EVLA Memo 226
Testing the Efficacy of the AIPS Program 'TECOR'

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August 4, 2023

Abstract

Accurate low-frequency polarimetry requires correction of the observed EVPA by the Faraday rotation induced by signal propagation through the Earth's ionosphere. The AIPS program 'TECOR' uses GPS-based TEC data to estimate the ionospheric rotation measure. We have utilized legacy calibrator observations, and observations of the planet Venus, to demonstrate that these corrections are accurate to about 1 degree at 1 GHz, over a wide range of observed times, source elevations, and measured ionospheric rotation measures.

1 Introduction

Propagation of linearly polarized radiation through an ionized, magnetized medium results in a rotation of the plane of polarization by the Faraday effect, given by

$$\chi_{obs} = \chi_0 + RM\lambda^2 \tag{1}$$

where χ_0 is the intrinsic electric vector position angle (EVPA), χ_{obs} is the observed EVPA, λ is the observation wavelength, and RM is the Rotation Measure, usually measured in radians/m^2. The RM is related to the electron density, magnetic field, and propagation distance by

$$RM = 2.62 \times 10^{-17} \int_{there}^{here} n_e \mathbf{B} \cdot d\mathbf{s} \tag{2}$$

where the electron density n_e is per cubic meter, the magnetic field $\mathbf{B}$ is in Gauss, and the length element $d\mathbf{s}$ is in meters.

The Earth's ionosphere is an ionized, magnetized layer located roughly 50 to 1000 km above the earth's surface, with a maximum density near 450 km. Ground-based observations of external sources will show Faraday rotation of the plane of polarization. As the rotation is proportional to the square of the radiation wavelength, the rotation is much greater at lower radio frequencies.

It is convenient to utilize the column density, defined as the integral of the number density along the line of sight, which is measured in TEC units : 1 TEC = 10^{16} electrons/m^2, rather than considering the integral of the number density over path length. In these units, and presuming the magnetic field to be uniform along the line of sight over which the column density is determined, the equation for ionospheric contribution, IFRM, to the RM, becomes:

$$IFRM = 0.262 B_{los} N_c \tag{3}$$

where B_{los} is the line-of-sight component of the magnetic field in Gauss, and N_c is the column density along the line-of-sight, measured in TEC units. A typical quiescent value for the column density is 15 TEC units, and the typical LOS value of the magnetic field is 0.25 G, leading to a typical quiescent value of the RM of $\sim$1 radian/m^2.

Ionospheric RM values for the VLA commonly range from 1 to 8 rad/m^2, so that at the VLA's lowest L-band frequency of 1 GHz, the induced rotation will typically range from 5 to 50 degrees – and potentially even higher during times of unusually active solar activity. If we define 'precision polarimetry' as obtaining a result accurate to 1 degree, we conclude that IFR corrections will be needed at the VLA's P, L, and S bands on a regular basis, and potentially at C-band during times of high solar activity.

The AIPS program 'TECOR' was written by Chris Flatters in the late 1990s to estimate the IFRM using GPS-based estimates of the ionospheric electron column density, combined with a model of the Earth's magnetic field. The TEC data are retreived from NASA's CDDIS data archive[1]. There are at least 16 different databases to choose from – we have utilized the (AIPS) default 'jplg' data. The TECOR program assumes a 'thin shell' model for the ionosphere, presuming the total electron content (TEC) to be located in an infinitesmally thin layer at a height of 450 km above the Earth's surface, and utilizes the value of the Earth's magnetic field at that elevation to determine the ionospheric rotation measure[2]. An example of the output generated by TECOR is shown in Fig. 1. The top panel in this figure shows the vertical total electron content (TEC), computed at the

