Implementing Polarimetry at P-band on the VLA

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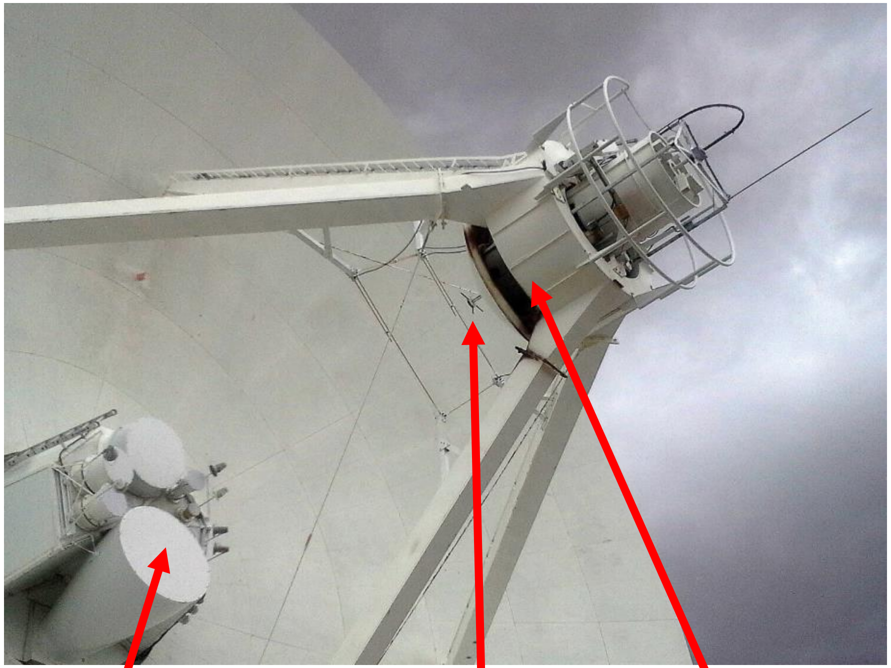
Low Frequencies on the VLA – A Short History

- The VLA was not designed for low frequencies.
  - The antennas employ Cassegrain optics, which prevents access to the prime focus.
  - 330 MHz system added in late 1980s, with feed ~70cm out of focus.
  - Results in a primary beam with very high 'wings'.
- The original system was relatively narrowband (~20 MHz centered near 330 MHz), and used circular polarization.
- Polarimetry was rarely attempted -- few users were interested in low frequency polarimetry – little demand to make the system work better.
- The EVLA Upgrade Project (2000 – 2012) brought a new electronics system, and the old narrowband receivers were replaced with a better wideband system.



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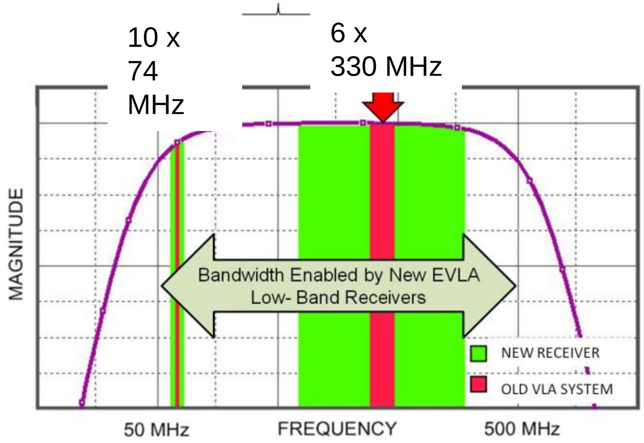
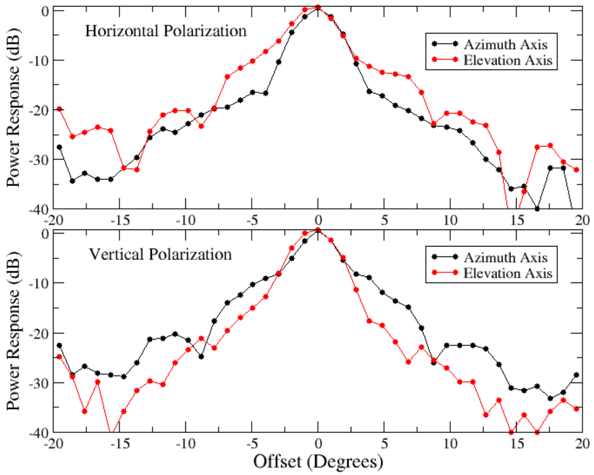
New Wideband Low Frequency Receivers

