Analysis of Wave Front Sensor Data 26 - 28 March 2002, 11 February and 11 April 2003

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1 Introduction

Wave front sensor data was taken during the nights of 26 - 28 March 2002, 11 February 2003 and 11 April 2003 using ALFOSC fitted with a Korhonen-Hartmann mask. The object of this analysis was to determine if there is a simple correlation between physical parameters of the telescope and aberrations of the primary mirror (M1). The main parameters investigated were time, zenith angle and M1 average temperature.

This report complements the work done by Vincent Belmont in his report *'Validation of the active Optics on NOT'*, March 2000.

From the three nights of data in March 2003, the data obtain on 26th March was essentially useless because of the very poor seeing and only internal calibration frames can be used from this night. The first part of 27th March was lost due to high humidity but later data was obtained, in two blocks, for decreasing and increasing zenith angles, (approximately 200MBytes, 280 files). The seeing again for the first period was not very good but improved considerable for the later second half of the night. The whole of the night 28th March was useful and about 440 Mbytes (600 files) of good data taken. All the analysis for these three nights has been concentrated on the final night's data.

The data taken on 11 February 2003 was for the whole night with nominal seeing of about 1 arcsec which has given satisfactory but not good results. This run particularly has shown that the seeing does need to be better than 1 arcsec to get data that can be usefully interpreted.

On 11 April 2003 the seeing was sub-arcsec for zenith angles less than 50 degrees resulting in better results than for February run.

It should be noted that between the 28 March 2002 and 11 February 2003 the telescope mirrors were removed for aluminisation and realigned after installation. Also four of the lateral support came off shortly after the aluminisation and where re-glued after the alignment.

Data from some measurements taken on 2 August 2003 are included in table 3 after a correction was made of the astigmatism.

2 Analysis

The analysis of the data has been described by Michael Andersen who has also written much of the code to do the Zernike polynomial fits to the spot patterns. Michael Andersen's procedure for acquiring and reducing the data is given in appendix A. The procedure also includes some added notes and suggestions to guide the user.

To summarize the reduction procedure; First IRAF routines 'daofind' and 'phot' are used to find the spots and to produce ascii output files containing the coordinates of all the found spots and their brightnesses for each wave front sensor CCD image file. These files are then used as input to an IDL program that analyzes the data, against a calibration frame to remove instrumental distortions, and gives Zernike terms as output which describe the aberrations of the telescope optics. Some simple (C shell) scripts have been written to combined all the Zernike data for a single night into one file where additional information, such as telescope zenith angle, can be included. The Zernike files have then been used to try and determine if there is any correlation between the behav-

Table 1: Aberrations Corresponding to the first twelve Zernike Terms

Zernike	Aberration Coefficient
Z_0	Piston
Z_1	X-tilt
Z_2	Y-tilt
Z_3	Focus
Z_4	Astigmatism cosine term
Z_5	Astigmatism sine term. This is 45° version of Z_4
Z_6	Coma cosine term
Z_7	Coma sine term. This is 90° version of Z_6
Z_8	Triangular Coma cosine term
Z_9	Triangular Coma sine term. This is 90° version of Z_8
Z_{10}	Spherical
Z_{11}	Quadratic Astigmatism cosine term
Z_{12}	Quadratic Astigmatism sine term. This is 90° version of Z_{11}

iors of the primary mirror and time, telescope position (zenith angle) and mirror temperature.

The temperatures of the mirror were obtained from the Thermal Monitoring System (TMS) that every two minutes records a large number of temperatures around the telescope and outside, including several temperatures of M1. The TMS runs on a DOS machine, where the data is not readily accessible without stopping the monitoring program, so it is allowed to accumulate data over typically a period of six months before it is transfer to another computer and archived on CD.

IDL programs exist to extract selected temperature sensor data from the TMS files and new routines were written to use this TMS data with the Zernike information to attempt to find relationships between the two.

Table 1 gives the relationship between the first twelve Zernike terms and their corresponding aberrations.

To convert the Zernike terms to actual amplitude and angle equations 1 and 2 are used.

$$Aberration\_Amplitude = \sqrt{{Z_{cosine}}^2 + {Z_{sine}}^2} \tag{1}$$

$$Aberration\_Angle = \arctan\left(\frac{Z_{cosine}}{Z_{sine}}\right) \tag{2}$$

3 Results

For all the nights that data was obtain plots have been produced to show how the zernike terms and aberrations change with respect to time and zenith angle, and only of 28 March also the dependents of primary mirror (M1) average temperature to some Zernikes is shown. To be able to compare the affects of time and zenith angle on the different night's the results has been plotted on common axes. To do this the mean value for each night has been subtracted and a modified polynomial fitted to the data. The polynomial fit includes rejection for bad (typical erroneous large) data points. The plots for all the zernikes or aberrations have then been plotted on the same amplitude scale so a direct comparison of the contribution of each component can be seen.

