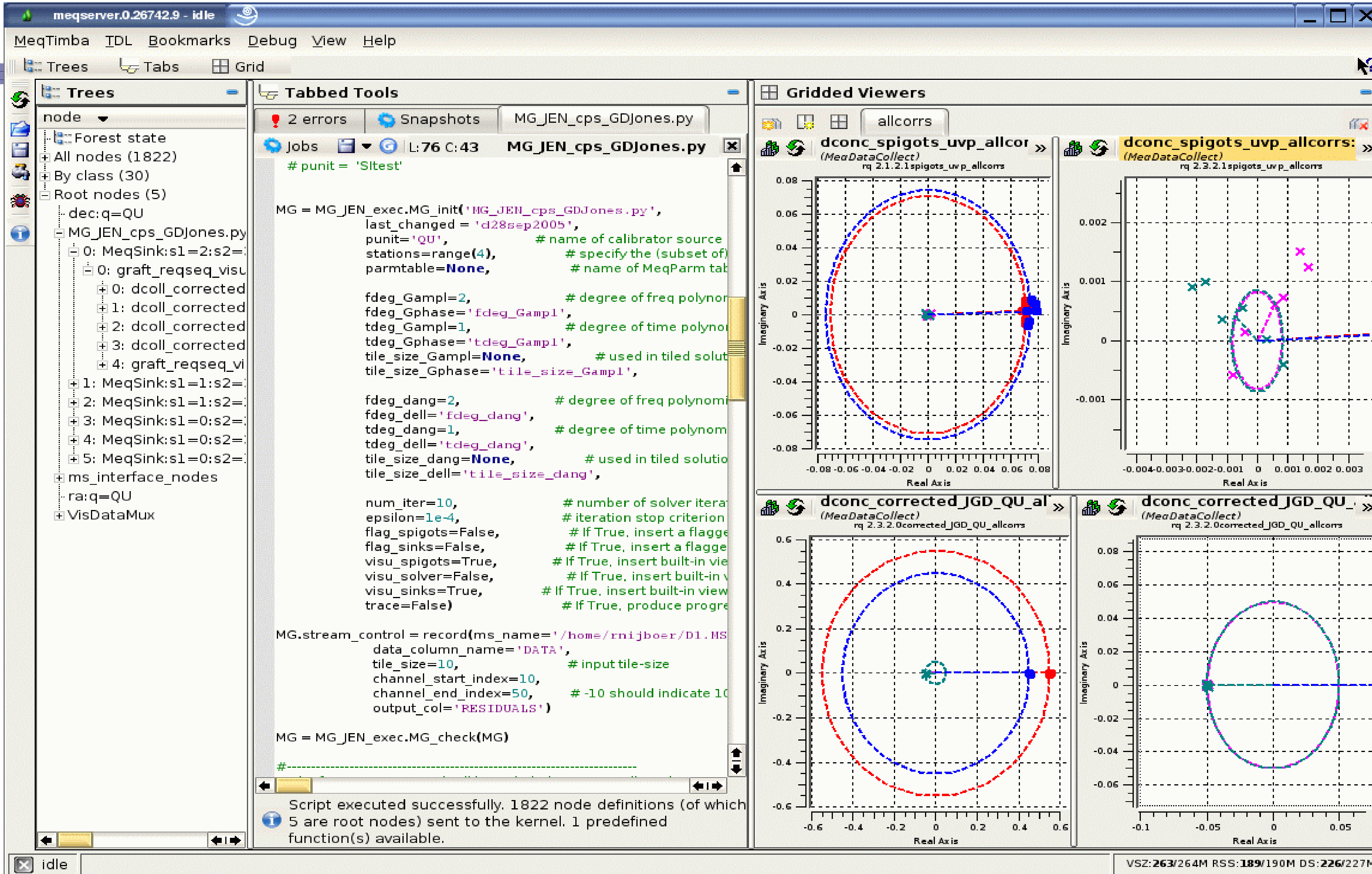
- Based on AIPS++ fitting (WNB)
- SVD (always inverts)
- Non-linear (requires iteration)
- Use solver metrics to monitor quality
- Local intelligence to minimise iteration
- Resample data to minimise cells (=equations)
- Use tiled solutions to minimise node overhead
- Optimize inversion where possible
- Alternatives?

