# Analysis of WFS Measurements from first half of 2004

(Report4)

*Graham Cox*

August 19, 2004

## 1 Abstract

Described in this report is the results of wavefront sensor measurements taken during the first seven months of 2004. It includes details of some instrumental problems encountered, which produced some unexpected features and the method of evaluating and resolving these problems. A final estimate of the true telescope aberrations versus zenith angle is given with proposed functions calculated for the correction of the most significant term, namely astigmatism. Also checked for were the possible effects of hysteresis of the aberrations due to altitude motion and telescope rotator position influence.

## 2 Introduction

On the 25 March 2004 a few hours of WFS measurements were obtain during the period of about 12.30 to 4.30 UT. Before this time the seeing was very variable sometimes been worse than 2.5 arcsecs. During the measurements the seeing was typically better than 1.2 arcsecs, and 0.7 arcsecs was measured from a short integration on a focus star. It was only possible to get data for zenith angles from 10 to 42 degrees. Follow-up observations were made on 6th April where only a few specific pointing were made to try and verify some of the findings from the 25th March data.

This is the first set of measurements taken with ALFOSC since the new camera and CCD have been installed, though because the pixel scale has been kept the same the reduction software is still valid.

Due to some unexpected and inconsistent results from the data of 25 March 2004 and 6 April 2004, extra measurements were made on 26 May 2004 to try and clarify the situation.

The measurement made on 26 May and more on 13 July 2004 finally show some consistency and from them it has been possible to determine satisfactory fits to the data that if implemented by the TCS should reduce the effects of the most significant aberration, astigmatism, by a substantial amount. From the 26 May data it is possible to calibrate the TCS Zenned amplitudes but the Zernike to rotator angles relationship still needs to be determined.

# 3 Results of 25 March and 6 April 2004 data

On 25 March it was possible to obtain a series of WFS measurements by tracking a single star for a few hours resulting in data for zenith angles from 10 to 45 degrees. The results of these observations are shown in figure 3. Table 1 shows the mean values subtracted from the March data, the mean of ten consecutive measurements made eight months earlier, at a zenith angle of approximately 20 degrees, after the large astigmatism was removed but before the new camera and CCD were installed, and also the means of the April data, though this latter data is of poor quality. From the data, as seen before, the variations in the higher order aberrations, namely tri-coma and quad-astigmatism, are relatively small compare to changes in astigmatism and focus. Also the mean values are in the same order of magnitude to previously measured results, been dominated by astigmatism, coma, spherical and focus, though spherical is higher than previously measured.

One interesting feature that has come from these results is that the slope of the astigmatism amplitude against zenith angle has appeared to have changes sign compared to measurements from 2002 and 2003 [1], though the range is about the same as before and the mean value is similar to the last measurements. It is known the CCD in the new ALFOSC camera it up side down with respect to the old detector, though since astigmatism is symmetrical about $180^o$ you would expect to get the same result. A check has been made against old data, taken on 11 April 2003, by just looking at the same zenith range, zenith angle decreasing from 10 to 45 degrees, and the slope is opposite with respect to 25 March 2004. The plot of astigmatism angle against zenith angle is consistent with previous results. The only explanation for this change must be because of the applied extra forces to M1, to correct for the astigmatism, causing different deformation in the mirror when tilted.

Though there are large apparent mean measured values for astigmatism, coma, spherical and focus none of these aberrations have been reported in any science observations, and in fact after the large clearly seen astigmatism was corrected for and check from point source observations to have been removed, the WFS analysis still gives a mean value of over 100nm. Also the apparent large coma has never been reported which would appear as elongated images with a comet type profile. For spherical it would be very difficult to separate this from poor focus or seeing affects so would not be expected to be seen.

To try and verify if the change of slope of astigmatism against zenith angle is real, a very few measurements where made on 6 April, these included taking two sets of measurements at the same zenith angle but for opposite rotator positions, namely 0 and 180 degrees. Also measurements for a range of zenith angles were made with the TCS astigmatism set to 0.8 and for the previous setting of 0.2, again to see if this influences the astigmatism behaviour. Unfortunately the results are not very good, presumably due to poor seeing and limited measurements made. From the measurements for the two rotator positions a significant change in the magnitude of astigmatism results, for ROT-POS = $0^o$ the astigmatism is 220nm but for ROT-POS = $180^o$ it is 121nm (both the mean of three measurements). The large value from ROT-POS zero is consistent with the mean value obtained for measurements for the same rotator position and for different zenith angles.

The measurements of zenith angle for the applied TCS astigmatism of 0.2 give a mean value of 96nm and a change of slope with respect to the TCS astigmatism of 0.8. The slope for TCS astigmatism of 0.2 is consistent with data from the previous years 2002 and 2003, before the applied TCS astigmatism was made.

A unexplained curiosity of the stellar wavefront mask images taken on 25 March and 6 April is that they all appear vertically elongated but with the centre hole obstruction elongated horizontal. This shape is seen for the TCS astigmatism set to 0.2 or 0.8. A typical WFS mask image can be seem in figure 1. Calibration images taken from the WFS

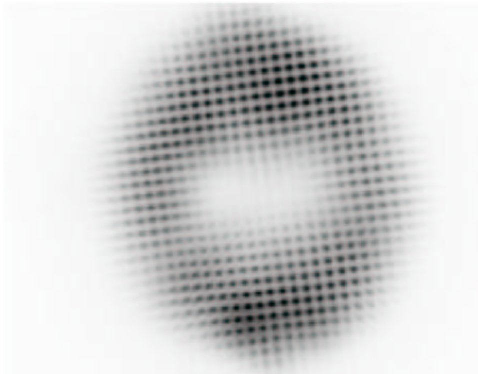

Figure 1: This is a typical WFS mask stellar image taken on night of 25 March 2004. Note the vertical elongation of the image with a perpendicular elongation of the centre obscuration.