Unfortunately it is difficult to separate the time and zenith angle influences.

3.1 Time Dependence

The plots in figure 1 show the evolution of the first twelve Zernike terms for all three runs. The plot shows about seven hours of data. The telescope starts at a zenith angle of about 60 degrees and tracked the same star toward zenith, then down to approximately zenith 60 degrees. From

Looking at the 28 March time data some trends can be identified which appear to only have a time dependence. It can be seen that Zernike Z7 coma sine term, has a rising linear slope throughout the night, this trend is also repeated on 11 February.

For Zernike terms higher than Z6 the affects are small compared to the higher order ones, e.g. focus and astigmatism.

3.2 Zenith Angle Dependence

The zenith angle plots for the three nights where produced by sorting all the data for the whole night with respect to airmass (zenith angle) so the data for increasing and decreasing zenith angle are combined (mixed) eliminating temperature and time dependences. Also for zenith angle influence, you can look at the plots against time knowing that on the first half of the night the telescope tracked toward zenith and afterward tracked down, this then allows you to separate the motion of the telescope in altitude.

Figure 2 shows the zenith angle dependence of the Zernike terms for all three nights. For this data a polynomial has been fitted to the continum, i.e. large deviation in the data due to bad measurements have been removed and the mean subtracted. Some Zernike terms show clear zenith dependence, these are give in table 2.

Comparing the curves of plot 2 some of the Zernike terms show similar dependences to zenith angle. Converting the Zernikes to actual amplitude and angles using equations figures 1 and 2 the results are shown in plots figure 3. This data has had the means subtracted so a direct comparison can be made between the aberrations. looking at the plots of aberrations, in all cases the angle changes little and for the higher order aberrations tri-coma and quad-astigmatism the amplitude variations are small both with approximate constant values of 20nm. The overall tilt appears to have opposite signs with the 28th march data showing an increase in tilt against zenith angle where the 11 February data, up to 50 degrees zenith angle, decreases. Astigmatism for both sets of data shows an increase for greater zenith angle though of different magnitude rates and at different angles. For 28th March the magnitude changes from 20nm for about 100nm with an approximately constant angle of 40 degrees, and for 11 February the magnitude goes from 150nm to 320nm with the angle changing from 40 degrees to 70 degrees for 5 to 50 degrees zenith angle. Focus shows a drop of about 50nm for a zenith angle increase from 5 to 50 degrees then an apparent rapid change beyond this, but this may be due to poor seeing at high zenith angles. The focus of 11 April 2003 is totally inconsistent with the other two