The many windows into MeqTrees

- Every node may be inspected individually
  - Contents of its state record
  - Plot of its result
- Built-in views of the results of groups of nodes
- History nodes collect intermediate results
- Debugger functionality (pause, resume, brktpnts)
- The meqbrowser itself is a new kind of user interface (incl. editing of script hierarchy)

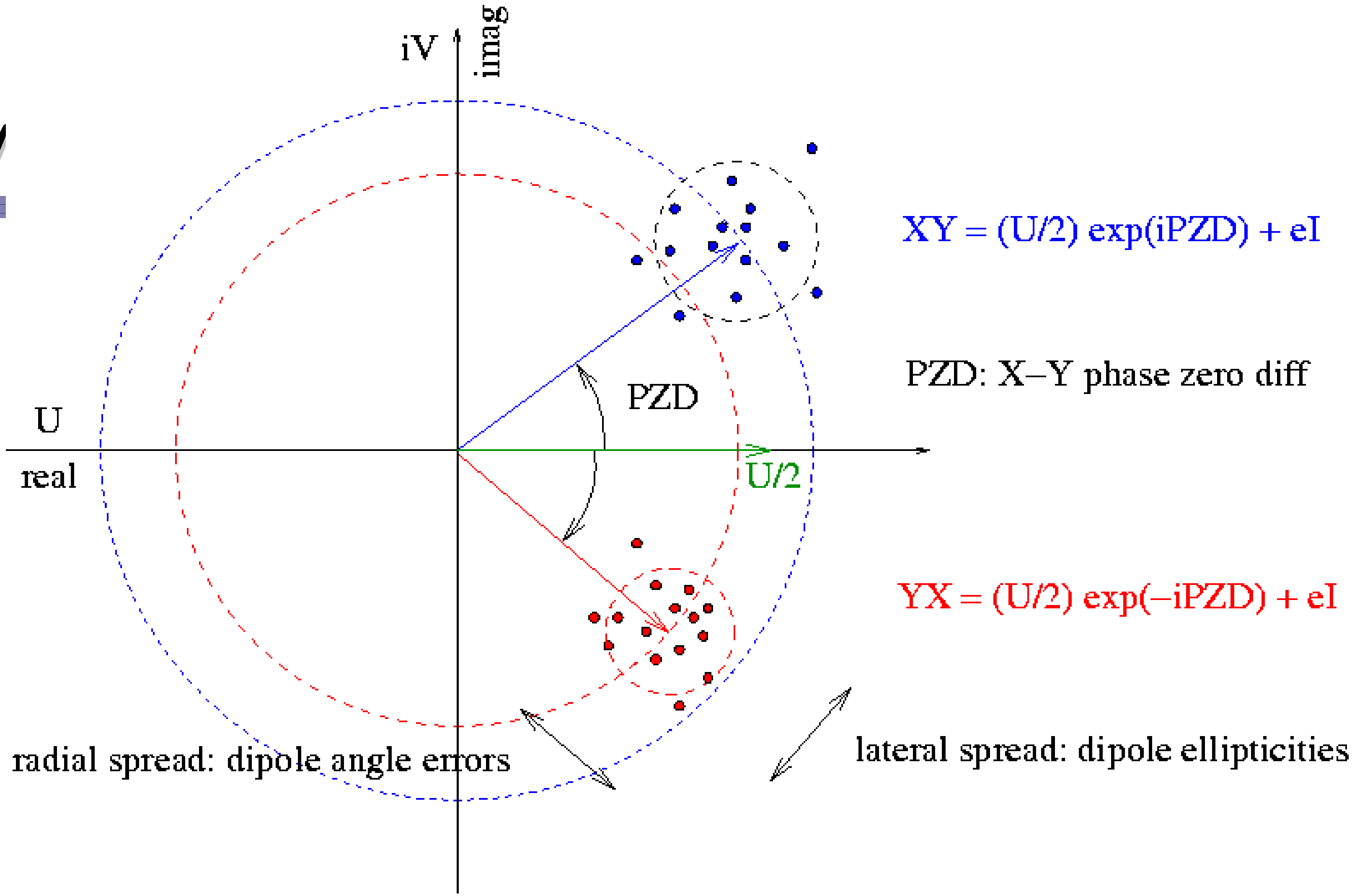
LOFAR

MeqBrowser with tree, script and views



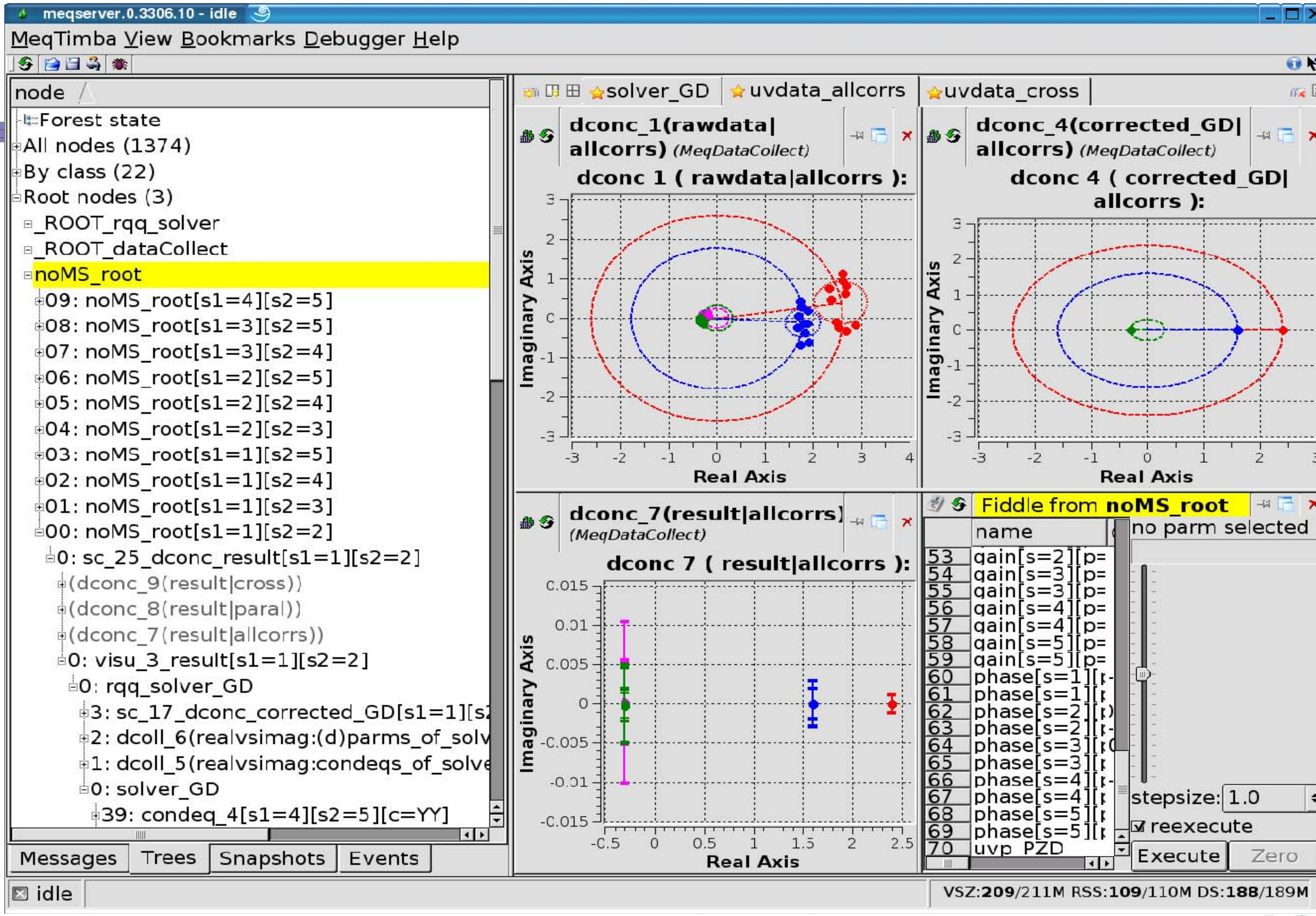
XY

WSRT polarization calibration



WSRT XY and YX data from a polarised (but: V=0) central point source, e.g. 3c286

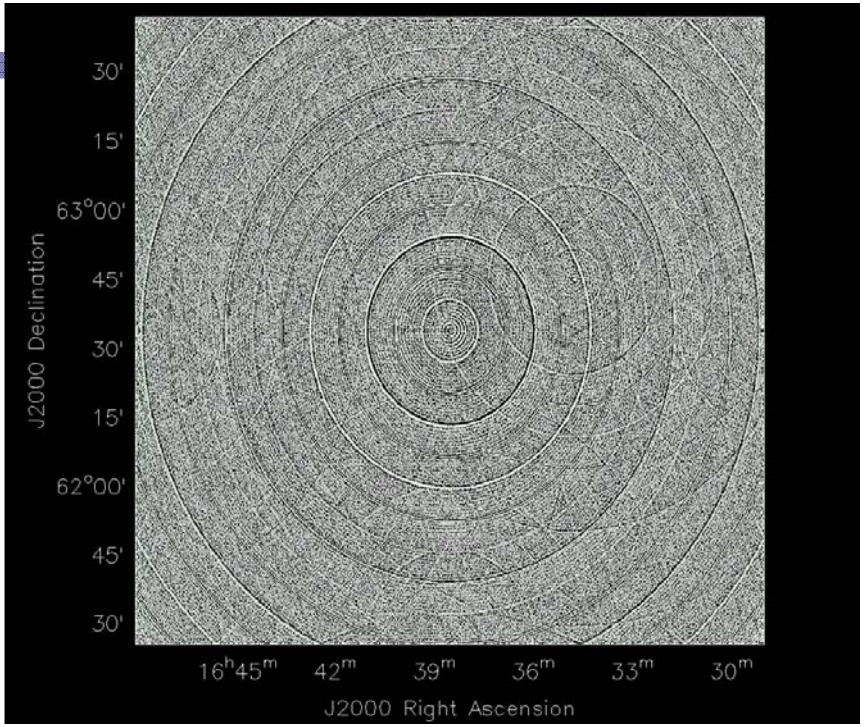
MeqBrowser with parm fiddler



