Polarization Measurements with LOFAR: Preparing for the Cosmic Magnetism KSP

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LOFAR Cosmic Magnetism KSP Management Team Member

On behalf of the LOFAR MKSP and the LOFAR collaboration
LOFAR Detection of Polarized Emission

• Not yet...

• We are working on a number of sources, different fields, pulsars, diffuse regions, imaging and beamformed data

• Calibration errors are difficult to deal with
  - Have large Q,U signals at Faraday depth of 0 rad m$^{-2}$, which strongly suggests instrumental errors
  - For the case of looking at the Crab pulsar, we have 10's of Jy of polarized flux density surrounded by an unpolarized nebula with more than 1000 Jy.

• Software is a pain in the rear

• But we are working on getting the calibration correct, and expect to confirm real polarization detection any week now...
Terminology 1:

**Frequency Coverage** is an Orthogonal Concept to Bandwidth for LOFAR

- **Aggregate Bandwidth**
  - Integration of instrument response as a function of frequency
  - For LOFAR, raw bandwidth: \( N_{sb} \Delta \nu_{sb} \), effective bandwidth: \( N_{ch} \Delta \nu_{ch} \)
- **Frequency Coverage**
  - Location of instrument response as a function of frequency
  - For LOFAR, effective frequency coverage: which subbands/channels are unflagged
- **Frequency Span**
  - Difference between maximum and minimum frequencies

\[\begin{align*}
\text{Bandpass} & \quad 0 \quad 1 \\
\nu [\text{MHz}] & \quad 120 \quad 130 \quad 140 \quad 150
\end{align*}\]
Terminology 2:

“Rotation Measure” Is Inadequate

- At low frequencies, there are virtually no directions with only a single component along the line of sight
  - See talk by Wolleben
- Rotation measure synthesis (RM synthesis) is necessary
  - Insistence on capitalization of Synthesis by MKSP PI
- Frequency coverage and weighting determine the rotation measure spread function (RMSF)
  - Analogous to the PSF from imaging
  - More appropriately, it is related to the dirty beam in interferometry
  - Similarly, one can have a clean beam, or restoring RMSF for RM synthesis
  - Re: coffee discussion yesterday, gaps in frequency coverage are handled just like gaps in (u,v) coverage --- they make your RMSF (beam) dirty, and you CLEAN
- RM synthesis transforms emission from frequency (or wavelength squared) space to Faraday depth (FD)
  - The term rotation measure is reserved for trivial single line fits
So What Is LOFAR?

• For the two or three of you in the audience who may not have heard a talk like this before
LOFAR: The Low Frequency Array

- Aperture array technology
  - digital processing
- Low Band (LBA)
  - normally 30 to 80 MHz
  - can do 10 to 80 MHz
- High Band (HBA)
  - 120 to 240 MHz
- 3rd input
  - open at International stations
  - extra LBA inputs for Dutch stations
    (better performance < 30 Mhz)
- 1.4 m to 1000 km baselines
  - 2"—0.25" maximum resolution

- Core (~2 km diameter)
- Remote (inside NL)
- International (outside NL)
### LOFAR Station Status

- **Status chart from 2010 April**
- **Most of the 36 Dutch stations are on the ground**
  - Core stations nearly complete
  - Remote stations should be finished by end of 2010 Summer
- **Approximately half of the International stations are complete**
  - Potsdam-Bornim hardware finished last week
  - All 8 international stations finished by end of 2010 Summer

#### Station/Item

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**Totals**: 31 30 25 29 29 22
LOFAR Image PR

- LOFAR HBA image from 2010 Winter
  - Dynamic range approaching 10 000 to 1
  - Single subband, so no MFS improvement on (u,v) coverage in this image
Wide Field Imaging Around 3C61.1

- This series of images allows you to see the ugly details
- PSF ugly
- But, the image was calibrated for only a single line of sight (no differential ionosphere correction)
- No significant emission (RFI) at the NCP

- Processing by S Yatawatta
Long Baseline Fringes

- First fringes to Effelsberg detected in 2009 August
- Fringes to Tautenburg and Unterweilenbach detected this winter
- Images of 3C196 made with effectively 4 stations using frequency synthesis over ~30—80 MHz
- Images in press release to come out soon
LOFAR Expected Performance