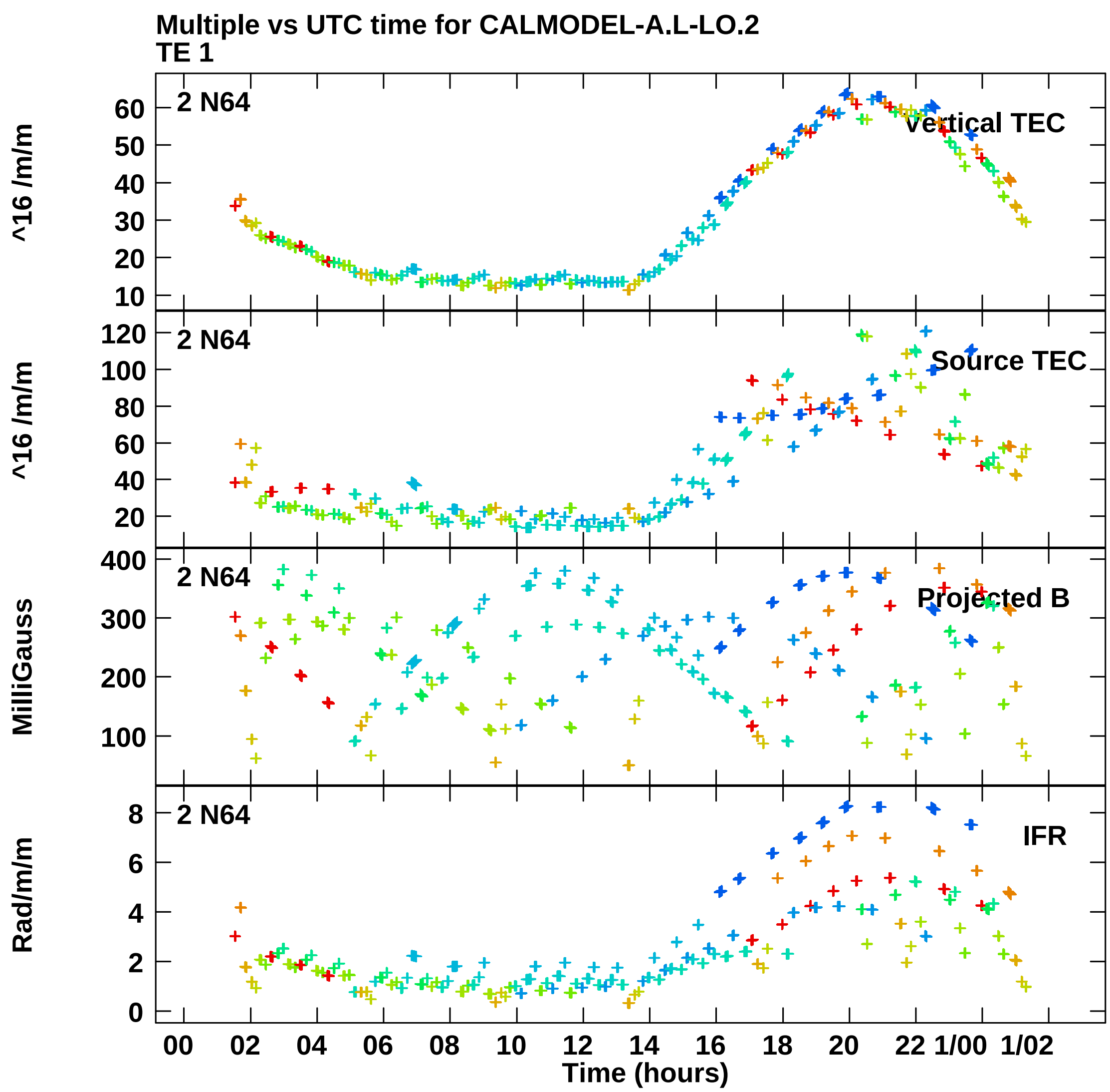

Figure 1: An example of the TECOR-generated estimates of the TEC, slant TEC, the projected component strength of the earth's magnetic field along the line of sight, and the estimated ionospheric rotation measure, for the observations taken on 16 February, 2014. The sources observed are are color-coded – 3C286 is in red.

position where the ray path to the source is at the fiducial height of 450 km. Units are in 10^{16} electrons/m^2. The second panel gives the slant TEC – the TEC adjusted for the angle at which the ray path passes at the fiducial height. The third panel shows the adopted value of the magnitude of the earth's magnetic field at the ray pierce point – units are in milliGauss. The bottom panel shows the computed ionospheric rotation measure,

[1]The process of retrieving these data is made very easy by use of the AIPS procedure 'VLATECR'.

