EVLA Memo 210
Lunar Polarimetry at L-band

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Abstract

The electric field position angle (EPA) for 3C286 and 3C138 at 1 – 2 GHz has been accurately determined by observations of the lunar disk with the VLA, while in the D configuration. The EPA of 3C286 at L-band is within 1 degree of the assumed value of 33 degrees. There is marginal evidence that, at the lower edge of the band, the EPA decreases to ∼31.5 degrees.

1 Introduction and Motivation

The linearly polarized thermal emission from a sphere (such as a planet or planetary satellite) must be radially oriented, reaching a maximum of near 30% near the limb. This fact can be utilized to calibrate the true EPA of linearly polarized sources, and can be utilized to assist in the development of polarimetry, especially for linearly polarized antenna arrays. The former application is described in detail in Perley & Butler (2013 – ApJS **206**, 16), where observations of Mars were used to show that the EPA of 3C286 increases slowly with increasing frequency, for frequencies higher than 8 GHz. The latter application was used by Perley & Greisen in EVLA Memo 207 in establishing polarimetry capabilities in AIPS for reduction of VLA P-band data.

MeerKat is now commissioning its linearly polarized systems, using the moon as a standard reference, in the same way that Perley & Greisen did for the VLA's P-band system. This effort has been led by Ben Hugo, who recently communicated to me the surprising result that the apparent EPA of 3C286 at L-band was observed to be 5 to 8 degrees less than the presumed value of 33.

Although Ben suggested (and subsequently demonstrated) that the likely origin of this unexpected EPA was misaligned feed orientations on the antennas combined with ionospheric rotation, the possibility that the EPA of 3C286 might be different than what has been used for decades encouraged me to check the result using VLA data. With our circularly polarized feeds, the VLA data are not affected by feed orientation issues, so this possible source of error in MeerKAT is avoided.

It is very difficult for the VLA to use Mars for this observation, as it requires observations of Mars when in opposition (and hence is of maximum angular size) at the same time that the VLA is in its A configuration. This is a rare occurance. Opposition occurs about every 26 months, with the next one occuring in December 2022. The array will not be in A configuration then, and projections of whether it will be at the next opposition in early 2025 are speculative, at best.

The moon can also be used for this purpose, although it is rather large – it fills the entire VLA primary beam at L-band. For this observation, we must be in the D configuration in order to not resolve out the expected polarimetric signal. By happenstance, the MeerKAT report was received 5 days before the end of the 2021 D configuration – and open time was available to do this observation. The declination of the moon at the time ($\delta \sim -21$) was not optimal, but the six hours of time during which the moon is above an elevation of 20 degrees was sufficient for a secure observation.

2 Observations and Calibration

The observations were taken in the morning of 31 May, 2021, when the moon was near 21h in right ascencsion, and −21 degrees declination. Observations of the polarized calibrators 3C286 and 3C138 were taken before and after the lunar observations. The unpolarized source J1407+2827 was also observed, as a safety precaution.

The phase calibrator was J2131-2036, which was very close to the moon on that day. The observation duration of 6.25 hours was set to the time interval at which the moon was above an elevation of 20 degrees. The frequency setup was standard L-band 'continuum' – 16 spectral windows of width 64 MHz and channel with 1 MHz, which thus spanned the 1 – 2 GHz band.

Calibration was by standard methods. Each spectral window was individually calibrated. Four SPWs were abandoned due to RFI – centered at 1168, 1230, 1552,and 1616 MHz. Band-limited RFI in other SPWs were flagged at the outset – no attempt at sophisticated RFI removal was attempted (nor was it needed). Polarization calibration followed standard methods, with the R-L phase set by assuming the EPA of 3C286 to be 33 degrees.

As described below, the resulting data from these standard operations suggested that the EPA of 3C286 was indeed rotated a few degrees CCW from the well-established value of 33 degrees. HOwever, as one explanation of this is ionospheric rotation, the program TECOR was run on the calibrated data. As reported below, this completely removed the apparent discrepancy.

2.1 Calibrator Occultation!

The VLA's OPT had informed us that the chosen calibrator J2131-2036 passed close to the moon during the observation. However, as OPT reported the minimum separation from the lunar center appeared to be about 0.8 degrees, it was decided to continue with the observation on this day, as this separation is sufficient to keep the calibrator out of the main beam. Unfortunately, the OPT's ephemeris is not very accurate, and in fact the calibrator was occulted by the moon (!) for 1 hour and 15 minutes, near the end of the observation. This event considerably complicated calibration, as the sharp limb of the moon contributed enough visibility to make gain calibration impossible for about 30 minutes on each side of the occultation (as well, of course during the occulation itself). Fortunately, the phase and amplitude stability of the array was extremely good (deviations of only a few degrees), so the affected calibrator data could be removed without harm to the imaging. There remained enough parallactic angle rotation of the calibrators to enable a good polarization leakage solution.