- Wide frequency coverage key to FD precision
  - Approximately inversely linear to $\Delta \lambda^2$
- Can reach 0.1 or 0.01 rad m$^{-2}$ for (sub-)mJy polarized emission
Cosmic Magnetism

- **LOFAR Key Science Project**
- Galactic and galactic magnetic fields play a central role in this KSP
- Need assistance with developing and commissioning LOFAR for polarization observations

MPIfR/Hubble Heritage Team

PI at 1.4 GHz (26m DRAO+30m Villa Elisa)

James M Anderson
Polarization Calibrators for LOFAR

• We have to go out and find our own calibrators for this frequency and resolution regime
Calibrators

- **Polarized Galactic emission**
  - Limited to short baselines
  - Extremely complicated rotation measure features

- **Pulsars**
  - Many pulsars are strongly polarized at low frequencies
  - Interstellar scattering probably limits baselines to less than a few hundred km for pulsars in the Galactic plane
  - 10 s ionospheric calibration timescale difficult to achieve with pulsars with pulse periods ~ 1 s (pulse to pulse variations)

- **AGN jets and lobes**
  - Probably require long baselines (> 100 km) to minimize beam depolarization
Fan Region (Galactic Emission)

- Westerbork LFFE observations
- Strong polarized emission
- Complicated FD structure
Pulsar Observations with LOFAR

- Many pulsars show strong polarization at low frequencies
- Averaging over pulse phase reduces fractional polarization --- may need to correlate with pulsar binning
- Pulsars already detected with LOFAR
- LOFAR polarized pulsar search planned to start as soon as initial detections made
AGN Polarization

- Many high brightness sources should have substantial polarization
- Expect significant polarization intensity out to long baselines
  - Important for International station calibration
- At LOFAR sensitivity, there should be a relatively high surface density of calibrators
  - Improves ionospheric mapping, but not sufficient

- Also important for use as probes of magnetic fields in other objects
Unpolarized Emission for Calibration

- Ionospheric Faraday rotation causes significant differential delay between stations at low frequencies
  - Strongest on long baselines, but significant at baseline lengths of a kilometer or less too
- Each station sees a different R-L delay
- For a linear detector system such as LOFAR, this causes the correlation to shift from the same hands (XX, YY) to the cross hands (XY, YX)
- This effect depends on inverse frequency, so it can be easily identified in the calibration
- Provides a (relatively) high signal to noise calibration of the relative ionospheric Faraday rotation across the array
Commissioning Plans

- Make polarization observations possible
Timeline (updated 2010 May 12)

- 2010 June       Polarized Pulsar Catalog Survey
- 2010 June End—July RM Synthesis Subband Optimization: Pulsars
- 2010 July Mid   RM Synthesis Software Testing
- 2010 July (Busy Week) RM Synthesis Subband Optimization: Fan Region
- 2010 August     RM Synthesis Software Testing
- 2010 September  Long Baseline Pulsar Calibrator Survey
- 2010 September  RM Synthesis Software Testing
- 2010 October    Jupiter Circular Polarization
- 2010 October    RM Synthesis Subband Optimization: AGN
- 2010 ???        Long Baseline MS³

Blue: specific interaction with Surveys KSP needed/desired
Polarized Pulsar Catalog Survey

• Find fundamental polarization calibrators on the sky for LOFAR
  - High frequency observations already give us the position angle
  - Contamination by Galactic emission able to be minimized

• Test basic ionospheric calibration
RM Synthesis Subband Optimization

- Determine standard subband selection setups for LOFAR polarization observations
  - RM synthesis optimization, RMSF, and so on
  - Calibration of instrument, ionosphere
  - Coordination with Surveys KSP for joint/piggybacking observations
Long Baseline Pulsar Calibrator Survey

- Find which pulsars for short-baseline polarization calibration are also good on long baselines
  - Expect scattering in the ISM to broaden most pulsars so severely that they cannot be detected on long LOFAR baselines
Jupiter Circular Polarization

- Circular polarization testing, including long baselines
RM Synthesis Software Testing