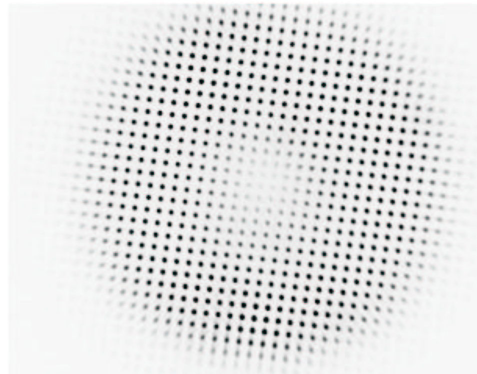

Figure 2: Typical WFS calibration mask image.

lamp in the aperture wheel look normal, an annulus, as in figure 2.

| Aberrations | 02/08/03 | | 25/03/04 | | 06/04/04 | |
|---|---|---|---|---|---|---|
| | Amp. | Ang. | Amp. | Ang. | Amp. | Ang. |
| Tilt (arcsec) | 2.5 | 35 | 0.17 | -14.2 | 0.2 | 12 |
| Astigmatism | 107 | 9 | 154.5 | -49.9 | 211 | -25 |
| Coma | 104 | -69 | 91.5 | -54.2 | 84 | 7 |
| Tri-coma | 43 | -9 | 31.6 | 6.8 | 35 | 32 |
| Quad-ast. | 15 | 35 | 18.7 | -1.4 | 30 | 10 |
| Spherical | -17 | - | -79.1 | - | -96 | - |
| Focus | 145 | - | 83.0 | - | -129 | - |

Table 1: The mean aberration amplitudes (nm) and angles (degrees) including a comparison of the mean of 10 consecutive measurements made August 2003. The 6 April data is for rotator position 0 and TCS astig. = 0.8

# 4 Results of 26 May 2004

The unexpected and inconsistent results from the data of 25 March 2004 and 6 April 2004, described above, compared to previous measurements, prompted a series of new tests to be devised to try and clarify the situation and data was taken on 26 May 2004. From the seeing monitor the seeing was very variable with a mean or around 1.2 arcsec, even though only four frames were lost (out of over one hundred taken) due to poor image quality.

The most important item was to first get round WFS-mask images and this was achieve (with advice from Michael Andersen) by setting the position of the WFS-mask more precisely aligned to the Lyot-stop. Also the calibration lamp was position accurately on the optical axis. This then produced the desired circular images confirming that the cause was vignetting of the primary mirror image by the WFS-mask Lyot-stop combination.

The first set of measurements on the sky where to see if the change in zenith dependence (shape) of the astigmatism, with respect to post aluminisation data, is real, an artifact of the poor WFS-mask images or due to the change in the TCS astigmatism Zernike. A set of measurements were made for the TCS astigmatism Zernike set to 0.8 (the current value for minimum aberration) and the previously used 0.2. Comparing the results of 26 May data shown in figure 4 with those of 25 March data of figure 3, it can be seen that the shape for the astigmatism amplitude for TCS Zernike = 0.8 is approximately the same for zenith angles greater than 15 degrees, namely as the zenith angle increases the astigmatism goes down with a minimum for zenith angle 30 - 35 degrees and then starts to increase. There does appear to be a difference for small zenith angles where the new results show the astigmatism amplitude continuing to increase as you approach zenith where as from 25 March data this aberration appears to fall off for small zenith angles. Another feature of the astigmatism, seen in 26 May data of figure 4, is it seems to rotate with respect to the zenith angle with an approximately linear relationship.

A check was made of the apparent rotator position affecting the amplitude of the aberrations. It was found that there is no relationship between rotator angle of $0^o$ and $180^o$ and aberration amplitude, as you would expect.

The zenith angle dependence was determined my making a series of measurements starting at angle 60 degrees, moving up to zenith in steps of 10 degrees and then back down to zenith angle 60 degrees. For each position three measurements were made and the mean of these three used for the value of each position. By plotting the up and down halves together, shown in figure 5, it was possible to see that there is negligible hysteresis in the aberration changes with respect to altitude.

Again only the high order aberrations, astigmatism and focus are significant. Large mean values for coma and spherical are found but these may simply been offsets within the software rather than true aberrations since there has be no reported asymmetry in images, which you would expect from coma and astigmatism, from observers.

# 5 Results of 13 July 2004 compared with 26 May data

A repeat of the 26 May measurements was taken to confirm the results, in particular the astigmatism trend. The procedure for taking the data was again to make three measurements at intervals of approximately 10 degrees for zenith angles from 60 up to 5 degrees then back down to 60 degrees. Also three sets of measurements were taken for three different focus positions, at a small zenith angle, to calibrate the focus in focus units.

Looking at the plots in figure 6 it can be seen that the 13 July data is consistent with that from 26 May, showing that the high order aberrations have only a small effect on the overall distortions. Looking particularly at the astigmatism result it can be clearly seen that the amplitude has a well defined and repeatable zenith dependency, though the angle does appear to have significant discrepancies especially near zenith. The May data gives a roughly linear angle of rotation with zenith angle. It was possible to check the July data at small zenith angles using the measurements take to determine the focus calibration. From the mean of these measurements an amplitude value of about 50nm was found at an angle of 60 degrees (after correcting for the different rotator angle used) which is consistent with the general data.