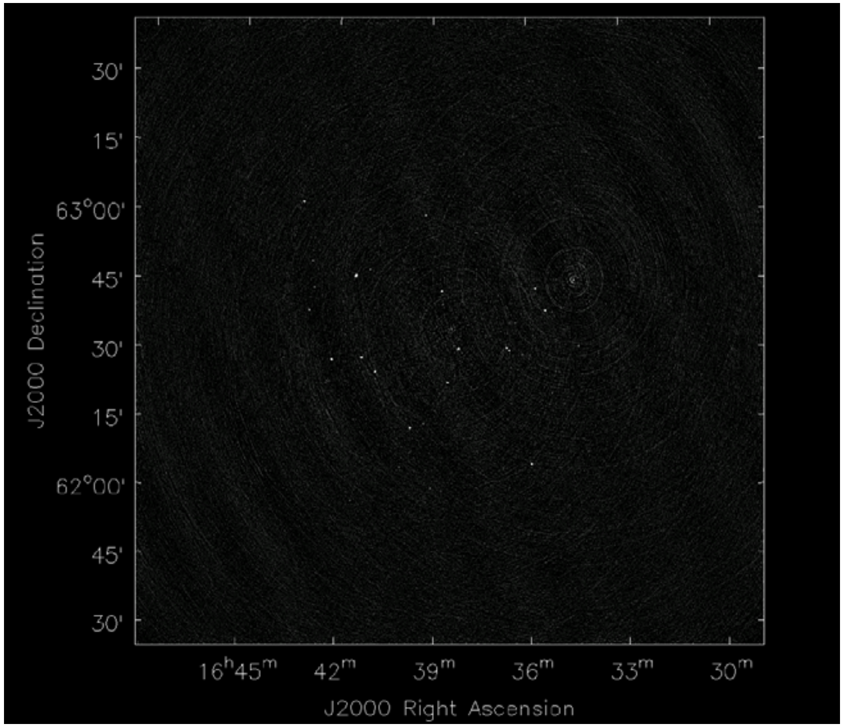
Results so far

- Stable kernel and browser
- 3c343 (Michiel Brentjens)
  - Also: Miriad, NEWSTAR, AIPS++
- M81/82 (Tom Oosterloo): Peeling in Miriad
- Minimim Ionospheric Model (MIM)
  - URSI poster by Jim Anderson
- Model of CLAR beam (Tony Willis)
- Model of LOFAR WHAT station beam