- Wideband circular polarizers were not available, so we (reluctantly) implemented linear systems.
- Much interest in low frequency polarimetry now – but how to implement?
- Effort to do this started two years ago --- nearly finished now.
- Process to understand and implement polarimetry at this band hindered by:
  - Our misunderstandings!
  - Lack of polarized calibration sources
  - High RM of some calibrators
  - Dynamic ionosphere and ionospheric RM
  - A nasty observing environment.

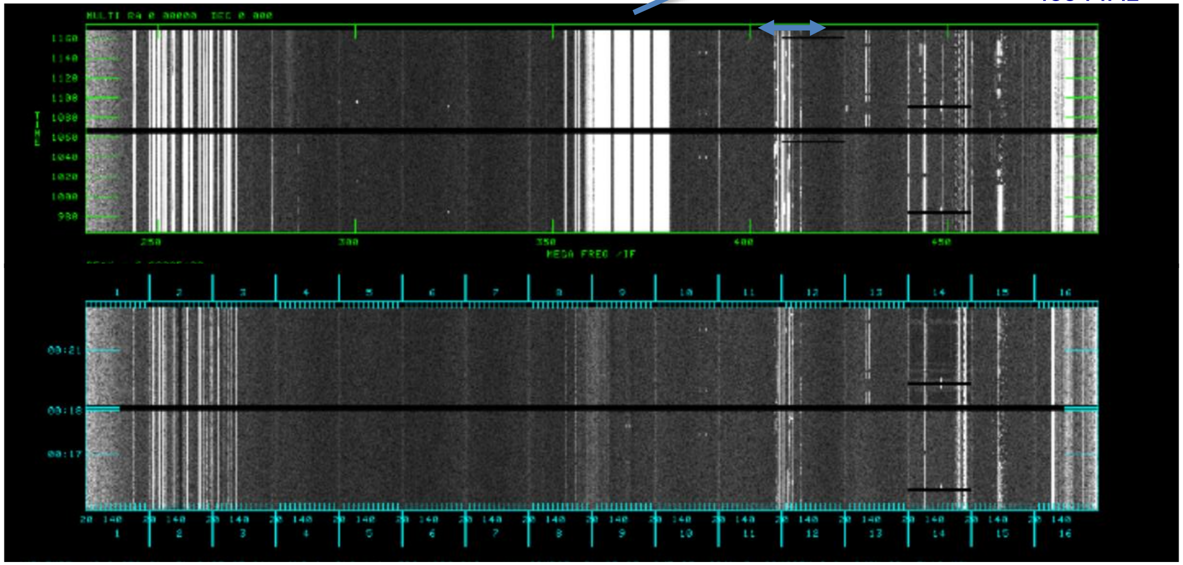




RFI Spectrum – tough, but manageable

- The 230 – 486 MHz range contains RFI.   It is much worse for C and D configurations, relatively benign for A and B.
- About 1/2 -- 2/3 of the spectrum is useable.
- Two example spectra are shown.