With the focus plot now given in focus units it is clear to see that the typical focus versus zenith angle is reasonable flat with the polynomial fit giving a maximum of $\pm 10$ units and with no very obvious zenith dependency.

Coma shows a very flat curve for angles up to zenith angle 60 degrees then with a possible increase at larger angles. This has been seen in previous measurements taken in 2002 and 2003 before the aluminisation and is probably due to incorrect correction of displacement of the secondary, by the so-called 0.6mm mechanism, at these low altitudes.

The spherical aberration does show a clear zenith dependency which if necessary could be compensated for though it does have a small amplitude.

The mean astigmatism values for both the May and July measurements are in agreement, at approximately 100nm, though actually interpreting exactly what the significant of the mean is is more difficult. The observations measure the sine and cosine terms of the respective aberrations and the plots show the amplitude and phase of these parameters. Amplitude can never be negative, except for spherical that has no phase, because this would simply represent a phase shift. e.g. for astigmatism a sign change will be the same as a rotation of 90 degrees, and in fact the astigmatism does rotate about zero symmetrically so if this was represented as a sign change in the amplitude the mean would be approximately zero. For both the May and July data the mean of all the angles are approximately zero and the fluctuations are due to measurement errors because of the small amplitudes of the respective aberrations.

Looking at the raw Zernike terms for astigmatism Z4 and Z5 we see a very interesting feature, the cosine and sine terms are straight lines as shown in figure 9 with the following fits.

$$AstigmatismCosine = -187 + 5.285z \tag{1}$$

$$AstigmatismSine = -29 - 0.4326z \tag{2}$$

| | | | |
|---|---|---|---|
| Z1: | Tilt X | = | -0.0586 + 0.000382z |
| Z2: | Tilt Y | = | 0.05077 - 0.000991z |
| Z3: | Focus | = | 58 + 0.0216z |
| Z4: | Ast Cos | = | -187 + 5.2845z |
| Z5: | Ast Sin | = | -29 - 0.4326z |
| Z6: | Coma Cos | = | 82 + 0.8296z |
| Z7: | Coma Sin | = | -12 + 0.0445z |
| Z8: | Tri-Coma Cos | = | -8 + 0.393z |
| Z9: | Tri-Coma Sin | = | -38 + 0.5151z |
| Z10: | Spherical | = | -31 - 0.3305z |
| Z11: | Quad Ast Cos | = | -3.66 + 0.00816z |
| Z12: | Quad Ast Sin | = | 7.1 - 0.2226z |

Table 2: Fit to WFS Zernikes in terms of zenith angle (z)

# 6 Zenith Dependency Correction

It can be seen from the 26 May and 13 July results that astigmatism has a strong zenith angle dependency and to remove this the TCS must apply a suitable correction. Using the IDL polynomial fitting function polynomials were determined for astigmatism amplitude and angle for the combined data from both months. It was found that a satisfactory fit to the angle is a straight line though the amplitude needs a third order polynomial. The fits to the astigmatism amplitude and angle are given in equations 3 and 4 respectively, for zenith angles (z) from 5 to 65 degrees. Also by trial and error a cosine function has been made to fit the data and is given in equation 5, for zenith angles in degrees. For both astigmatism amplitude equations the mean of 100nm, subtracted from the plotted and fitted data, has been included giving a minimum at zenith angle 33 degrees of approximately 55nm.

$$AstigmatismAmplitude = 238 - 12.2z + 0.23z^2 - 0.0009z^3 \quad (3)$$

$$AstigmatismAngle = 70 - 2.1z \quad (4)$$

$$AstigmatismAmplitude = 255 - 200cos(4.4\pi z/360 - \pi/2.4) \quad (5)$$

Subtracting the polynomial fit from the original data it is found that the residuals of the astigmatism amplitude have be reduced to standard deviation of approximately 21nm, as seen in figure 7. Doing the same for the spherical aberration a reduction in the standard deviation by 3nm can be achieved, essentially making the slight curve in the zenith dependency straight, which is considered insignificant and will not be implemented, though the mean of approximately -45nm should be removed.

It is possible to use the 26 May data to determine the relationship between the so called TCS astigmatism amplitude parameter and the astigmatism amplitude given by the ALFOSC WFS, since on this night two values for the TCS astigmatism amplitude were used. From the astigmatism amplitude data at zenith angle 33 degrees, where the astigmatism angle is approximately equal to zero, the difference between the two measured values is 140nm and the TCS astigmatism amplitude change is -0.6. So in round numbers 100nm is equivalent to -0.43 on the TCS. To determine the TCS astigmatism angle extra measurements are need.

From the observations the TCS astigmatism amplitude and angle were adjusted to give minimum aberrations at a zenith angle of approximately 30 degrees, this position corresponds to a change in astigmatism amplitude wrt the astigmatism at zenith angle (z) equal to zero of 185nm or 0.787 in TCS units. Since all the measurements were made with a TCS astigmatism set to 0.8 this also has to been added to the result giving a final value of 1.587, this gives a TCS astigmatism minimum value of 0.8 at zenith angle 30 degrees.