MeqTree: 3C343.1 & 3C343



Uncalibrated Image



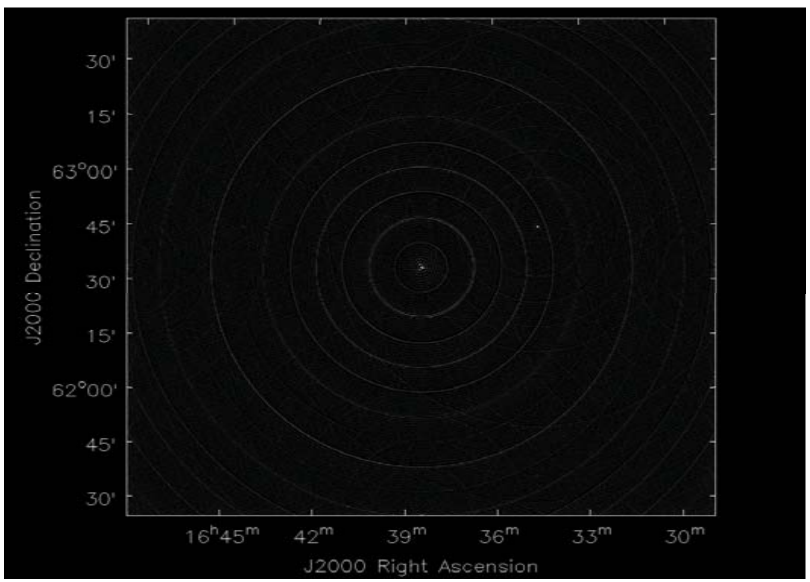
Calibrated Image
2 sources subtracted

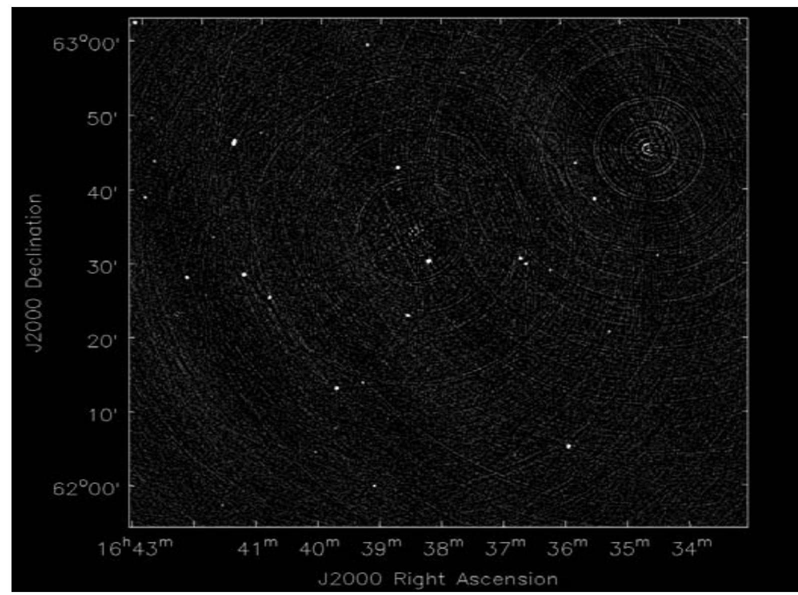
Result by Michiel Brentjes

LOFAR

MeqTree: 3C343.1 & 3C343

The MeqTree System is a reduction module that implements Generalized Self-Cal and allows automated Peeling