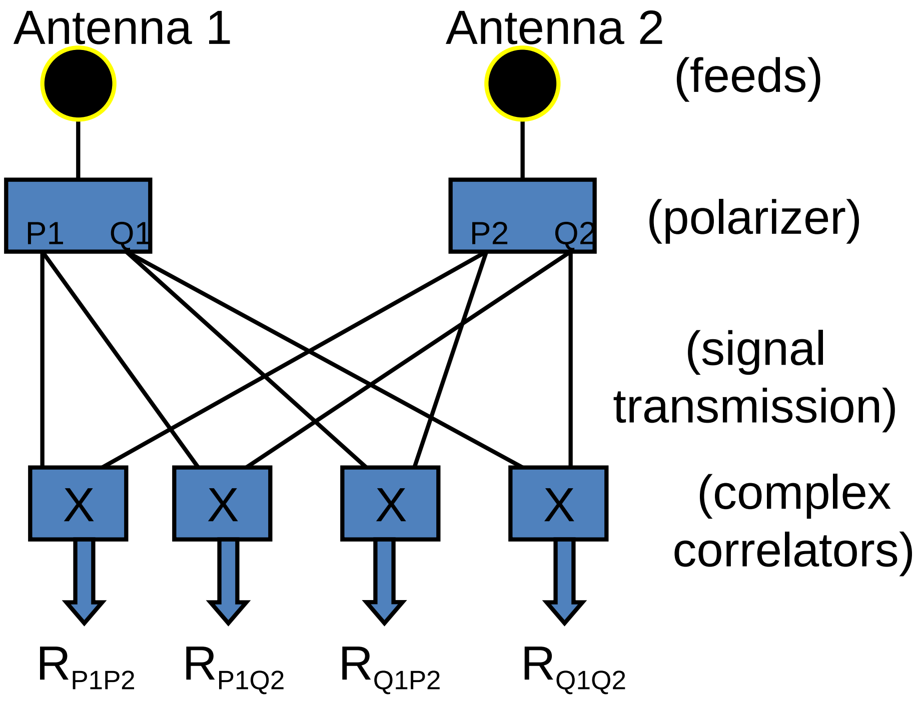
MUOS: Mobile User Objective System.
4 geosynchronous satellites. (USN)



Results reported here from this band

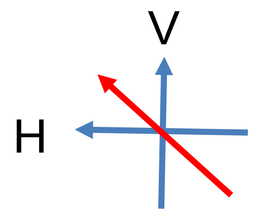
A Brief Primer on Interferometric Polarimetry

- Two antennas, each with two differently polarized outputs (p,q), produce four complex correlations. $\mathcal{R}_{p1p2}$ $\mathcal{R}_{q1q2}$ $\mathcal{R}_{q1p2}$ and $\mathcal{R}_{p1q2}$
- From these four outputs, we want to generate the four complex Stokes' visibilities, $\mathcal{I}$, $\mathcal{Q}$, $\mathcal{U}$, and $\mathcal{V}$, whose (spatial) Fourier transforms give us the desired images.
- Analysis gives the relation between the correlations and the Stokes' visibilities.



Some Brief Analysis

- It is relatively straightforward to analyze the response of the system to radiation with arbitrary polarization, using the Jones matrix formalism
- If one tries to include 'everything', the equations get a bit messy.
- So I'll show the analysis for a relatively simple, but representative, system, sufficient to get the basics sorted out.
- Assumptions:
  - Orthogonal dipoles on an az-el mounted antenna, all with same parallactic angle Ψ_P.
  - Dipoles misoriented (w.r.t. antenna frame) by angle θ.
  - No cross-polarization leakage (D terms = 0).
  - Dipole phasing such that a source with +U polarization results in 'H' and 'V' signals in phase.



Phase relationship between channels has major effect on imaging!

Some Equations…

- With this simple model, the relationship between the radiation (characterized by Stokes parameters I, Q, U, and V), and the complex visibilities, R, provided by the interferometer are:

$$R_{v1v2} = G_{v1}G^*_{v2}\left\{I\cos\Delta\Psi + Q\cos\Sigma\Psi + U\sin\Sigma\Psi - iV\sin\Delta\Psi\right\}$$
$$R_{v1h2} = G_{v1}G^*_{h2}\left\{I\sin\Delta\Psi - Q\sin\Sigma\Psi + U\cos\Sigma\Psi + iV\cos\Delta\Psi\right\}$$
$$R_{h1v2} = G_{h1}G^*_{v2}\left\{-I\sin\Delta\Psi - Q\sin\Sigma\Psi + U\cos\Sigma\Psi - iV\cos\Delta\Psi\right\}$$
$$R_{h1h2} = G_{h1}G^*_{h2}\left\{I\cos\Delta\Psi - Q\cos\Sigma\Psi - U\sin\Sigma\Psi - iV\sin\Delta\Psi\right\}$$

Where the G terms are the parallel hand complex gains,

$\Delta\Psi = \theta_1 - \theta_2$, (difference in misalignments)

$\Sigma\Psi = 2\Psi_p + \theta_1 + \theta_2$, where Ψ_p is the parallactic angle.