Therefore for the TCS the equation to apply to remove the astigmatism, taking into account there is a sign change within the TCS, is given as:

$$TCS\_Ast\_Amp = 1.587 - 52.46\text{x}10^{-3}z + 9.89\text{x}10^{-4}z^2 - 3.87\text{x}.10^{-6}z^3 \quad (6)$$

Similarly for the estimated cosine fit the equation becomes:

$$TCS\_Ast\_Amp = 1.66 - 0.86cos((4.4\pi z)/360 - (\pi/2.4)) \quad (7)$$

Plots of equations 6 and 7 are given in figure 8.

# 7 Determining the relationship between the TCS and WFS values

As stated above a value for the relationship between the TCS astigmatism amplitude and the measured ALFOSC WFS value has been determined as is give as 100nm measured is equivalent to -0.43 on the TCS. To try and get the angles a series of measurements were made for TCS positions from zero to 135 degrees in steps of 45 degrees at a zenith angle of approximately 20 degrees. The results of these measurements are given in figures 12 and 13. Figure 12 shows the relationship between TCS astigmatism angle and the Z4 and Z5 (cosine and sine terms respectively) Zernikes coefficients and figure 13 the amplitude and angle relationship. The error bars for all the plots are $\pm 1$ sigma.

From the amplitude and angle graphs for the applied TCS astigmatism amplitude, figure 11, they show that the applied TCS astigatism amplitudes of 0.2 and 1.2 for the given zenith angle of about 20 degrees and TCS angle of 10 degrees, is at 90 degrees with respect to TCS amplitude 0.8, which is can be seen from the measured change of angle as well as amplitude. This is what you would expect since a negatively applied astigmatism is equivelant to a 90 degree rotation.

The affect of the rotation of the applied TCS astigmatism angle, seen in the two graphs for TCS applied astigmatism angle, figure 13, and shows the default applied amplitude of 0.8 at 10 degrees is at a minimum and adds to the actual mirror astigmatism after a 90 degree rotation, which is what you would expect.

The results shown in 11 and 13 of the applied TCS astigmatism amplitude and angle agree exactly with each other and suggest the rotator angle and the TCS astigmatism angles are the same in magnitude though it is impossible to say if the sign is correct.

## 8 Conclusion

Looking at the data presented in this report and comparing it with the data taken before [1] the aluminisation and problems with the lateral supports, it is clear that after the primary mirror has been removed from the telescope it is necessary to make a sequence of wavefront sensor measurements to determine the aberration zenith angle dependences.

From the zenith angle dependency measurements it is clear that astigmatism has the most significant changes and should be compensated for. Two equations have been determined that should implement the TCS astigmatism correction. Spherical also shows a clear zenith angle dependency and could be corrected for, though this is of a much small amplitude than the astigmatism.

The proposed measurement procedure of taking a few WFS measurements at roughly every 10 degrees zenith angle seem to be sufficient to obtain data that demonstrates the affects of telescope altitude on mirror aberrations, and that satisfactory results can be obtained for seeing as poor as 1.2 arcsec, though better the seeing better the data.

Also it is important to get the optical elements aligned correctly within ALFOSC to ensure we get good and correct results. A procedure has been produced and placed on the web [2] describing the correct method to get reliable WFS data from ALFOSC, and which was used for both the May and July observations.