The passage of a bright calibrator through the main beam also influenced the lunar imaging – however this effect was relatively minor.

3 Visibility Plots

As a bright, uniform circular body without an atmosphere, the visibilities from the moon will show well defined visibility maxima, modified only by the radial attenuation due to the primary beam. We show in Fig 1 the observed visibility amplitudes in the lowest frequency spectral window (at 1040 MHz), where the beam attenuation is relatively minor.

The visibility plots are quite striking, and show the high quality of the data. The phases (not shown) alternate between 0 and 180 degrees for each 'lobe' of the visibility function – as expected for a bright, sharp disk.

In fact, the visibility plots do show deviant amplitudes, from the expected bessel-function maxima for limited periods of time – the half hours preceding, and following, the occulation. (The data from these times have been omitted in the plot above). These apparent deviations are due to the presence of the moving calibrator, as it enters and departs the antenna main lobe, outside the lunar disk.

The spread in maximum amplitudes in the innermost visibility maxima show that the lunar disk is not perfectly circular – the emission is weaker near the poles, due to a lower temperature in those regions. This is seen in the generated images.

4 Imaging

I, Q, and U images were made from each useable spectral window. Deconvolution of the 'I' images is tricky, due to the very large and featureless lunar disk. as single-scale 'CLEAN' breaks the emission into a sea of little 'lumps', while my attempts at employing multi-scale 'CLEAN' utterly failed. Fortunately, for the purpose of this report, only the Q and U images are required, for which these well-known imaging problems are not a problem.

At the lowest frequencies, standard single-component deconvolution worked well enough to enable display. I show in Fig 2 examples of the I, Q, and U images at 1040 MHz, along with the polarized intensity $P = \sqrt{Q^2 + U^2}$. All are corrected for the primary beam attenuation. Ionospheric rotation was estimated and removed through the use of TECOR. The calculated ionospheric RM varied from 1.5 to 2.1 rad/m/m.

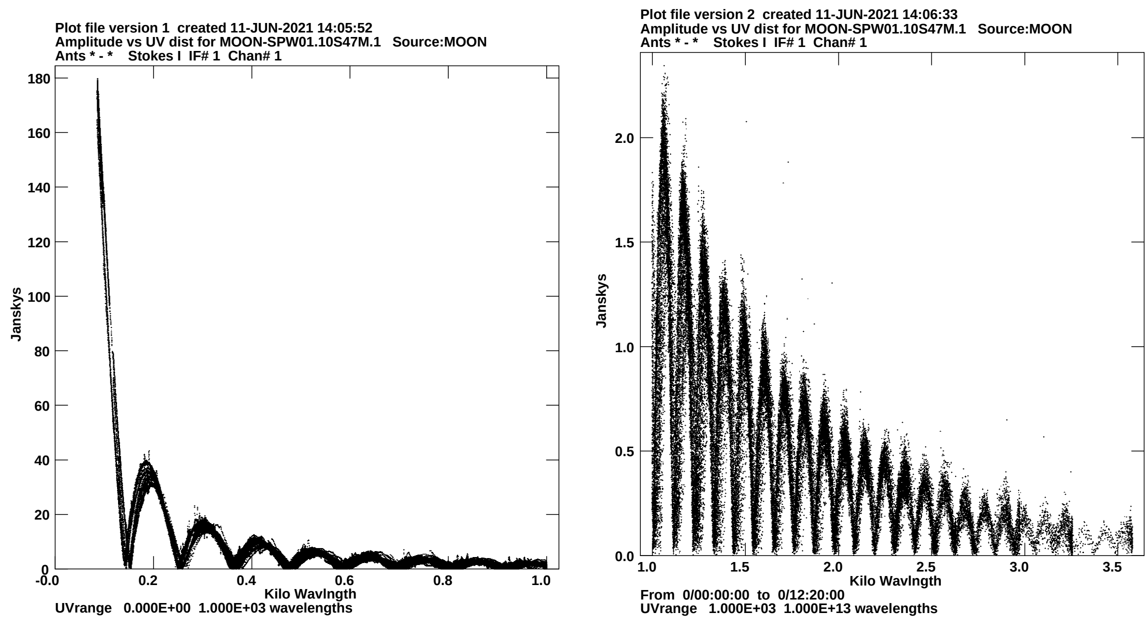

Figure 1: The visibility amplitudes of the moon at 1040 MHz. The left panel shows the function for baselines out to 1 Kλ, the right panel shows the function from 1 Kλ out to the maximum baseline. The maximum visibility of $\sim$ 180 Jy is half the total flux.