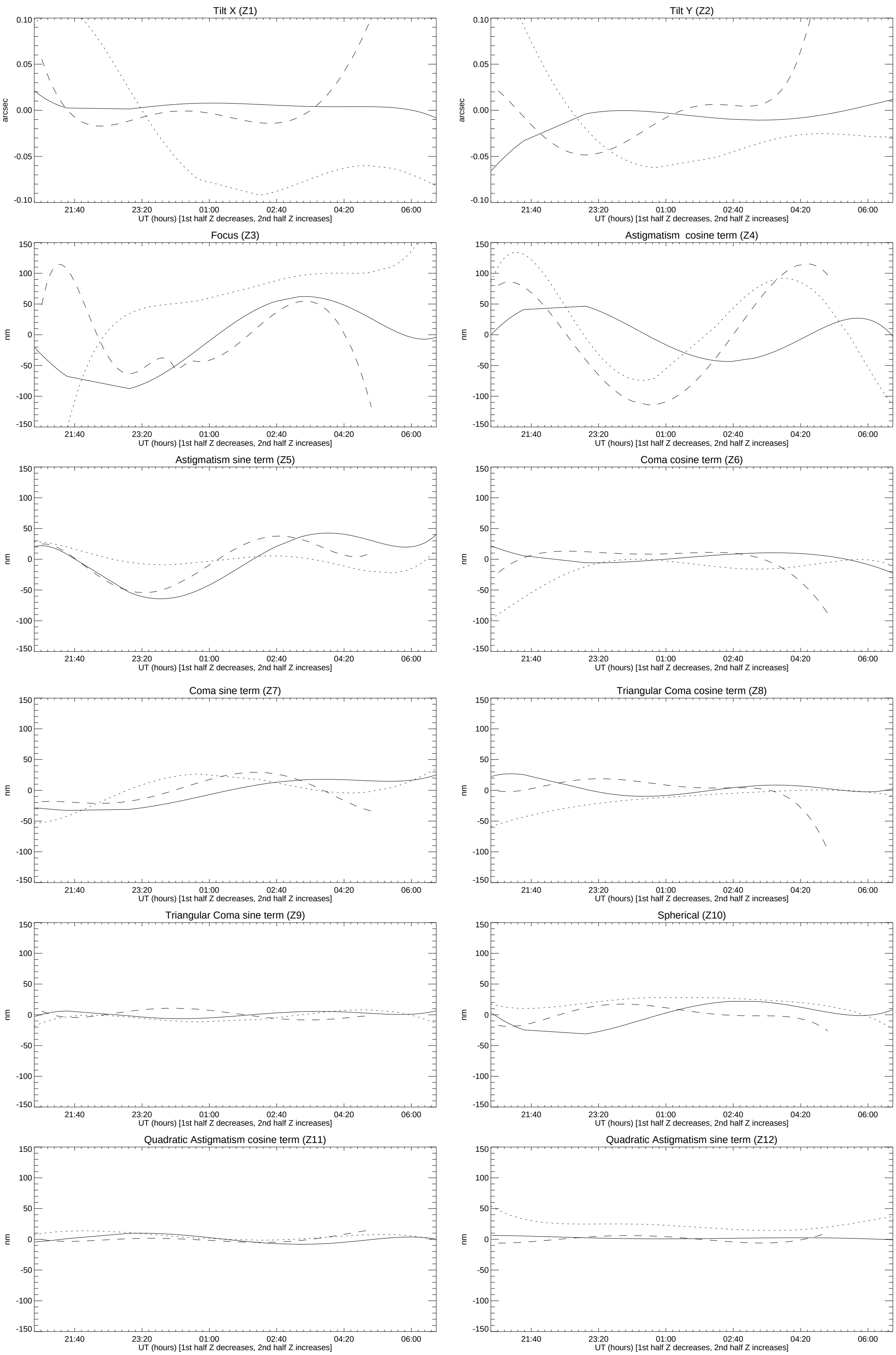

Figure 1: Zernike evolution against time for 28/3/02 (solid), 11/2/03 (dots) and 11/4/03 (dashes).

Table 2: Zernike terms with a apparent dependences on zenith angle

Zernike	Aberration Coefficient
Z2	Y-tilt
Z3	focus
Z4	astigmatism cosine term
Z6	coma cosine term
Z10	spherical
Z11	quadratic astigmatism cosine term

Table 3: The mean aberration amplitudes (nm) and angles (degrees)

Aberration	28/3/02		11/2/03		11/4/03		02/08/03	
	Amp.	Ang.	Amp.	Ang.	Amp.	Ang.	Amp.	Ang.
Tilt (arcsec)	0.239	38.6	0.2	16.9	0.2	46.3	2.5	35
Astigmatism	85.3	-12.2	288.4	-47.7	307.3	-47.1	107	9
coma	62.6	10.1	113	-21.1	80.4	25.4	104	-69
tri-coma	41.3	-19.7	60.7	2.6	33.5	-18.5	43	-9
quad-ast.	16.4	10.5	59.8	2.9	18.2	-21.2	15	35
spherical	-47.2	-	-67.4	-	-60.2	-	-17	-
focus	367.6	-	381.7	-	0.0	-	145	-

dates, on the night the focus was correct (80 focus steps) between the first half of the night and the second half. As a consequence of this it has been necessary to subtract the mean value separately for the two halves of the night.

Staying with the 28th March data set but now looking at the time graph, (figure 1) all the zenith angle changes can be seen, but what is potentially more interesting is the rates of change seem to be dependent on the direction of movement in altitude. For Z3 focus, Z4 astigmatism cosine term and Z10 spherical, all these change more rapidly in the first half of the night when the telescope is approaching zenith. This could suggest possible hysterics or may be a temperature dependence.

To be able to compare the trends of the aberrations the means were subtracted, these values are shown in table 3. A significant increase in the amplitude of astigmatism has occurred after the aluminisation in 2002. Smaller increases in coma and spherical can also be seen.

Between 11 April 2003 and 2 August 2003 the TCS applied astigmatism was increased from 0.2 at angle 0 degrees to 0.8 at 10 degrees. The results from the 2 August 2003 are a mean of ten consecutive measurements taken at zenith angle 20 degrees over 5 minutes. It can be seen the astigmatism has been reduced back to the approximate value for before aluminisation on mid-2002 where on obvious elongation of the images can be seen. It can also be seen from table 3 that all the other aberrations have stayed roughly the same. i.e. changing the astigmatism has no affect on the other aberrations, (except possibly spherical) as shown in Belmonts report.