## References

[1] www.not.iac.es/telescope/, *Analysis of WFS data, March 2002 - April 2003*

[2] www.not.iac.es/telescope/, *WFS Measuring Procedure*

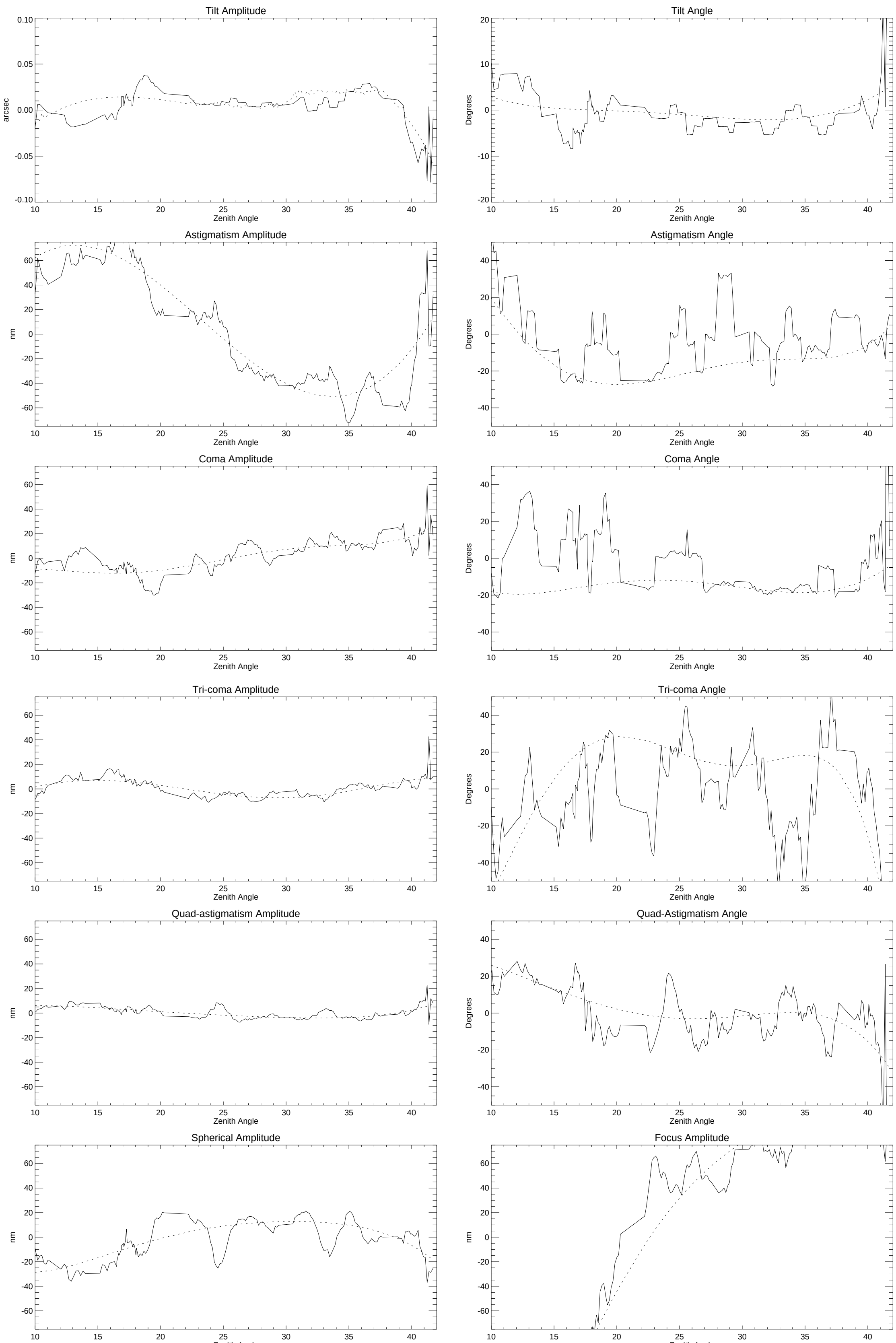


Figure 3: Aberration evolution against zenith angle on 25 March, the dotted line is a 5th order polynomial fit. Table 1 gives the mean offset subtracted from the data.

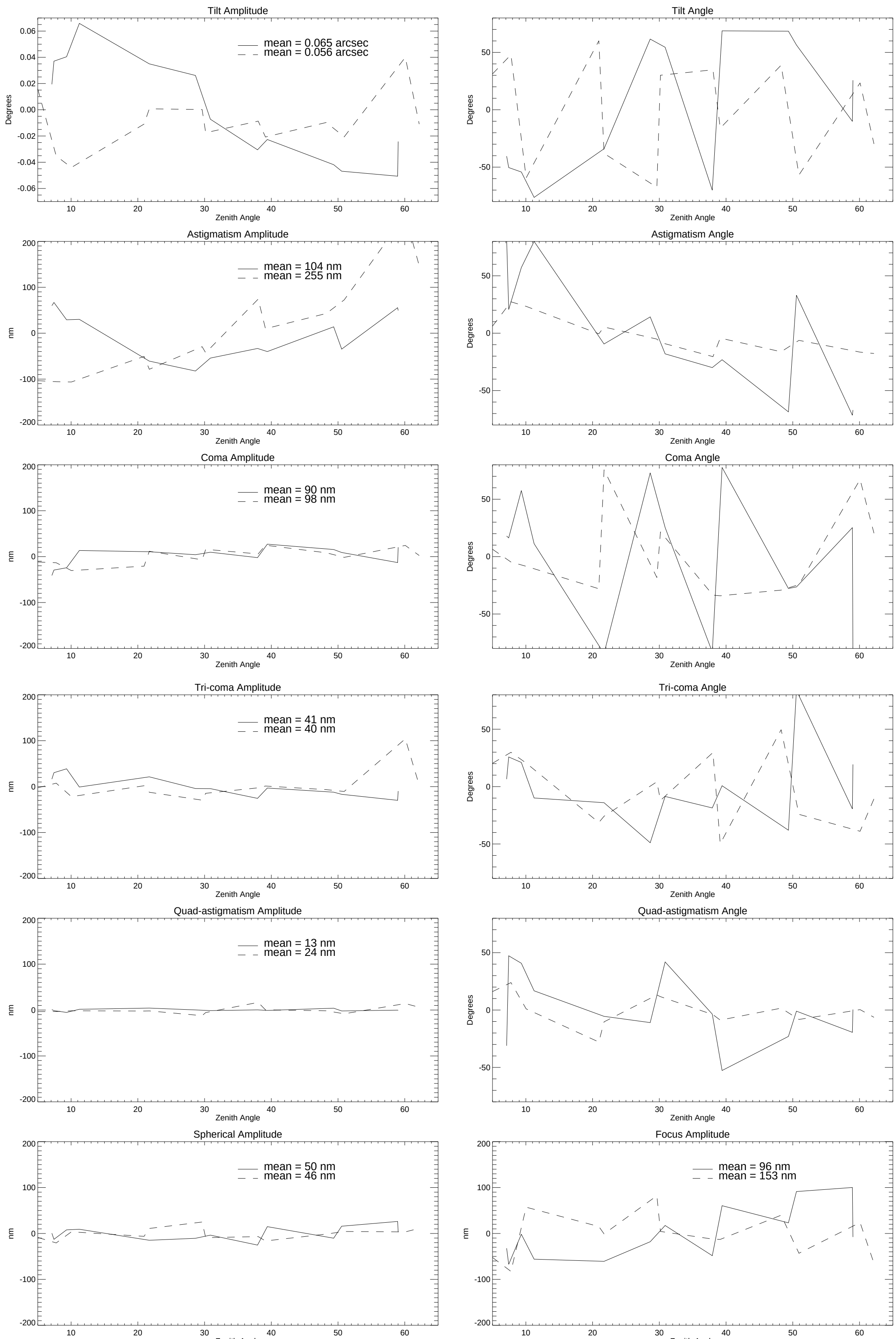


Figure 4: Aberration evolution against zenith angle on 26 May. Shown solid line is the TCS_AST Zernike = 0.8 and dash line for the old TCS_AST Zernike = 0.2.