The images show a slightly elliptical orientation – this is due to higher emissivity in the equatorial regions due to solar inclination angle. The lunar pole is tilted CW by 20 degrees, in good alignment with the apparent minor axis of the image brightness. The slight eastward maximum is towards the sun, which on the day of observation followed the moon by about 8 hours. The maximum fractional polarization is about 20%. The Stokes 'Q' and 'U' images clearly show the EPA is very close to radial.

A contour plot, with overlaid polarization vectors, of the emission at 1040 MHz is shown in Fig 3.

5 Analysis

The mean deviation of the lunar EPA from radial was measured with the special AIPS program 'MARSP', which was written by Eric Greisen for the analysis of the polarized emission of Mars. The correct lunar EPA must be radial, so any average deviation observed in these data must be caused by one (or more) of: ionospheric rotation; rotation or offset inherent to 3C286; or 'instrumental mishap' – something intrinsic to the telescope or calibration.

As it was believed that the ionospheric rotation would be low (observations late at night, no strong solar activity), initial analysis was done without TECOR – the results indicated a clear rotation with RM $\sim$ 1.4 rad/m/m. An ionospheric RM of 1.4 is a little higher than usual, but hardly outside the range of possibility. After application of TECOR, the observed deviations from radial virtually disappeared, with a residual slope in the RM of -0.5 $\pm$0.2 rad/m/m. An offset angle of 1.5 $\pm$ 0.6 degrees remains – this may indicate the true EPA of 3C286 at L-band is closer to 31.5 degrees. Better data, (especially from S-band) and/or more careful analysis, will be needed to determine if this is correct.

The data, before and after TECOR, are shown in Fig 4.

6 Conclusions and Acknowledgements

Polarimetric observations of the moon made with the VLA confirm that the EPA of 3C286 at L-band (1 – 2 GHz) is very close to that which has long been utilized in polarimetric calibration at the VLA. It is marginally determined that the true EPA is closer to 31.5 degrees than 33 at this band, but further work will be needed to confirm this.

A secondary conclusion is that the AIPS program TECOR, which is based on ionospheric TEC data combined with a simple dipole model of earth's magnetic field, is sufficient to allow removal of ionospheric Faraday rotation, at least for conditions of modest TEC and low solar activity.