[2]Readers should note that an important error in the geometry computation within TECOR was corrected on 24 January 2023 – AIPS users should ensure that they use versions 31DEC21 and later, but only those that have been updated after 24 January 2023.

in radians/m^2.

The accuracy of these estimated IFRM values has not, to our knowledge, ever been tested. In this memo, we describe our efforts to judge the accuracy of these estimates, using data from various L-band observations of polarized calibrators, and observations of the planet Venus.

2 Observations and Methodology

The basic procedure was to compare the EVPA results from observations of highly polarized sources, both with, and without, the TECOR-generated estimates of the IFRM. These comparisons are most sensible if the observations were taken during a time where the IFRM changed significantly, and at a low-enough frequency that the ionospheric-induced rotations are easily measured.

We developed two methods of comparison – one which does not require prior knowledge of the intrinsic source EVPA, the other where the intrinsic angle is known in advance. The details for each are discussed in the following section.

To perform these tests, we utilized legacy VLA observations taken as part of the ongoing VLA calibrator monitoring program. These observations are intended to track the spectral flux density and polarization of the primary VLA calibrators, as well as to enable detailed checks of the VLA's instrumental systematics. Besides these general goals, the observations have enabled determination of the true EVPA of the standard calibrator 3C286 at high frequencies, as described by Perley & Butler (ApJS, **206**, 16 (2013))

We utilized six calibrator monitoring observations, taken from 2013 through 2021, as shown in Table 1. The

Table 1: **Observations Used in this Report**

Date	Configuration	IFR Range	Sources
09-Sep-2021	C	0 – 4	3C286, 3C138, J0217+7349, J1800+7828, 3C273, 3C279, J0359+5057, 3C345, 3C454.3, J2225-0457
31-Jan-2019	C	0.6 – 1.0	3C286, 3C138, J0217+7349, J1800+7828, J1733-1304
25-Jan-2016	DnC	0.2 – 1.0	3C286, 3C138, 3C353, J0133-3629, J0444-2809
16-Feb-2014	A	0.2 – 8	3C286, 3C138, J0217+7349, 3C380
11-Oct-2014	C	0.2 – 8	3C286, 3C138, J0217+7349, J1800+7828, 3C353, 3C274
03-May-2013	D	3.4 – 4.6	3C286, 3C138, J0948+4039, J0217+7349, J1800+7828

two observations taken in 2014 (in A-configuration for calibrator structure, and C-configuration for the flux densities) were especially useful for testing, as these were taken during the solar cycle maximum, with resulting IFRMs ranging from 1 to over 8 rad/m^2.

For each of the calibrator observations, we extracted those sources showing significant polarization, and with at least four observations, for analysis. Only the L-band data were utilized, as the effect of ionospheric RM is very small for higher frequencies.

In addition to these six datasets, we utilized the special observations of Venus at L-band, taken 03 March 2022 in the A-configuration. The purpose of this program was to determine the intrinsic EVPA of 3C286 by using the known EVPA of Venus. Details of this project, which also included observations of the moon and Mars, will be reported in a subsequent Memo. The intrinsic EVPA results of these observations for 3C286 were utilized in the observations reported here.

3 Calibration and Analysis

Calibration was done twice for each database – once with the IFR corrections applied, and once without the corrections. Following the calibration, the determination of the polarization was done using IMAGR.

Noting again the Faraday effect relation:

$$\chi_{obs} = \chi_0 + RM\lambda^2 \tag{4}$$

we note there are two tests that can be performed:

- **Single Spectral Window** Here, we utilize a single spectral window, and plot the observed EVPA against the TECOR-estimated IFRM. For those observations with no correction, we should observe a linear relation whose slope is equal to λ^2 if the measures of the IFRM are correct. With the corrections applied, the slope should be zero. The advantage of this method is that the intrinsic EVPA, χ_o, does not need to be known – it is an offset common to both plots. If the estimated IFRM is too high or too low, it will show up as a scale error in the value of the slope in the uncorrected data, and with a residual slope in the corrected data.