- Software testing on Groningen cluster
- RM synthesis software package being developed by MPA-Garching (T Riller)
- Part of the LOFAR pipeline processing system
  - So it needs to be able to operate without human interaction
- Staged development plan
  - Get the basic single-thread version working first
  - Implement RM CLEAN
  - Multi-threaded/multi-core version for cluster
  - Model fitting
- Long term plans for enhancements, wavelet transform, direct 3-D transformation from visibility data, allowing for components with different spectral indices, and so on
Long Baseline MS^3

• Including long baselines into MS^3
  - Million Source Shallow Survey
  - Initial all-sky survey for commissioning work and all-sky calibrator measurements

• Searching for polarization calibrators for long baselines

• Will concentrate on the brightest ~5 sources per station beam
  - Will produce early, sub-arcsecond images for a few thousand AGNs
  - Spectral information
  - Hopefully polarization information (RM synthesis cubes) for many of them
Software and Commissioning Challenges

- Simplifying the hardware means the software gets much more complicated
LOFAR Antenna Beam

• Linear polarization dipoles
• Sensitivity strongly depends on azimuth and elevation angle
• Strong polarization leakage off-axis
  - Antennas fixed to ground, so nearly everything is off-axis
  - “Zenith” the only on-axis direction
  - Leakage typically 25—50%

• Little polarization sensitivity at low elevations
• Strong frequency dependence

Because of high leakage terms, need to achieve effectively just as high dynamic range as Stokes $I$
  - You don't win even if the true $Q$, $U$, and $V$ are small

Analytic LBA dipole model by Yatawatta
Station Beams (Including HBA Tile Effects)

- Push to use wide-fields of view
- Time variable
- Must calibrate station beam out beyond half-power point
  - Very bright sources in sidelobes, especially at low frequencies
- Regular grid of HBA tile antennas introduces grating lobes

Stations built on ground with different rotations of antenna patterns to minimize interferometric sidelobe response
Dipole Polarization Orientation

- Design considerations for LOFAR require dipoles to be aligned as well as possible for all stations
- HBA antennas have to be backrotated to correct for station layout orientation
- All stations end up with slightly different polarization beams
- Long baselines cannot be aligned perfectly for all directions on the sky
- Software calibration important
Polarization Calibration by the LLBWG

- LOFAR Long Baseline Working Group
- VLBI community used to working with complicated systems that frequently don't work exactly right...
Differential Faraday Rotation

- Each plot shows the Faraday differential delay (color) and signal strength (brightness) for different baselines, as a function of time (~6 hours) and frequency (30—80 MHz)
LBA Polarization Swaps

- Long baseline observations showed that the signal was in the cross-handed correlations, after correcting for ionospheric Faraday rotation
  - Frequency increases going to lower plots at left
  - Should end up with mostly same-handed (magenta) signal, but instead have cross-handed (cyan) signal

- Initially suspected that the German stations had connected the polarization wrong, but instead the Dutch stations have a feature that the polarization is swapped in a specific observing mode
HBA Polarization Swaps

- Another polarization problem first detected in an International LOFAR station
- HBA antenna construction subcontractor in the Netherlands connected the X and Y cables at random when an (untrained) worker was moved in the assembly line
- Affects stations installed after 2009 October
- All stations being checked and polarization swaps fixed
Details (If TimeRemains)
Station Electronics: Gory Details

- Polyphase filterbank converts the time series data from each dipole/tile into $512$ (513) frequency subbands
  - 195.3125 kHz subbands for 200 MHz clock
  - 156.2500 kHz subbands for 160 MHz clock
  - 16 bit complex number (16 bit real, 16 bit imaginary) for each subband every 5.12 $\mu$s (200 MHz) or 6.40 $\mu$s (160 MHz clock)

- Beamformer hardware processes up to 248 of these subbands
  - 248 subbands determine bandwidth available to beamformer
    - 48.4375 MHz for 200 MHz clock
    - 38.7500 MHz for 160 MHz clock
  - Arbitrary subband selection by astronomer
  - Frequency coverage not required to be contiguous
  - Calibration will work best in full production system with wide frequency coverage
Frequency Comb