- These look rather messy, but in fact are easy to deal with, so long as you know the angles and gains.
- However, determining these quantities presents some challenges.

Solutions …

- Basic math can then be used to give us the solutions, written below:

$$I = (R^{cal}_{v1v2} + R^{cal}_{h1h2})\cos\Delta\Psi + (R^{cal}_{v1h2} - R^{cal}_{h1v2})\sin\Delta\Psi$$
$$Q = (R^{cal}_{v1v2} - R^{cal}_{h1h2})\cos\Sigma\Psi - (R^{cal}_{v1h2} + R^{cal}_{h1v2})\sin\Sigma\Psi$$
$$U = (R^{cal}_{v1v2} - R^{cal}_{h1h2})\sin\Sigma\Psi + (R^{cal}_{v1h2} + R^{cal}_{h1v2})\cos\Sigma\Psi$$
$$iV = -(R^{cal}_{v1v2} + R^{cal}_{h1h2})\sin\Delta\Psi + (R^{cal}_{v1h2} - R^{cal}_{h1v2})\cos\Delta\Psi$$

where the R^{cal} means the visibility has been corrected for the parallel hand gains. For example, $R^{cal}_{v1v2} = R_{v1v2} / G_{v1}G^{*}_{v2}$

- So, 'all we have to do' is to determine the G terms, the misalignment angles, and the parallactic angle. What can go wrong?
- Quite a lot. Issues of signs and conventions are important.
- And at 330 MHz, full calibration is definitely challenging.

Calibration – How to Do It at P-band

- The choice of a linearly polarized receiving system presents a problem in calibration if knowledge of the calibrators' Q, U, and V are not known in advance.
- For E-W interferometers such as WSRT and ATCA, long observations are required to make an image, so the method of Conway and Kronberg can be used to determine the calibrator polarization along with the antenna polarization.
- For 2-d interferometers, like the VLA and GMRT, which can employ a 'snapshot' mode, such long observations are often not done, so calibrator Q, U, V unknown.
- Easiest thing to do is to utilize unpolarized sources for calibration. Then,

$$R_{v1v2} = G_{v1}G^*_{v2}\left\{I\cos\Delta\Psi\right\}$$
$$R_{v1h2} = G_{v1}G^*_{h2}\left\{I\sin\Delta\Psi\right\}$$
$$R_{h1v2} = -G_{h1}G^*_{v2}\left\{I\sin\Delta\Psi\right\}$$
$$R_{h1h2} = G_{h1}G^*_{h2}\left\{I\cos\Delta\Psi\right\}$$

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Parallel-Hand Calibration

- For an unpolarized source, we use:

$$R_{v1v2} = G_{v1}G_{v2}^{*}\{I\cos\Delta\Psi\} \approx G_{v1}G_{v2}^{*}I$$

$$R_{h1h2} = G_{h1}G_{h2}^{*}\{I\cos\Delta\Psi\} \approx G_{h1}G_{h2}^{*}I$$

- We can use the existing programs to determine the delay, bandpass, and parallel-hand gains.
- But -- the calibration regimen refers all phases to the reference antenna.
- After calibration, the phase difference between the reference antenna's parallel hand signal chains remains.
- For a circular system, the result is to rotate the Stokes vector in the Poincare sphere about the V axis. Equivalent to a rotation of the antenna on the sky.
- But for a linear system, the rotation is about an axis in the (Q,U) plane, rotated by $2\Psi_p$ from the Q axis. This 'mixes' the linear and circular polarizations. At Ψ_p=0 or 180, the rotation is about the Q axis. At Ψ_p = +/- 45, it is about the U axis.

Crossed –Hand Phase Calibration

- This proceeds in two steps:
  1. Determine the crossed-hand delay.
  2. Determine the crossed-hand phase offset.
- The first requires a strong unpolarized source.
- The second requires imaging a strongly polarized calibrator, and determining the phase which gives Stokes V = 0. Analysis shows:

$$\phi = \arctan\left[\frac{-V}{U}\right]$$

- In practice, this requires determining the V and U images of a strongly polarized source when the parallactic angle is 0 or 180 degrees.
- The phase is applied uniformly to the 'V' side for all antennas.