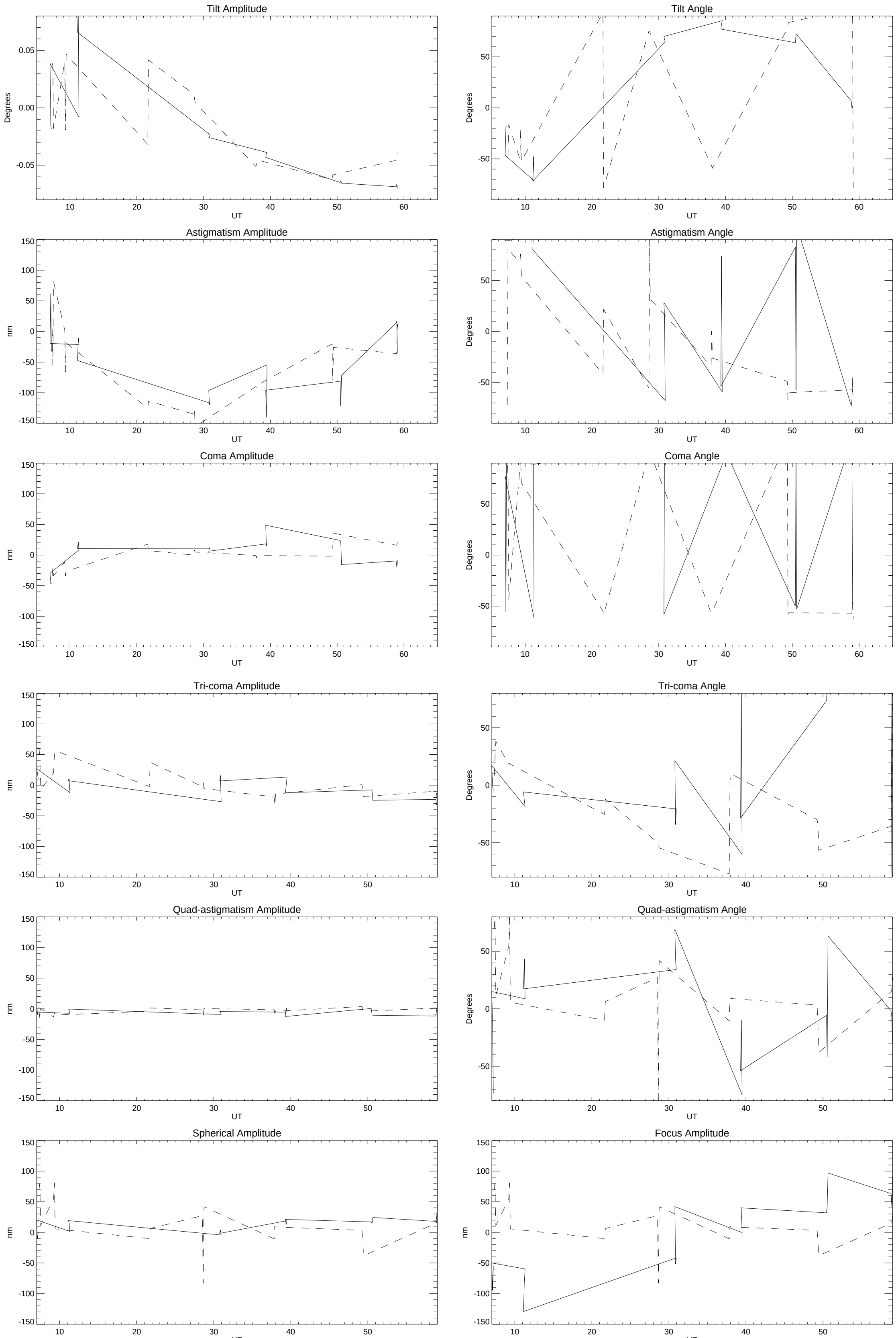


Figure 5: Aberration hysteresis against zenith angle on 26 May. Shown solid line for decreasing zenith angle and dash line for increasing zenith angle.