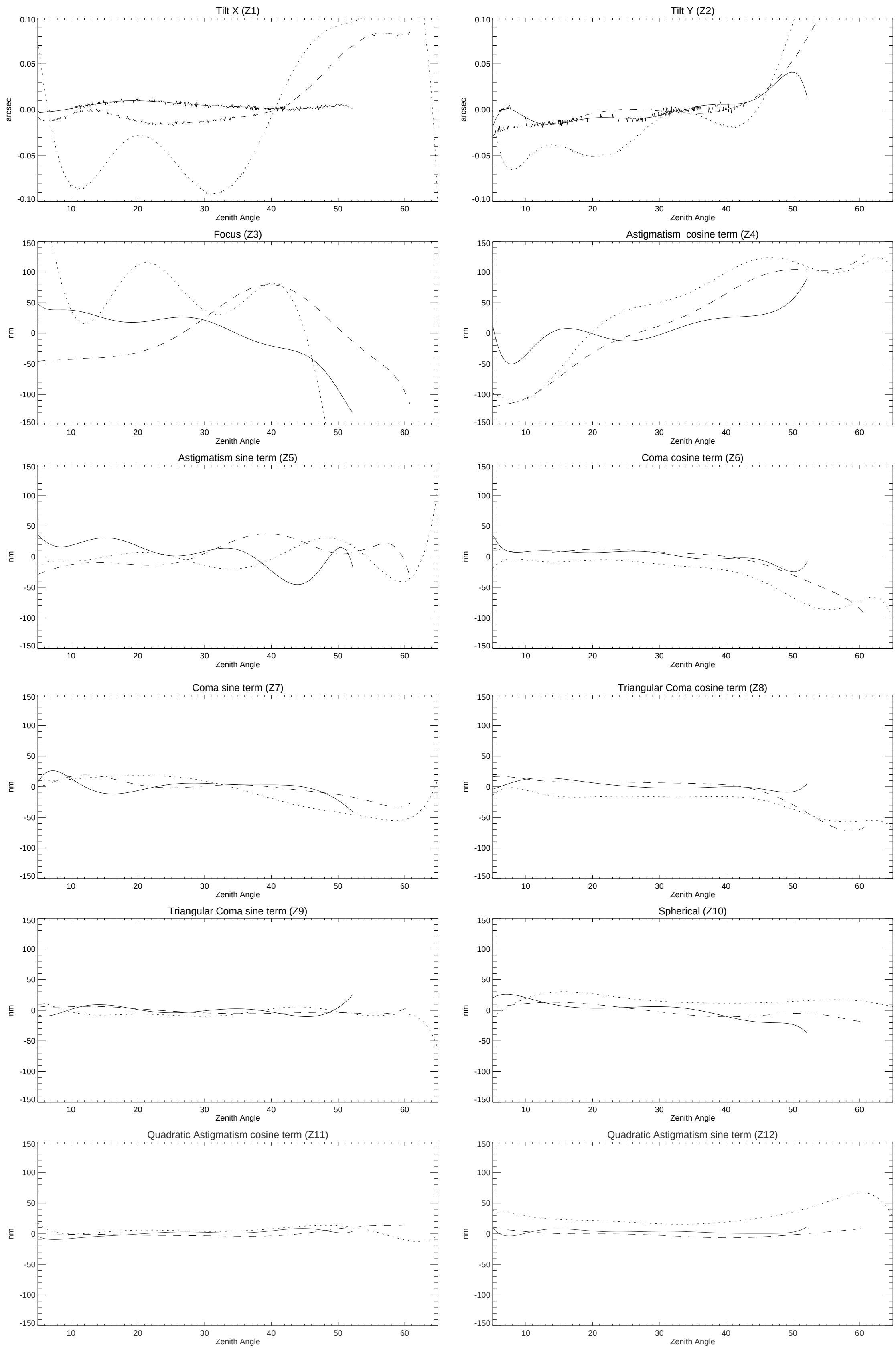

Figure 2: Zernikes against Zenith angle for 28/3/02 (solid), 11/2/03 (dots) and 11/4/03 (dashes) with mean subtracted.