Misalignment Angles

- Finally, we have to determine the misalignment angles. This is done using the cross-hand data (unpolarized source):

$$R_{v1h2} = G_{v1}G^*_{h2}\left\{I \sin \Delta\Psi\right\}$$

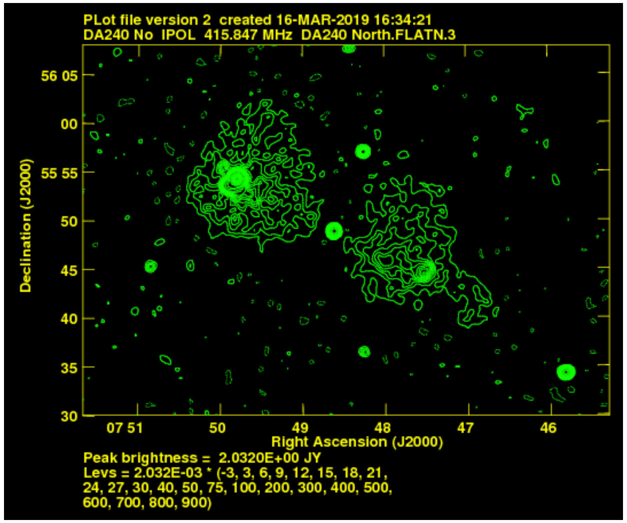
$$R_{h1v2} = -G_{h1}G^*_{v2}\left\{I \sin \Delta\Psi\right\}$$

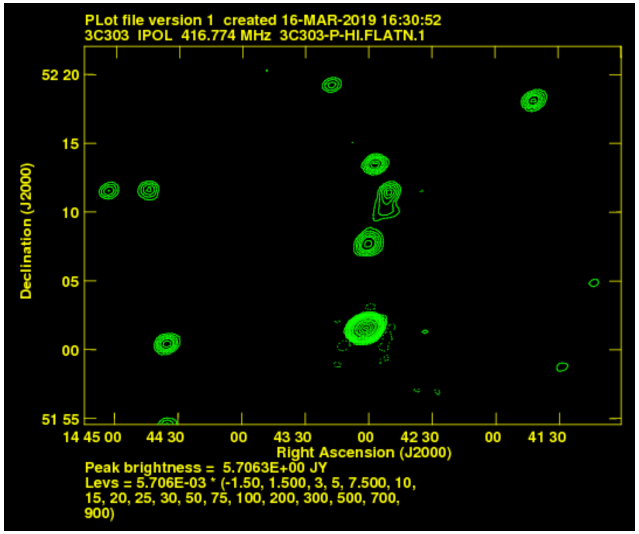
- In practice, the AIPS program 'PCAL' does this. (And it solves for the leakage terms (antenna ellipticity) at the same time!).
- Note that we require misaligned feeds in order to use this method!
  - The antenna polarization (leakage) is also removed in this step. (analysis not shown).

- Final Step: Remove the ionospheric rotation.
  - This step has not been worked out yet.
  - Easy to do in image plane.

The Polarized Test Sources …(hard to find)

- The WSRT used DA240 (hotspot in eastern lobe) and 3C345 as their polarized reference sources.
  - DA240 is strong and highly polarized (20% of ~2.5 Jy), with low RM (3 rad/m^2), but will resolve out in A configuration. OK for C and D. Don't know about B.
- 3C345 is weakly polarized (2% of 9 Jy), with modest RM (20 rad/m^2), so harder to use. It is unresolved to all configurations.
- Frank Schinzel suggested 3C303's hot spot. This is very similar to DA240's, but the RM is higher – about 25 rad/m^2.
  - This is enough to depolarize the signal over about 20 MHz bandwidth…





The Polarized Test Sources …(hard to find)