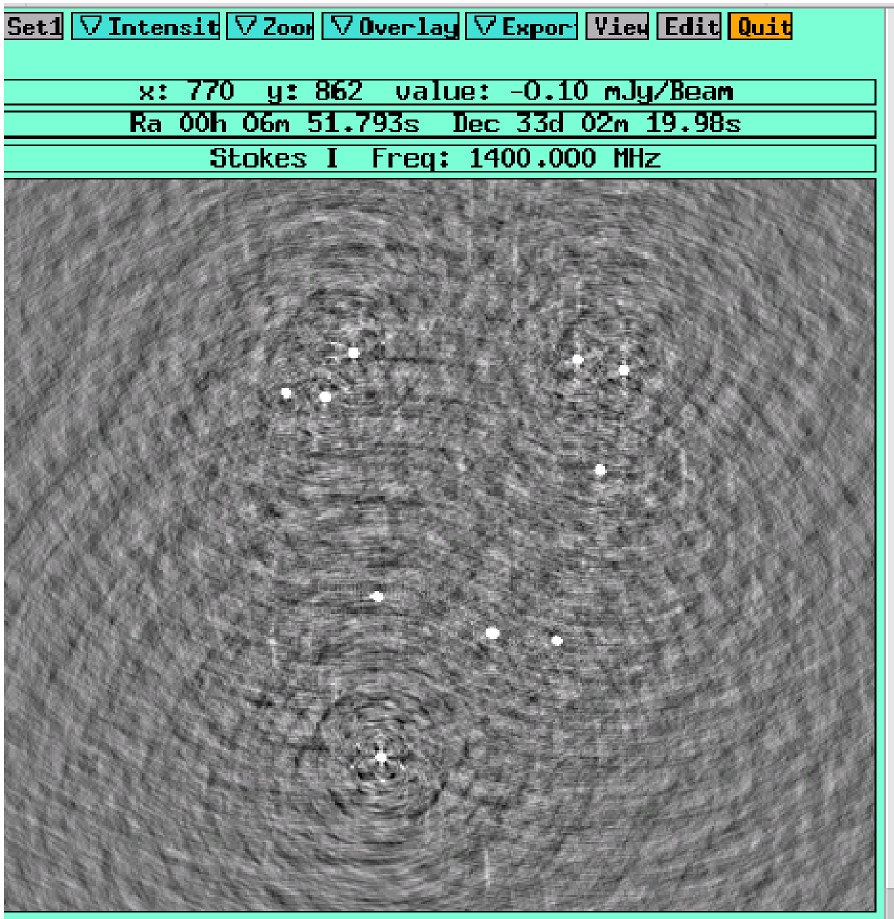


Result by Michiel Brentjes

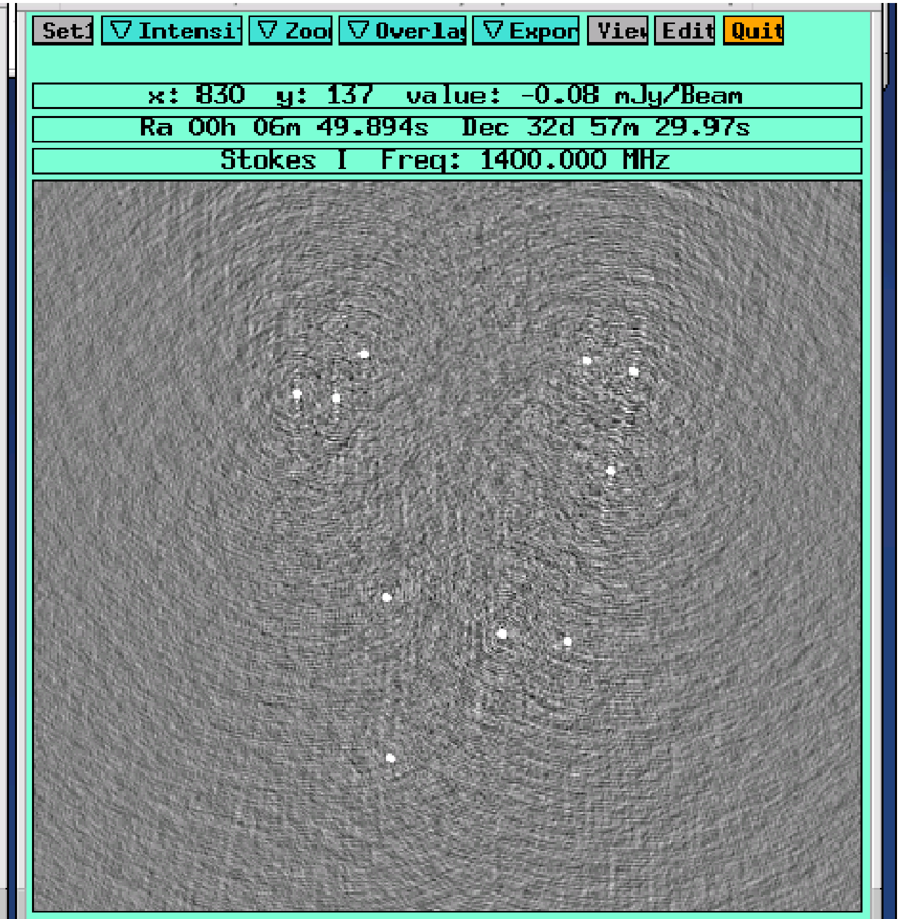
LOFAR Self-Cal will be based on experience with the MeqTree System