- **Multi-Spectral Windows** Here, we plot the observed EVPA as a function of λ^2. For the uncorrected data, the slope should equal the actual RM, which can be compared to that estimated by TECOR. For the corrected data, the slope should be removed, with all values equal to the intrinsic EVPA at each frequency. It is important to note that in this method the intrinsic source EVPA must be known in advance, as any change in this intrinsic value with wavelength – which could be due to a frequency-dependent geometry change, or a rotation due to the source environment – will appear as a residual RM of unknown size which cannot be distinguished from an error in the TECOR calculation of the IFRM. For this reason, we utilize the Venus observations for this test, as the intrinsic EVPA of Venus at these frequencies is known to be radial, and Venus has no significant magnetic field.

4 Results

4.1 Single-SPW Tests

We illustrate the first test with data from a single source, 3C286, from observations taken 16 February, 2014. The results are shown in Fig 2, showing the observed EVPA with, and without, the IFRM correction for spectral windows 01 (left) with center frequency 1.04 GHz, and 08 (right), with center frequency 1.49 GHz. A single offset has been applied to all the data to give zero angle at zero RM. The results are very encouraging – the

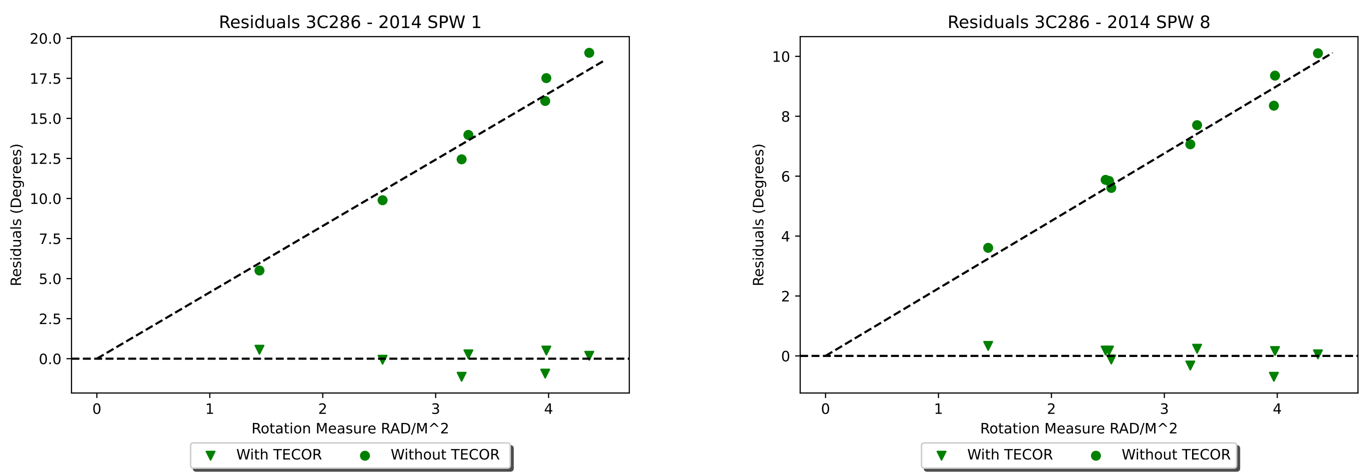

Figure 2: The EVPA of 3C286 on 16 February, 2014, at (left) 1.04 GHz, and 1.49 GHz (right) with and without the IFRM corrections.

fitted slopes in the uncorrected data, for the two SPWs, are 0.080 m^2 and 0.038 m^2, while the corrected values have a nearly zero residual slope.

The data shown in this plot were taken on a single day, on a single source, leaving open the possibility that 'we got lucky'. More confidence in TECOR's corrections will come with multiple sources, on multiple days. The results from this, utilizing all the identified polarized sources from all six datasets, are shown in figure 3. In this figure, only sources observed at least four times in a given observation are used, in order to enable a reliable EVPA offset for each to be determined. These data were fitted with a single slope common to all sources, and a source-dependent offset, to ensure the data lie on the same lines. We again see that the observed slope very