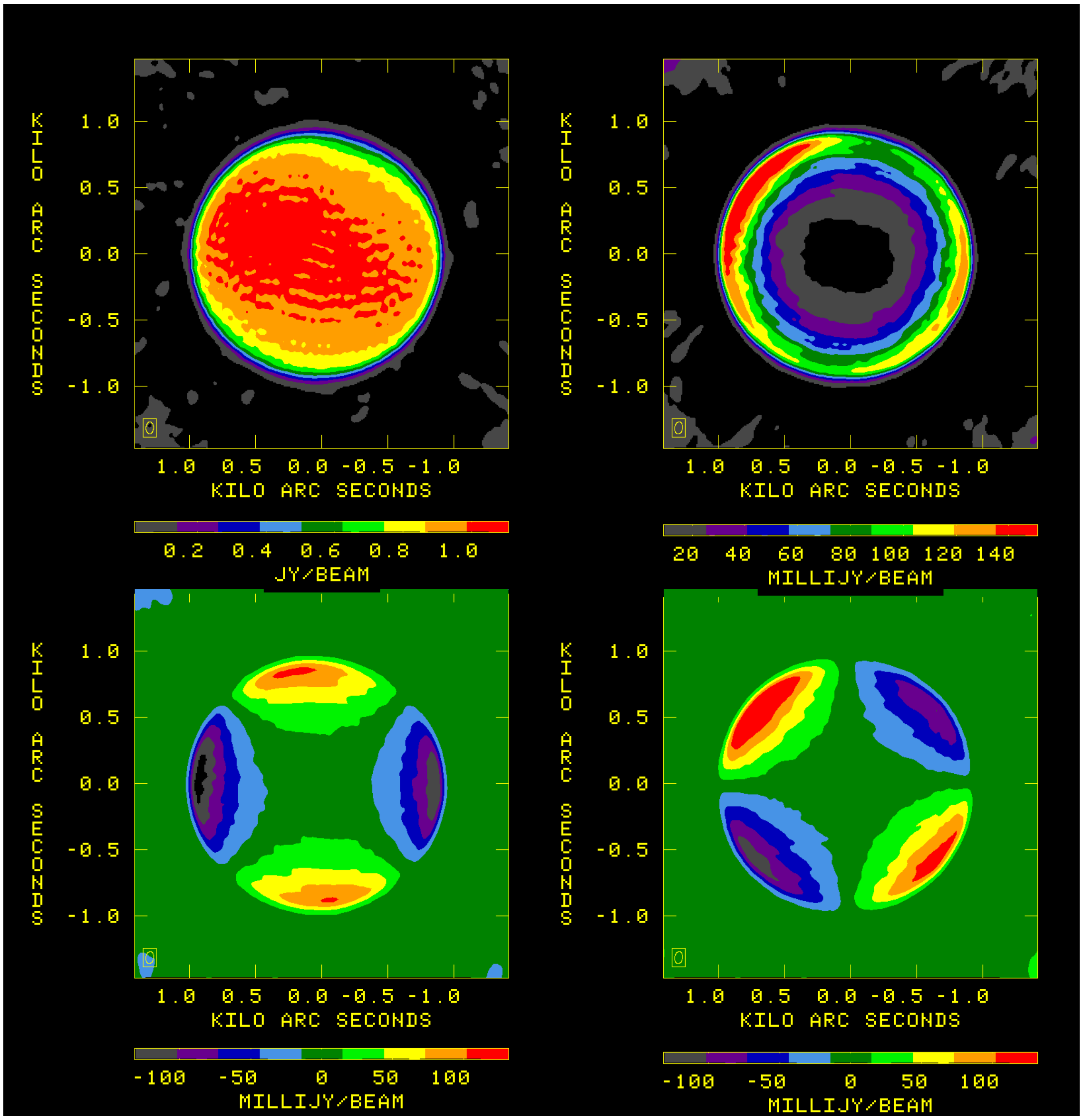

Figure 2: Images of the moon at 1040 MHz. All are corrected for primary beam attenuation. Stokes 'I' in the upper left, polarized intensity in the upper right, Stokes 'Q' in the lower left corner, and Stokes 'U' in the lower right. The evident corrugations in the 'I' image are due to a CLEAN instability.

A remarkable observation is that the intrinsic RM of 3C286 is less than 0.5 rad/m/m (in absolute value), and the EPA remains at 33 degreees, even at 1 GHz where its fractional polarization is sharply declining. VLA P-band observations show this source is completely depolarized by a frequency of 450 MHz, and it will be interesting to see the change of EPA for 3C286 between 500 and 1000 MHz. Observations of the moon utilizing the 580 − 1015 MHz band are now being scheduled to determine these characteristics.

Thanks to Bryan Butler and Eric Greisen for useful discussions.