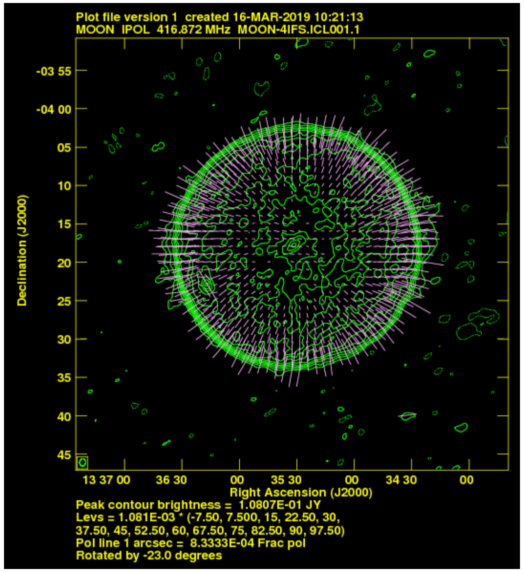
- Pulsars are known to be highly polarized, but require pulsar gating for SNR to be sufficient. Not an attractive option.
  - We tried using a range of pulsars in our first test, but none were detectable in polarization.
- The best source to convince ourselves we have things right is the Moon. Its polarized distribution is known to high accuracy (even if the signals are rotated by the ionosphere).
  - The moon MUST show a polarized ring of emission, of 30' diameter (i.e., the rim of the moon is polarized), with the E-field pointing radially away from the center.
  - But, the moon has low brightness (~220 K, so ~60 Jy at 420 MHz), and large angular size.
  - Is useful only for C and D configs. (resolution of 140 and 45 arcseconds, resp.)

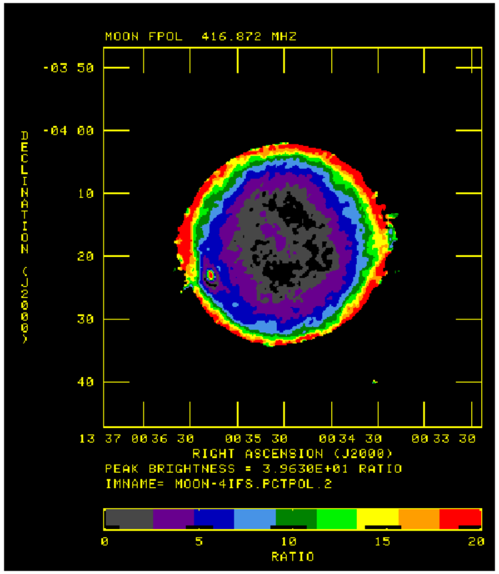
The Test Observations

- Test 1: D configuration, 10 May 2017, for 6 hours.
  - 1.5 hours on the moon. Rest of the time on pulsars, 3C295, 3C345, and DA240. This test was set up by Frank Schinzel.
- Test 2: C configuration, 06 August, 2017, for 8 hours.
  - 6 hours on moon, rest of time on 3C345, 3C295, 3C48, and a local calibrator
  - DA240 was not up, and so was not observed.
- Test 3: C configuration, 30 December, 2018, for 12 hours.
  - Much more time spent on DA240, 3C303, and 3C345.
  - Observations of unpolarized sources 3c147, 3C295, and 3C286 to set the gains and flux density scale.
  - 3C273 (12 degrees away from the moon) was used as local calibrator.
    - We had hopes it would show detectable polarization, but it is less than 1%.

Final Image in Contour Form

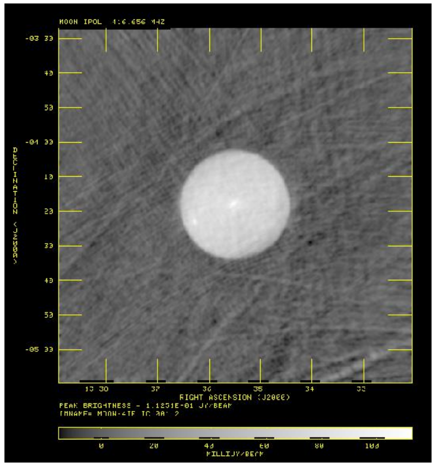
- Total lunar flux ~ 60 Jy.
- Polarization maximum on the edge ~ 25%.
- Vectors shown rotated by -25 degrees – this due to ionospheric rotation. (RM ~ 0.74 rad/m^2).
- Radial orientation exactly as expected.
- I image can be made a lot better by removing the (moving) background sources.
- The H-V phase offset was -16 degrees in the high frequency SPWs, and +11 for the low frequency SPWs (using ea03 as the reference).