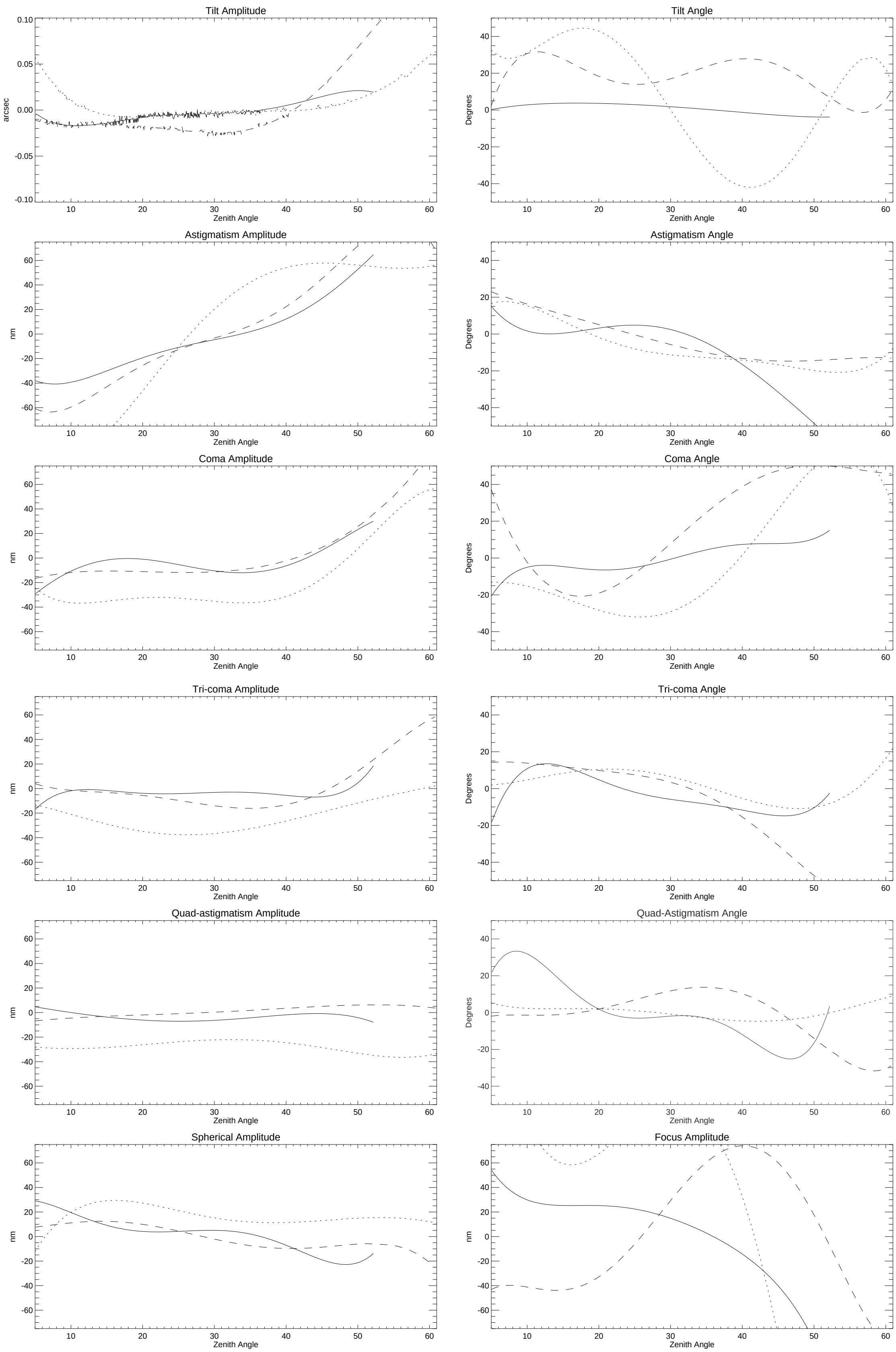

Figure 3: Aberrations against Zenith angle for 28/3/02 (solid), 11/2/03 (dots) and 11/4/03 (dashes) with mean subtracted.

3.3 Temperature Dependence

Mentioned in the section on zenith angle dependence, there may also be a temperature influence in some of the Zernike terms manifesting itself in the rate of change over time for a constant change in zenith angle. The plots in figure 4 show a selection of Zernike terms against the average temperature of the primary mirror as measured by several TMS sensors attached to the underside of M1. The plot in the top left corn of figure 4 is the average temperature of M1 for the night. As can be seen from all the plots of the selected Zernike terms most show no obvious temperature dependence, though a clear ‘hole’ in the bottom left corner of the Z4 astigmatism cosine term plot is seen and there may be a dependence against temperature of the Z6 coma cosine term.

4 More Observations and Analysis

It is necessary to determine the relationship between the WFS software Zernikes and the TCS Zernikes. This can be done by applying known aberrations to M1 through the TCS and then measure the Zernikes with the WFS. Then using equations 3 and 4 find the coefficients relating the two.

$$Ztcs_{cosine} = a.Zwfs_{cosine} + b.Zwfs_{sine} \tag{3}$$

$$Ztcs_{sine} = c.Zwfs_{cosine} + d.Zwfs_{sine} \tag{4}$$

For a given rotator angle b and c should be approximately equal to zero and $a = \pm d$. To get the amplitude and angle then use equations 1 and 2.

To try and separate zenith angle and temperature influences a series of measurements should be take at the same zenith angle for a period of time. This cam be accomplished by repeatedly selecting star from the catalogue as they pass through a common zenith angle tracking on each one for a short while.

Something else that would be potentially useful would be temperature sensors on the top surface of M1, e.g. near centre baffle where there is an unused area and close to the outer edge. At the moment all the primary mirror sensors are on the underside.

Additional analysis that could be carried out on the exist data is the influence of differential temperatures across the primary mirror or ambient temperature on the telescope.