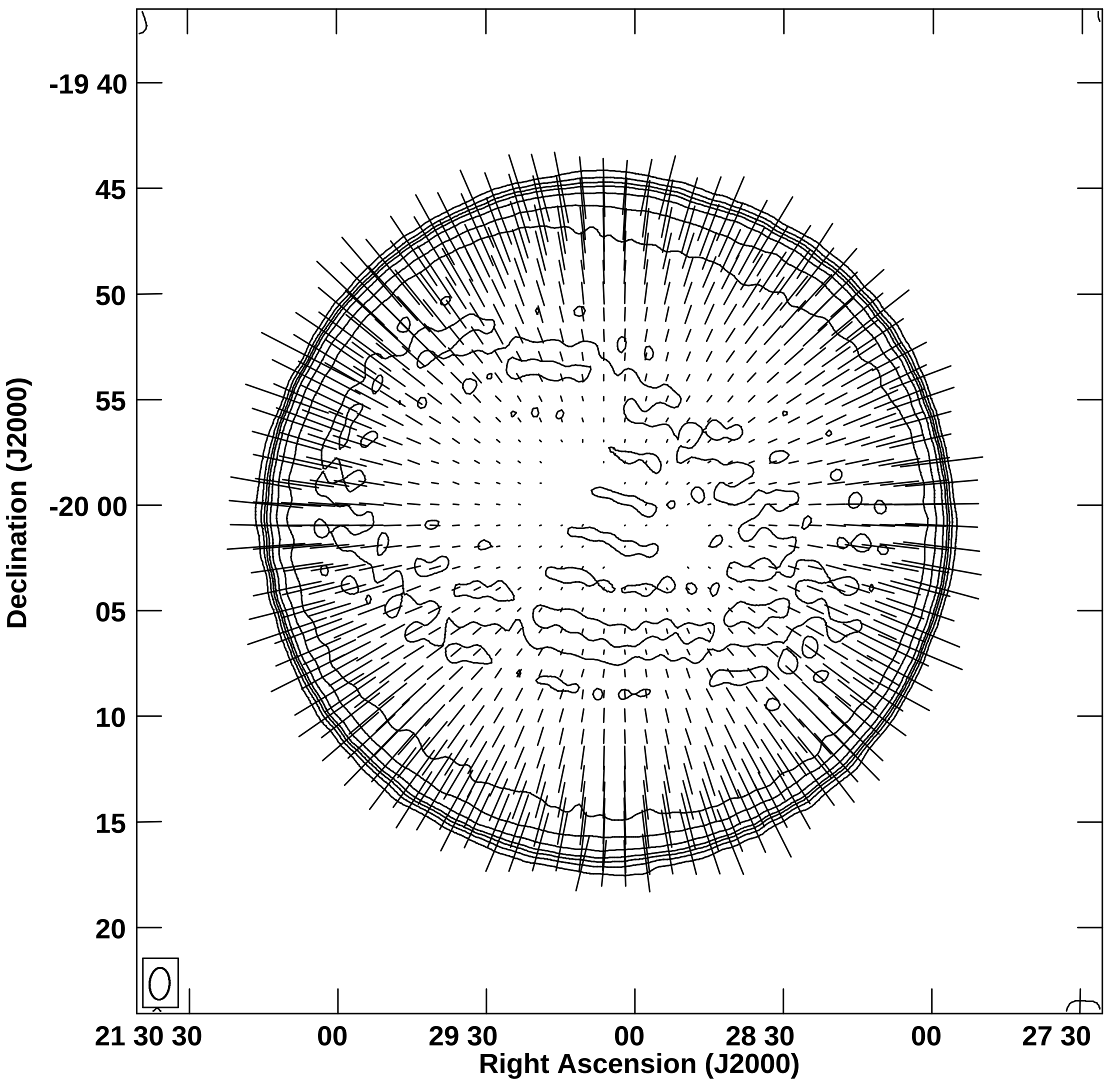

Figure 3: A contour plot of the lunar emission at 1040 MHz, with overlaid vectors showing the observed E-field orientation. After ionospheric correction, the alignment is nearly perfectly radial, indicating that the intrinsic EPA of 3C286 is within 1 degree of 33.

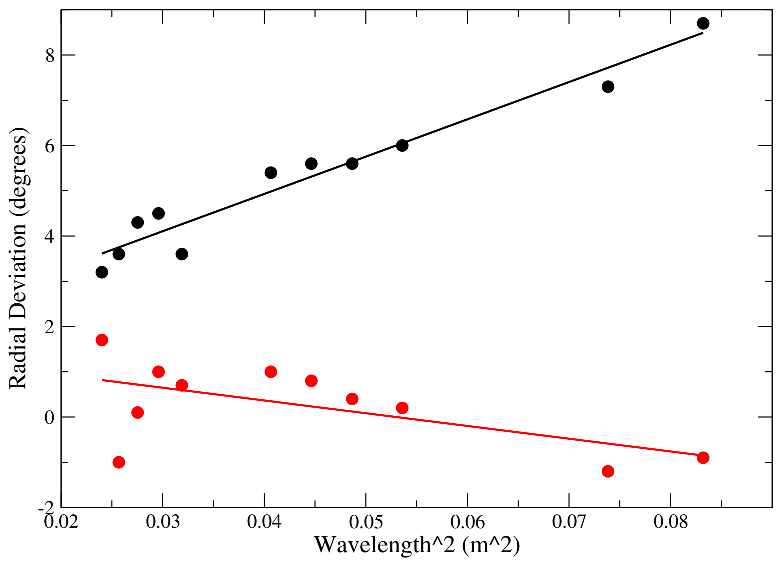

Figure 4: The observed EPA offsets from radial for the moon. The black points and fit are without ionospheric correction. The red points and fit are with the corrections applied by TECOR. The offsets are very slightly overcorrected by the ionospheric rotation estimation. The zero-wavelength offset of ∼1.5 degrees is marginally significant – more careful observations will be needed to confirm this.