First external user (Tony Willis, Penticton, Canada): CLAR simulations

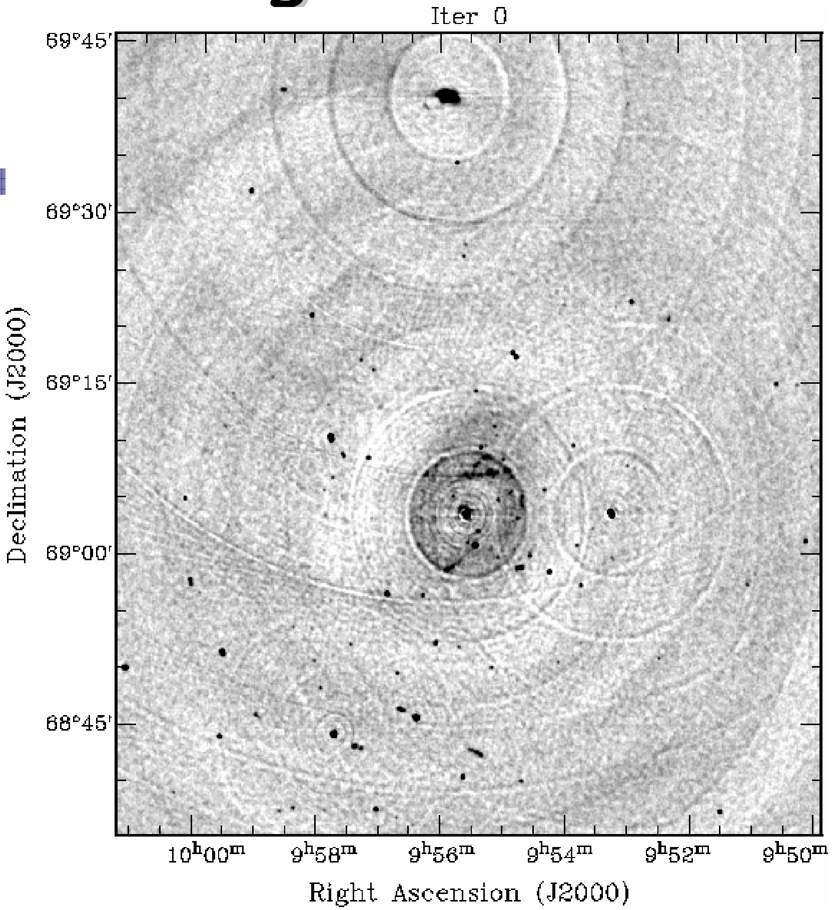
AIPS++ (20 min chunks, image-plane)