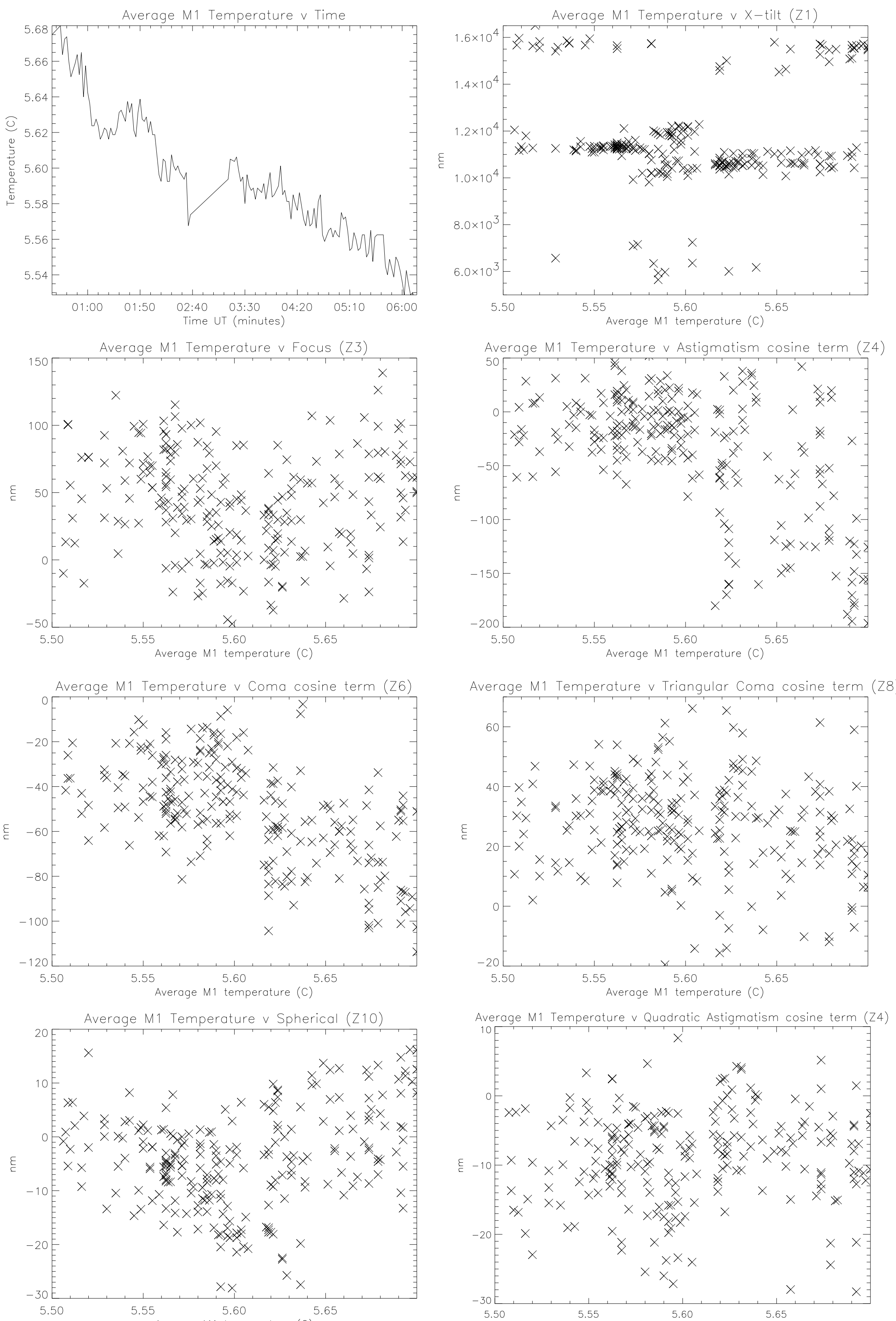

Figure 4: Zernikes against M1 average temperature for 28/3/02.

A Data Acquisition Procedure

A.1 Wavefront Measuring using ALFOSC and MIA software

A.1.1 Setup

Already a star catalogue of suitable objects has been created. Due to the small holes in the mask bright objects are required, ideally Mv 3 or 4 but this would give poor sky coverage. Also to make the analysis easier objects close to the altitude of the telescope of 28.45 degrees where chosen because for this position the rotator does not move very much when away from zenith. A catalogue of stars of Mv 4- 5 was created for objects ± 4 from 28.45 degrees and for all RA.

Put WFS lamp (LED) in aperture wheel. If possible position 1.

Put WFS KH mask with singlet lens in grism wheel.

Put H-Alpha narrow filter (#21) in FASU.

A.1.2 Calibration

Switch on the calibration lamp, little switch on same board that lamp is on, in aperture wheel.

Using the B#74 filter find the position of the calibration lamp image on the CCD. Window the CCD to 600x600 (e.g. xbeg = ybeg = 700, xsize = ysize = 600), get the coordinates of the image and enter in the 'slitpos.def' file.