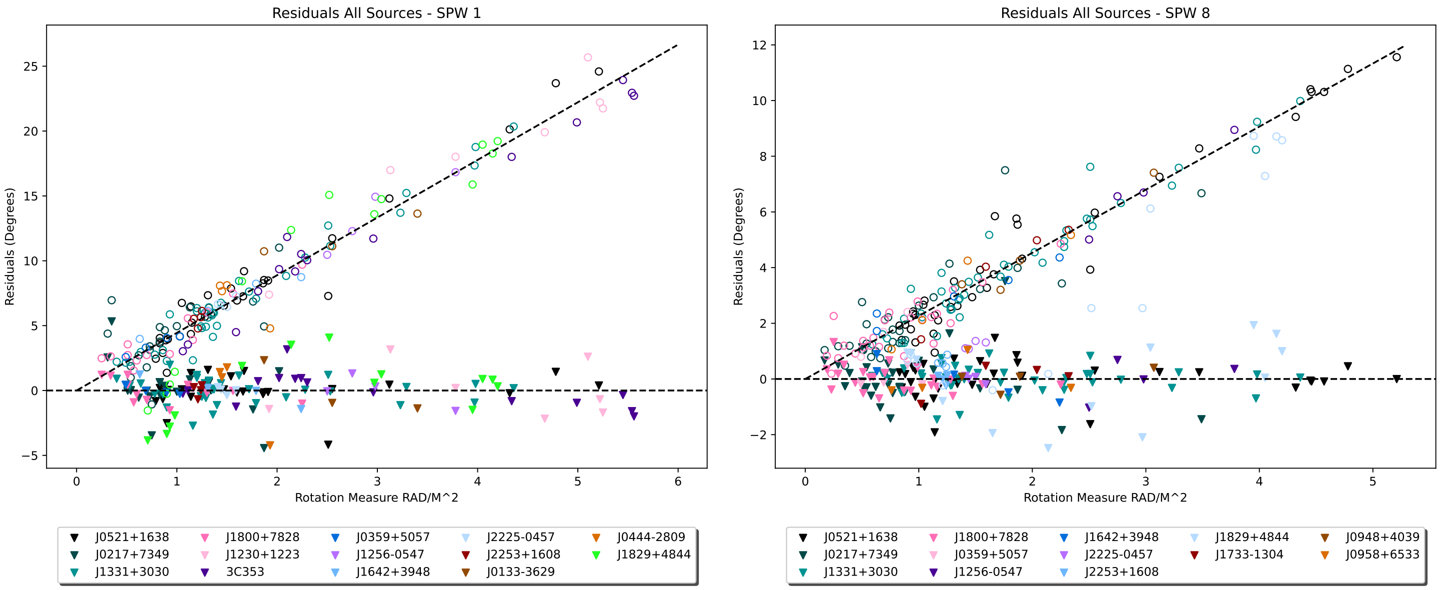

Figure 3: The EVPAs of multiple sources, taken on multiple days, with and without the IFRM corrections. SPW01 on the left, and SPW08 on the right. Most of the observed scatter is due to the weakness of the calibrators' polarized fluxes.

nearly matches the known wavelength-squared value, and that the corrected data have no discernible residual slope, indicating that the corrections are effective in removing the ionospheric-induced rotation.

The results from the slope fitting are given in table 2, showing the slopes to the uncorrected and corrected data. All slopes are within 1.5-σ of the expected values for the two spectral windows utilized.

Table 2: **Results from Slope Fitting**

Source	SPW	Slope (m^2)	λ^2	Corrected Slope
3C286	1	0.0797 $\pm$ 0.0039	0.0830	-0.0038 $\pm$ 0.0041
3C286	8	0.0378 $\pm$ 0.0023	0.0404	-0.0027 $\pm$ 0.0021
All	1	0.0804 $\pm$ 0.0016	0.0830	-0.0016 $\pm$ 0.0015
All	8	0.0411 $\pm$ 0.0011	0.0404	0.0010 $\pm$ 0.0009

4.2 Multi-SPW Observations of Venus

In this approach, we fit the change in EVPA caused by the ionospheric RM vs λ^2 – the slope will equal the actual IFRM, which can be then compared to that generated by TECOR. However, this requires prior knowledge of the intrinsic source EVPA, χ_0, since the source will generally have its own RM from the environment in which it lies, and may also have a frequency-dependent EVPA of its emission. The intrinsic EVPA is not known for the great majority of calibrators (and is likely to be time-dependent in any event), so we must look to planetary bodies to do this test. Fortunately, Venus, Mars, and the Moon have well-known polarization characteristics – the EVPA must be radial. (See the Perley & Butler paper, previously cited, for the physical basis of this statement.) As part of a separate study to determine the intrinsic EVPA of 3C286, observations of the Moon, Mars, and Venus were taken at L, S, C and X bands. For the study reported here, the L-band A-configuration observations of Venus taken last year are ideal, as the ∼1.5 arcsecond resolution is a good match to the ∼30 arcsecond diameter of Venus.