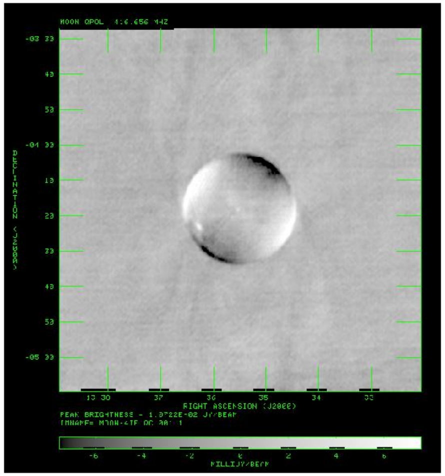


The individual Stokes Images

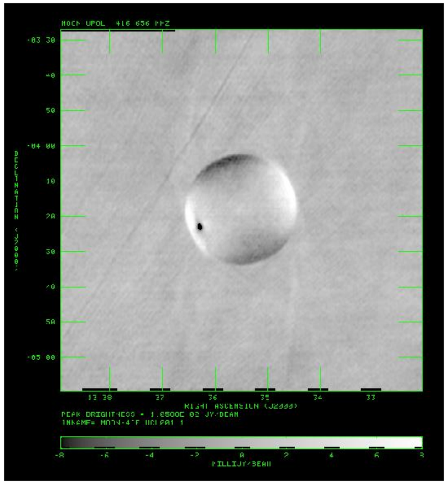
I



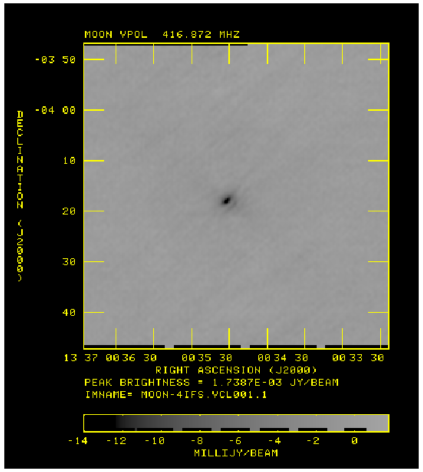
Q

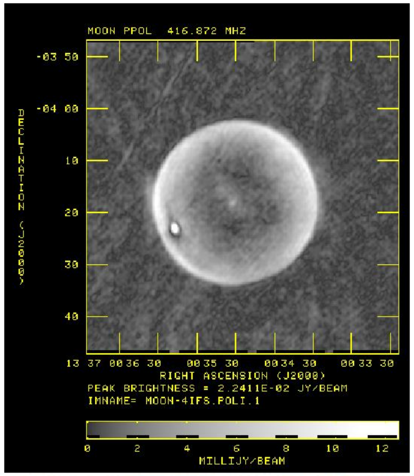


U



V





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Intensity

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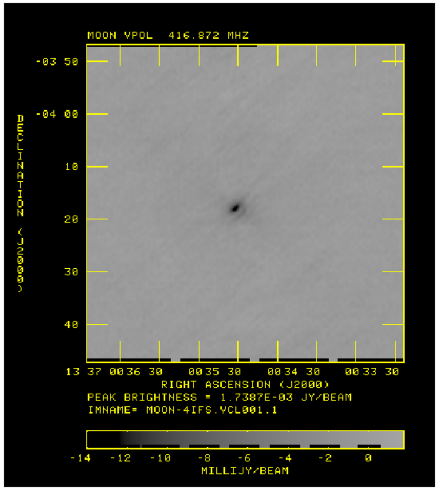
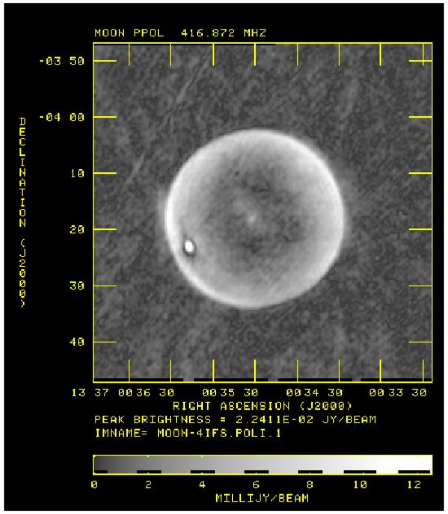
Some Features to Note