Put the WFS mask in and the R#76 filter and take some calibration [spot] frames (e.g. exp 20). Ensure the spot image is centred in the 600x600 window with clear space all around it.

Switch off the calibration lamp, you should not need it again.

The reason for determining the position of the calibration lamp image on the CCD is to ensure the path of the light through ALFOSC is the same for it and the star. It is necessary to get the position of the image with the CCD windowed because you get different values with a full frame, and you operate with a windowed detector.

A.1.3 Measurement Procedure

Preset to a suitable star (from wfs4ra.cat), with rot-auto (always) type rot-pos -2 [degrees] and when tracking again (i.e. rotator has arrived at position -2) preset to star again.

Use H-alpha narrow (to reduce the light level) in series with R filter, take an image (e.g. using 'small', Bias script). Check the window position is ok.

```
small: autosave-
       xbeg 700
       ybeg 700
       xsize 600
       ysize 600
       exp 0.2
       autosave+
```

```
seth 20000
imexa
```

Use *imexamine* and ‘t’ command to move star on calibration lamp position.

Remove HaN filter and put in the WFS mask and do 30 sec exposure. Same window as calibration lamp.

A.2 Observations

Various observing modes can be adopted. One of the best is to track the same star all night from horizon to horizon. This will give a large data base of values that can be easily correlated to the zenith angle. Another option is to point near to the north pole (Polaris is a bit low) to minimize telescope zenith movement, but with large rotator movement, to get data mainly with temperature as the dominant parameter.

For tracking a star all night horizon to horizon do:

1. Put the telescope near horizon and run mexp 30 50 while tracking up.

The rotator ideally should move as little as possible so use a star as close to 28 45’ (telescope declination) as possible. The value 50 exposures is completely arbitrary but obviously it is better to do relatively short runs at a time and check the progress. It is a good idea to reset the rotator back to -2 degrees between each set of multi-exposures, and if necessary re-position the star on the calibration lamp CCD coordinates as described in the Measurement section.

A.3 Reduction

A.3.1 Finding the spots

Reduction goes in two steps. First the spot positions must be extracted. This is done with ‘daofind’ and ‘phot’ within IRAF. Use the following sequence of commands to start IRAF and load the ‘daophot’ package:

```
‘cl’                # in the iraf directory of the account
‘digiphot’          # to load the ‘digiphot’ package
‘daophot’           # to load the ‘daophot’ package
‘cd working_dir’    # go to the dir with the data
```

First you must determine the approximate standard deviation of the background and the FWHM of the spots with the ‘datapars’ task. The standard deviation may be measured in the M2 shadow using the ’m’ keystroke in imexamine.[1] The FWHM is essentially impossible to measure with imexamine because of the large density of spots. Set it to a value you best estimate from looking at the image or set it to the current seeing (it must be close to that). It is not important to get the standard deviation and FWHM exactly right, just they are about right. You are probably better off setting a high rather than a low standard dev.

[1] To get the standard deviation, before you enter IRAF (cl) start SAOimage (ds9) then follow the instructions including the cd to the working directory. Then display the desired image using ‘display’ command then ‘imexamine’ and with the cursor in the dark secondary obscured area press ‘m’ to get info on the pixels in the defined box (default 10x10).

To get the zenith angle from the fits header use the airmass, zenith angle = arccos(1/airmass)

You should now do the following steps.

```
‘unlearn daopars’   # parameters have default values
’unlearn datapars’  # parameters have default values
’unlearn daofind’   # parameters have default values
’unlearn phot’      # parameters have default values
’unlearn fitskypar’ # parameters have default values
’datapars’          # set the FWHMPSF and SIGMA parameters from
                    # imex and enter AIRMASS for airmass.
                    # enter FWHMPSF & FWHM in pixels, scale = 1.
’photpars’          # set APERTUR to ~FWHM (use an int number).
```

You should now be ready to extract the spot positions. Use the following sequence of commands (image ig020033 used in this example), while just accepting default values:

```
’daofind ig020033’    # You may have to rename for IRAF
                      # to accept it.
                      # o/p of daofind is <filename>.coo.1
’phot ig020033’       # Determine brightness of spots.
                      # o/p of phot is <filename>.mag.1
                      #dump coords/mags
’pdump ig020033.mag.1 "XCEN,YCEN,MAG" yes > ig020033.coo’
```

It is possible to run both ‘daofind’ and ‘phot’ in batch mode using file lists, e.g.

```
cl> daofind @imlist default verify- &
cl> phot @imlist @coordlist default verify- &
```

It is not obvious how the run ‘pdump’ in batch mode so create a script that contains a ‘pdump’ line for every input file and output file pair. Then execute the script by:

```
cl> cl < ppdump270302.cl

e.g.ppdump270302.cl

pdump lc270026.mag.1 "XCEN,YCEN,MAG" yes > lc270026.coo
pdump lc270027.mag.1 "XCEN,YCEN,MAG" yes > lc270027.coo
pdump lc270028.mag.1 "XCEN,YCEN,MAG" yes > lc270028.coo
                            :
                           etc
```