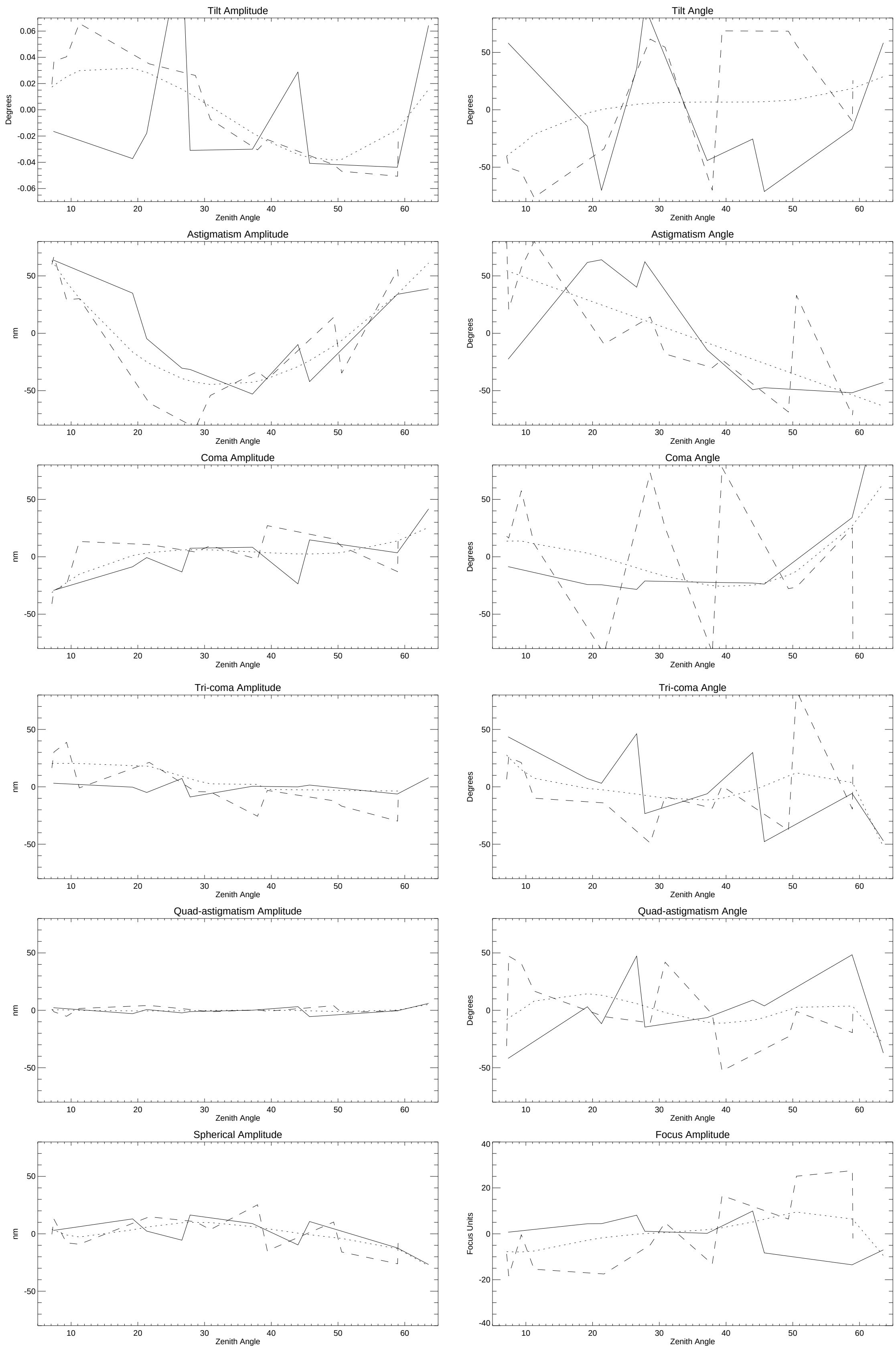


Figure 6: Aberration evolution against zenith angle on 26 May (dashed line) and 13 July (solid line). Included is a polynomial fit of both sets of data combined. (dotted)

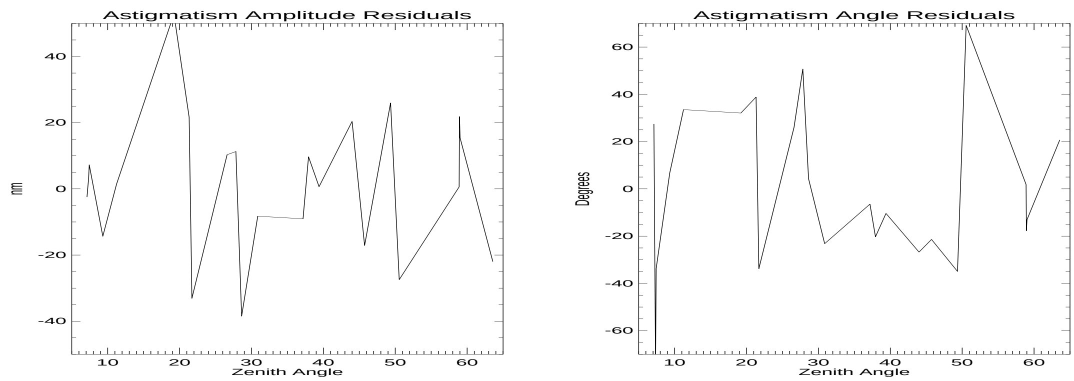


Figure 7: Residuals of the astigmatism amplitude and angle after the above polynomial fits, of the combined data from both dates, has been subtracted.