- The Stokes 'V' image shows a response from the moon's center.
- We interpret this as 'earthshine' – reflected signals of terrestrial origin.
  - I have not checked to see if this is frequency dependent
- More curious is the bright, strongly polarized spot on the SE limb:
  - This is reflected sunshine! The line from the lunar center through the spot points directly to the sun.
  - The polarization of the spot is exactly transverse to the radius from the center – exactly as predicted (due to refractive effects at the lunar surface).
  - Thanks to Justin Bray for pointing this out to me.



V



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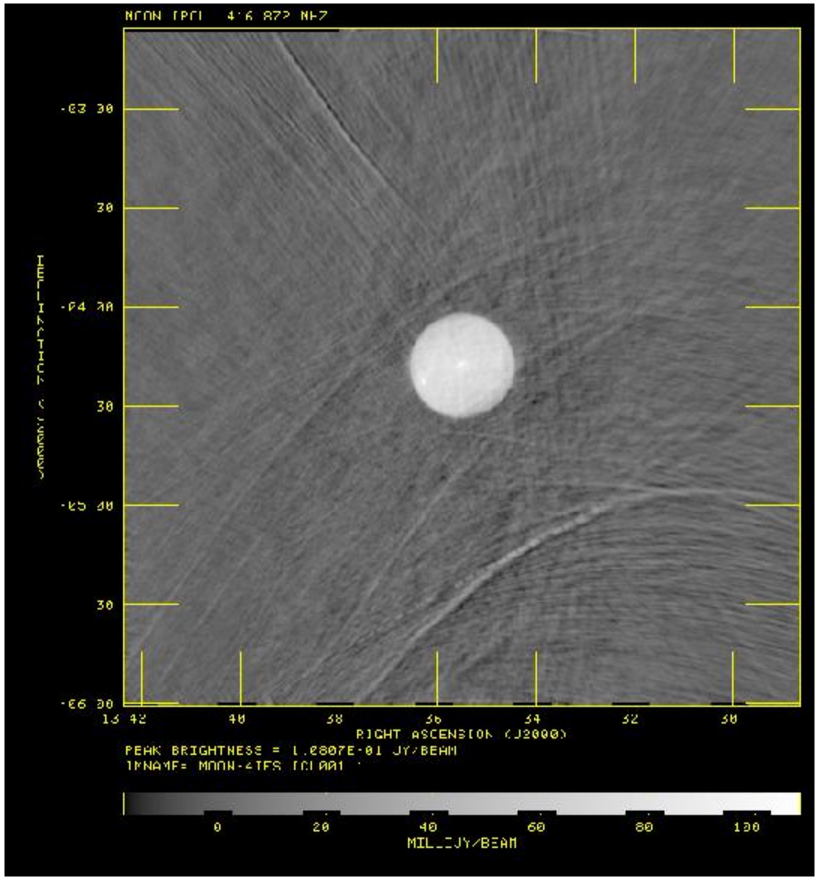
About Those Curious Lines in Stokes I…

- The Stokes I image has curious arcs (parabolas) arching through it…
- These are the rotating and translating sidelobes of background sources which are 'moving' through the field of view (which is following the moon).
- In general, the sources themselves are not visible (one exception), but the six-armed sidelobes are!



Summary

- We have (mostly) figured out how to utilize the VLA's linear polarization 'low-band' feeds to enable polarimetry at low frequencies.
- Most of our troubles were 'self-inflicted', due to ignorance or engrained thinking based on how circularly polarized systems work.
- The last remaining issue is how to best manage the ionospheric rotation in (Q,U).
- There is a need for more polarized calibrators at these frequencies.
- An upcoming EVLA Memo will fully describe how all this works.