You should now have a list of files ‘image.coo’ but some of these will have ‘INDEF’ put in the MAG column by IRAF. This need to be replaced by e.g. ‘12.5’. The following csh script can fix this.

```
#!/bin/csh

set files = `ls ./coo/`
foreach file ($files)
  cat $file | sed s/INDEF/12.5/ > $file.2
end
```

NOTE: The output files that contain the coordinates for the wavefront sensor software now have the extension '*.coo.2', not '*.coo'.

A.4 Calculating the Zernike Coefficient

You need MIA (Michael Andersen's) IDL libraries and software for the following.

The software is located in a directory called 'kh_red/' To run it, start IDL from there. To verify that all required routines are available, do the following in IDL:

```
IDL> @run
```

If IDL complains about some routine missing, IDL can't find that routine.

The software uses two setup files, both located in the 'etc/' directory within the 'kh_red/' directory. The main setup file is 'kh_wfs.par', which you need to edit for the correct paths for the *.coo and *.red files. The field for these paths is limited in size so don't make the path too long! This file specifies the name of the WFS (here ALFOSC). It also specifies the number of Zernike terms to fit. In general, don't fit much more than what you need for setting the active optics. But you may try out different values here. In addition you specify where to get input and where to put output, so that you don't create a huge mess out of all the files you will soon have (you may also use other disks).

After having read this file, the software searches for a file 'name.def' in the 'etc/' directory (here ALFOSC.def). This file defines the layout of the mask. This is essentially what defines the WFS and all subsequent calculations are based on these parameters. Do not modify this file.

To run the KH_RED program, edit the 'doit.pro' file for correct input and then just do:

```
IDL> @doit
```

To reduce a large number of coordinate files it is necessary to repeat the commands in the doit.pro file for every input file.

When the KH_RED program is run with an input spot coordinate file, it searches for a file 'name.cal' in the 'etc/' directory (in this case 'ALFOSC.cal'). If this file is not present, KH_RED assumes that we are reducing a calibration image. The output will thus be a new calibration file (here ALFOSC.cal).

When the calibration file is present, Zernike coefficients are calculated and written to a file.

A.5 Useful Information

Some useful notes (for me) about IRAF:

To exit 'datapars' use ':q' or '< CNLT > D'.

Attach a fits extension to the files using the IRAF task 'rename' and an image list of the files.

```
 cl> imrename @imlist @imlist//.fits
or
 cl> imrename lc270* lc270*%%.fits%
```

To create an image list do the following in IRAF.

```
lc> ls lc*fits > imlist      Where 'lc*fits' is the file names
lc> ls lc*coo.1 > coordlist
```

To extract the airmass and put in a file using IRAF.

```
 cl>  hsel @zerlist AIRMASS yes > airmasslist
```

Where '@zerlist' is a list of the *.z021 output file names (but with .fits extension) (rather than the full fitslist that may include files where kh_wfs failed in obtaining the Zernike terms). Airmasslist is the resulting file containing only the airmasses.

Use 'myzer' (my script) to create a file containing all the Zernike coefficients, one per column. Add the zenith angles (or airmass) as the first column using emacs rectangle editing.

- Run myzer in the directory with the *.z021 files.
- Then change the .z021 extensions to .fits for all the files in the zerlist file.
- Copy the zenlist file to th directory with the original fits files. in IRAF run 'hsel @zerlist AIRMASS yes > airmasslist'.
- Now copy the airmasslist file back to the directory with the *.z021 files.

Sort using the Unix sort command 'sort -k# in_file -o out_file' where # is the field position.

B Thermal Monitoring System M1 Sensor Definitions

Sensors with position values missing DON'T work.

Pos'n	#	Sensor definition	
16	201	Main mirror, 260mm from center, north	Glass
17	202	Main mirror, 260mm from center, south-east	Glass
18	203	Main mirror, 260mm from center, south-west	Glass
19	204	Main mirror, 600mm from center, north	Glass
20	205	Main mirror, 600mm from center, south-east	Glass
	206	Main mirror, 600mm from center, south-west	Glass
22	207	Main mirror, 940mm from center, north	Glass
	208	Main mirror, 940mm from center, south-east	Glass
24	209	Main mirror, 940mm from center, south-west	Glass
	210	Main mirror, on the edge, north	Glass
	211	Main mirror, on the edge, south-east	Glass
27	212	Main mirror, on the edge, south-west	Glass
	213	Main mirror, on top of the edge, north	Glass
	214	Main mirror, on top of the edge, south-east	Glass
	215	Main mirror, on top of the edge, south-west	Glass