- No requirement to have contiguous frequency coverage
- Best astronomical performance often achieved with large frequency coverage
- Distribute subband allocation across the entire band (a frequency comb)
- Using multiple combs with offset subband selections during the same observation allows the entire frequency range to be covered
- Can also allocate more subbands around some frequency to weight observations for particular goal
LOFAR Data Rates

- Correlator polyphase filterbank generates 256 channels per subband by default
  - 763 Hz channel width for 200 MHz clock
  - 610 Hz channel width for 160 MHz clock
  - Total of 63488 channels for standard 16 bit mode
  - 253952 channels for 4 bit mode

- **Visibility output rate** limited to 50 Gb/s (6.25 GB/s) by current storage cluster input rate
  - For LOFAR operation (18 Core, 18 Remote, 8 International stations):
    - LOFAR Core (18 C stations), 1 s integrations
      - 16, 8, and 4 bit data modes all fit under storage rate limit
    - LOFAR Remote (18 C + 18 R stations), 1 s integrations
      - 16, 8 bit data modes all fit under storage rate limit (but I have ionospheric worries)
      - 4 bit fits for LBA, does not fit for HBA
    - LOFAR International (18 C + 18 R + 8 I stations), 0.25 s integrations
      - All bit depths have storage rates too high
      - 127 Gb/s for 16 bit mode, 508 Gb/s for 4 bit mode (15.9, 63.5 GB/s)
Processing the HBA Station Beam

- Station beam 2.5 to 1.2 degrees in size (120 to 240 MHz)
  - Assume 2 degree beamsize for imaging
- LOFAR synthesized resolution ~ 0.4 to 0.2 arcseconds
  - Assume typical 4 pixels across beam for imaging
  - $1.1 \times 10^{10}$ pixels per station beam (47 GB per frequency)
- Faraday depth resolution 0.1 rad m$^{-2}$, range ±100 rad m$^{-2}$
  - $2.3 \times 10^{13}$ pixels per FD cube (93 TB)
- Extragalactic Faraday depth search
  - Faraday depth resolution 1 rad m$^{-2}$, range ±10 000 rad m$^{-2}$
  - $2.3 \times 10^{14}$ pixels per FD cube (930 TB)
  - Faraday depth resolution 0.01 rad m$^{-2}$, range ±10 000 rad m$^{-2}$
  - $2.3 \times 10^{14}$ pixels per FD cube (93 PB)
RM Range and Frequency Resolution

- Default correlator resolution (256 channels per subband) allows one to measure a maximum Faraday depth of $\pm 13\,000\,\text{rad}\,\text{m}^{-2}$ at 120 MHz.
- $|FD| \leq \nu^3 / (2c^2 \Delta v_{ch})$
- 30 50 120 240 MHz 200 MHz clock
- 200 900 13 000 100 000 rad m$^{-2}$
- For HBA observations, can average significantly in frequency if one is willing to accept a maximum FD of only 1000 or 100 rad m$^{-2}$
Frequency Combs: High Band

- Frequency coverage and RMSF shown for 120 and 210 MHz bands of 8 MHz and 16 MHz bandwidth, and the MKSP comb proposal
- Channel weights for each group arbitrarily shifted vertically for clarity
- Takes into account LOFAR instrument sensitivity
Frequency Combs: MKSP High Band

- Frequency coverage and RMSF shown for MKSP comb proposal for a single RCU mode 5 comb, the combined RCU mode 5 combs, and the combined HBA combs
- Instantaneous RMSF relatively clean (single RCU comb)
  - Critical for calibration measurements on 10 s to 1 min timescales
- Combined combs greatly reduce RMSF sidelobes at high RMs
- Subband bandpass flagging forces minimum sidelobe level
Frequency Combs: Low Band

- Frequency coverage and RMSF shown for 15, 30, and 60 MHz bands of 8 MHz and 16 MHz bandwidth, and the MKSP comb proposal
- MKSP believes low band calibration extremely difficult
  - Ionosphere really nasty with $\nu^3$ dependence, Solar maximum coming
The End

- LOFAR MKSP web page
- Pretty pictures
  - http://www.astron.nl/dailyimage