Following calibration (with and without the IFRM correction), Stokes' Q and U images were made of Venus in each of the 16 spectral windows. One of these (SPW09) was heavily affected by RFI, and was not used. From these images, COMB was used to generate the polarized brightness (POLI) and polarization position angle (POLA) images. The AIPS task 'MARSP' was then used to determine the offset of the observed position angle from the known intrinsic radial orientation. These operations were done for images made from all the data, and for images made from four one-hour-long time ranges, each of which had a notably different IFRM. The results are shown in Figure 4. This plot shows how well the data fit the simple λ^2 model. The fifteen plotted points

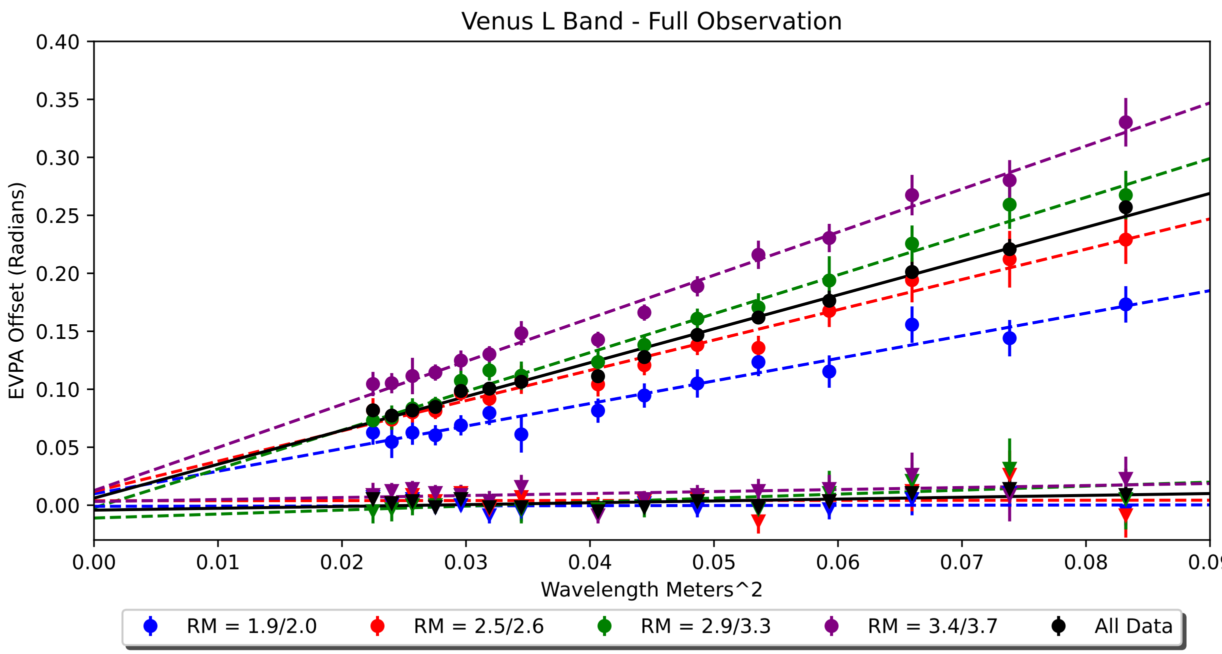

Figure 4: The measured EVPA of Venus at L-band, with and without the IFRM correction. The round points are from data uncorrected for the IFR, the triangle points are the corrected values. The black solid lines are for the entire 4.5-hour-long data set, during which the TECOR-derived IFRM for Venus increased from 1.9 to 3.4 radians/m^2. The colored points and fitted lines represent four hour-long determinations, showing how the measured slopes match the TECOR-derived values of the IFRM. The legend box at the bottom shows the pair of IFRMs – the TECOR value followed by the measured slope, for each time period.