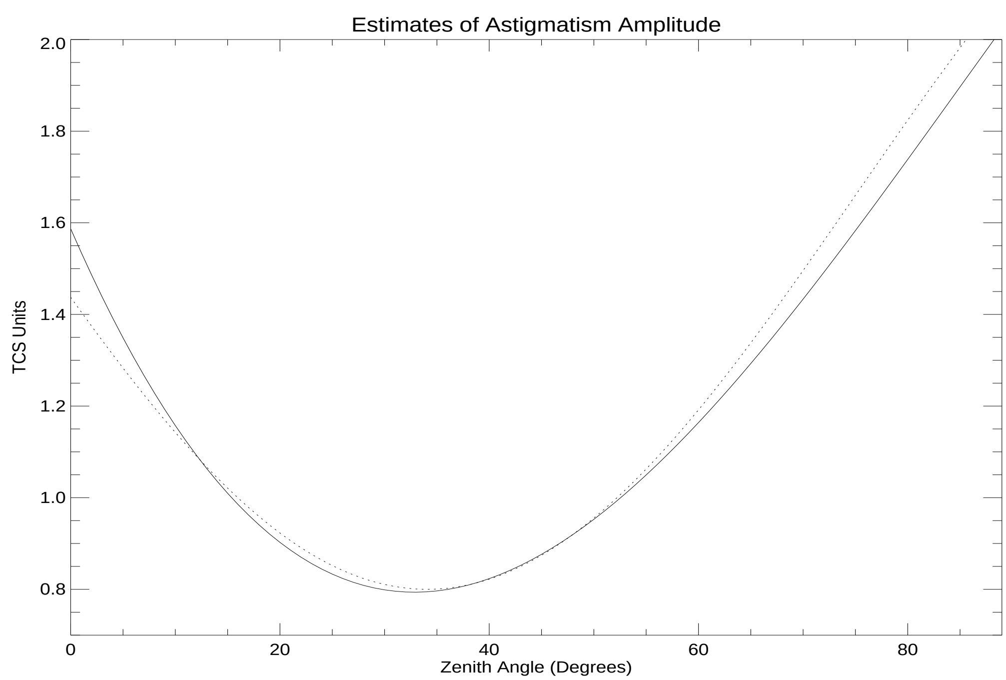


Figure 8: Two estimates of the Astigmatism Amplitude versus Zenith Angle. The solid line is a polynomial fit and the dotted a best guess Cosine fit.

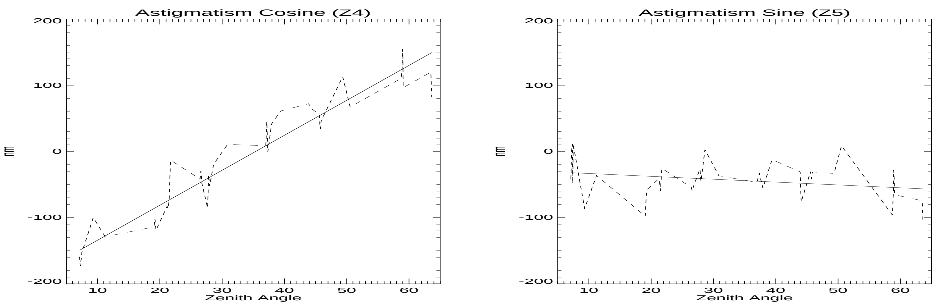


Figure 9: Zernike terms (Z4 and Z5) of the astigmatism with straight line fits.

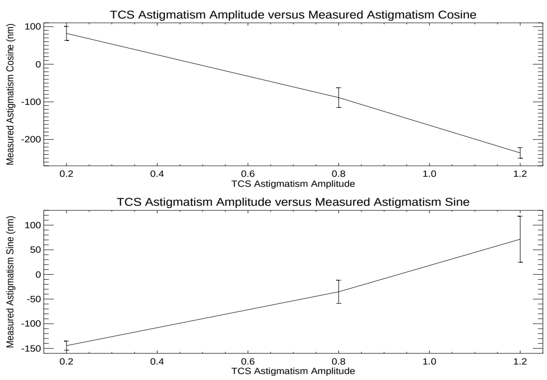


Figure 10: Relationship between applied TCS astigmatism amplitude versus measured Zernikes Z4 and Z5, Cosine and Sine respectively.

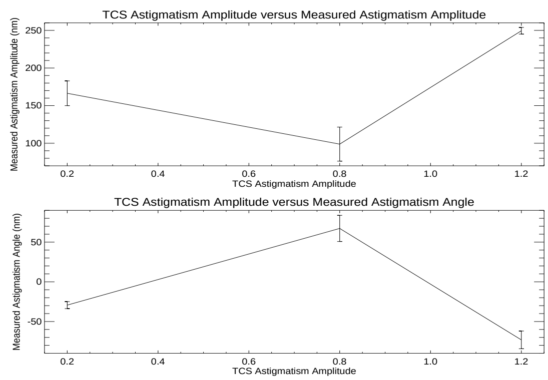


Figure 11: Relationship between applied TCS astigmatism amplitude versus measured amplitude.

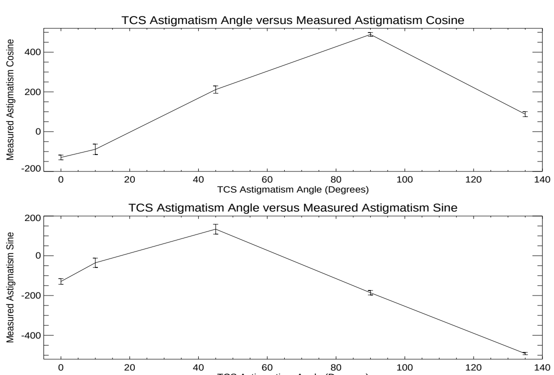


Figure 12: Relationship between applied TCS astigmatism angle versus measured Zernikes Z4 and Z5, Cosine and Sine respectively.

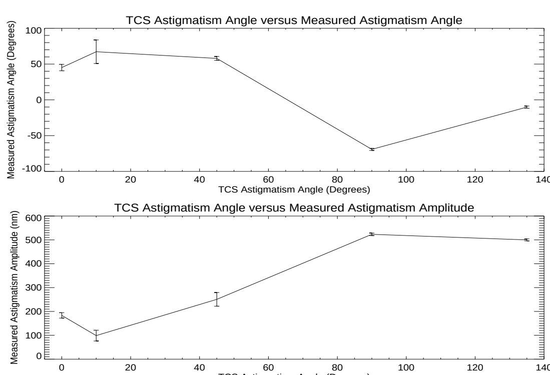


Figure 13: Relationship between applied TCS astigmatism angle versus measured angle.