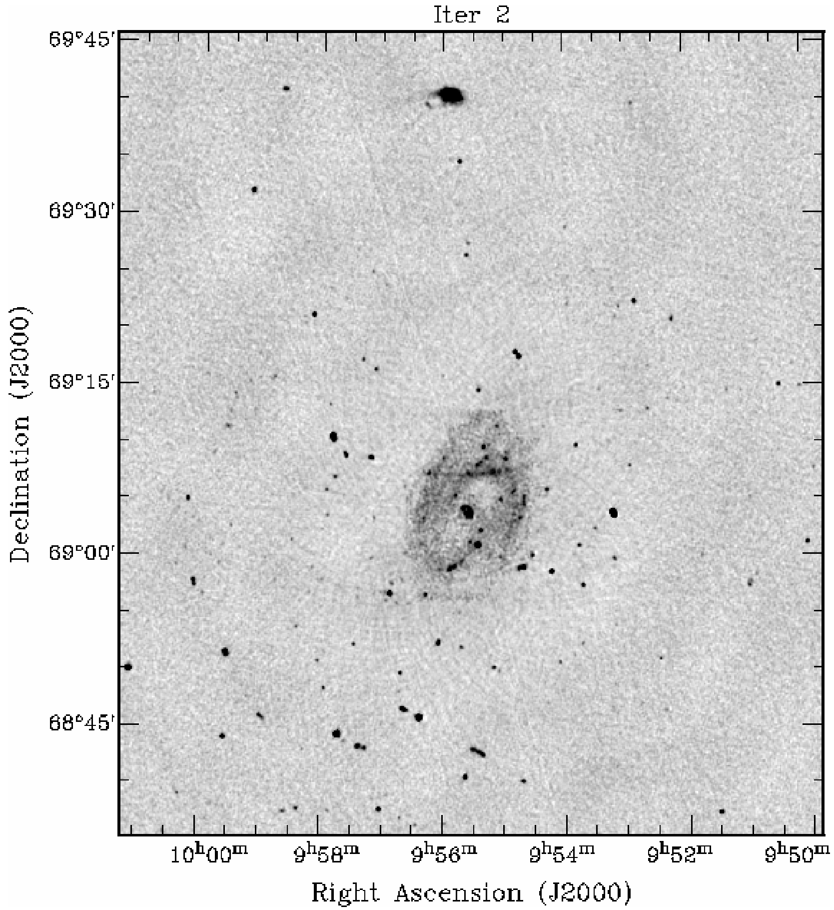
MeqTree (continuous, station-specific)



Peeling on M81 & M82



standard selfcal entire field



2-patch peeling (miriad)

(Result by Tom Oosterloo)

Conclusions

- LOFAR calibration will not be easy
- We have a lot of new ideas
- But more are needed
- The stage is set for M.E. development