along the frequency-axis are from the fifteen (relatively) RFI-free spectral windows provided by the EVLA. (The 9th spectral window, near .038 m^2 is wiped out by INMARSAT transmissions, even in A configuration). The 4.5-hour long observation was subdivided into four approximately one-hour-long blocks, each of which has a notably different IFRM. The uncorrected data for each time window are fitted with the four colored fits – the measured RMs and TECOR-derived IFRMs are in the caption bar. The error bars are 1-σ values provided by the AIPS program MARSP, which calculates the mean deviation of the observed EVPA from radial. The corrected data are shown at the bottom of the plot – virtually all values are within 1 degree of zero. The y-axis intercepts are all within 2-σ of the expected value of zero.

The detailed fitting results are given in Table 3. Readers will note that, for the two observations with the

Table 3: **Results from L-Band Fitting of Venus**

	Time Range	TECOR IFRM (rad/m^2)	Slope Off	Slope On
All	12:30 – 17:16	–	2.92 ± 0.08	0.16 ± 0.06
T1	12:30 – 13:30	1.9	1.95 ± 0.13	0.01 ± 0.08
T2	13:45 – 14:40	2.5	2.61 ± 0.11	0.01 ± 0.14
T3	14:50 – 15:45	2.9	3.34 ± 0.11	0.34 ± 0.11
T4	16:02 – 17:16	3.4	3.71 ± 0.12	0.17 ± 0.11

highest IFRM, there is an apparent underestimation of the IFRM by TECOR. This is statistically significant only for the ‘T3’ observation. It cannot yet be determined if this underestimation is real – we have in hand two lunar L-band observations with similar IFRM ranges, which may help judge the reality of this. Work on this will have to be deferred to a later date.

It should also be noted that the 'jplg' database, from which these corrections are made, provides the TEC on a 2.5 by 5 degree grid (latitude, longitude), once every two hours. The TECOR program does a spatial-temporal interpolation to derive the IFRM along the ray path. The uncorrected data shown in the figure takes no account of the change in IFRM during the averaging interval, over which the IFRM is notably changing.

5 P-band – The Ultimate Test

The preceding sections describe our efforts to determine the accuracy of the IFRM corrections, using data from the VLA's L-band – 1 – 2 GHz. For normal observing conditions, the corrections at L-band are relatively small – a few tens of degrees at most. But at P-band (240 – 460 MHz), even the minimal IFRM of 1 rad/m^2 will rotate the observed plane of polarization by a full radian, while the more extreme values will rotate the plane of polarization by a full turn or more. It is thus critical for P-band polarimetry that these corrections be applied, and be reliable. Conversely, tests using P-band data are in principle much more precise in judging the accuracy of the corrections.

But there are additional problems in dealing with low-frequency data – there are no strongly polarized, unresolved sources to assist in decoupling the various complicating technical problems which accompany the linear feeds utilized for the VLA's P-band system. For a linear system, different calibration and imaging regimens are required than for the circular syatem, as described in EVLA Memos #207 and #219. We have, as part of the effort to enable calibration of linearly polarized systems into AIPS, taken observations of the Moon along with suitably polarized calibrators (principally DA240, 3C303, and 3C345). We have established that the AIPS software is rotating the observed plane of polarization by the correct amount, as given by the TECOR-generated IFRM, but have found that the resulting EVPA lunar images have an offset of unknown origin. This is not due to the IFRA corrections. We have not yet been able to determine the origin of the discrepancy. When this is found, a subsequent memo will be produced.

6 Summary

The AIPS program TECOR appears to provide excellent estimates of the ionospheric rotation measure (IFRM) accurate to a 1-σ value of $\sim$0.2 radian/m^2 for data taken at the VLA. Use of this program, along with observations of the primary flux and polarization calibrator 3C286 (whose stable EVPA is believed known) is recommended for all polarimetric observations at L and S bands, and, if the IFRM is unusually high, at C-band.

The judgement of the efficacy of TECOR-based corrections at the VLA's P-band is still 'a work in progress'. Results from this work will have to be deferred to a later date.