Blanco optics report.
R.Tighe, 31May2010.

1.- Introduction:
The optical consequence of correcting the radial support of the Blanco main mirror is expected to be mainly psf stability over the observing sky, as well as over the years. This is probably the most important requirement of Decam. The mirror is free to move axially under the action of the active optics actuator system but constrained radially to stay close to the center of the cell, by balanced and smoothly acting radial astatic lever actuators. A stable and un-stressed main mirror support will:
i) Allow better coma correction because only the elastic flexure of the top-ring and serrurier need to be compensated.
ii) Allow better astigmatism correction especially at large zenithal angles, because by preventing lateral motion of the mirror in a gentle way it avoids unwanted frictional and/or binding forces to build up at points on the mirror circumference, which will bend the glass as well as distort the calibrated wavefront-to-pressure correction factors used by the axial active support.
iii) Prevent breakage of radial supports. When one breaks, the radial support system goes out of balance and induces others to start failing. The IQ variability over the sky increases as the number of broken radial supports increase.
(key words: sky-map, look-up table (LUT), aberrations).

2.- Blanco M1 displacement w/r to cell as radial supports break:

The M1 displacement is measured with 4 Mitutoyo linear gauges (N,S,E and W). Center is zenith, circles are Zd 15, 30,45 and 60 Deg. Az is from N to W in steps of 30Deg (1).

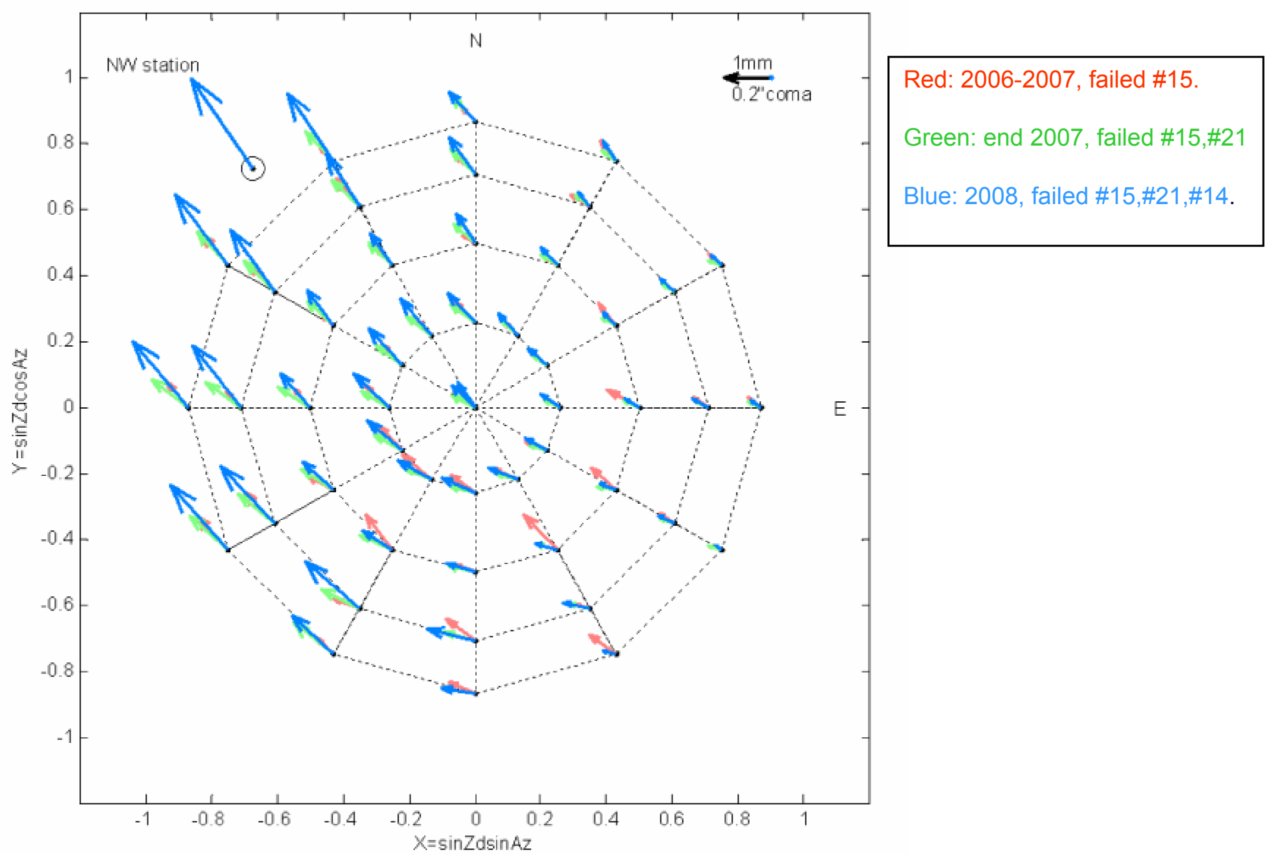


Fig.1. The Sky-map used to build the Blanco aberration correction look-up tables. The arrows represent the mirror displacement w/r to the cell as radial supports break.

3.- M1 displacement w/r to cell before and after radial support repair:

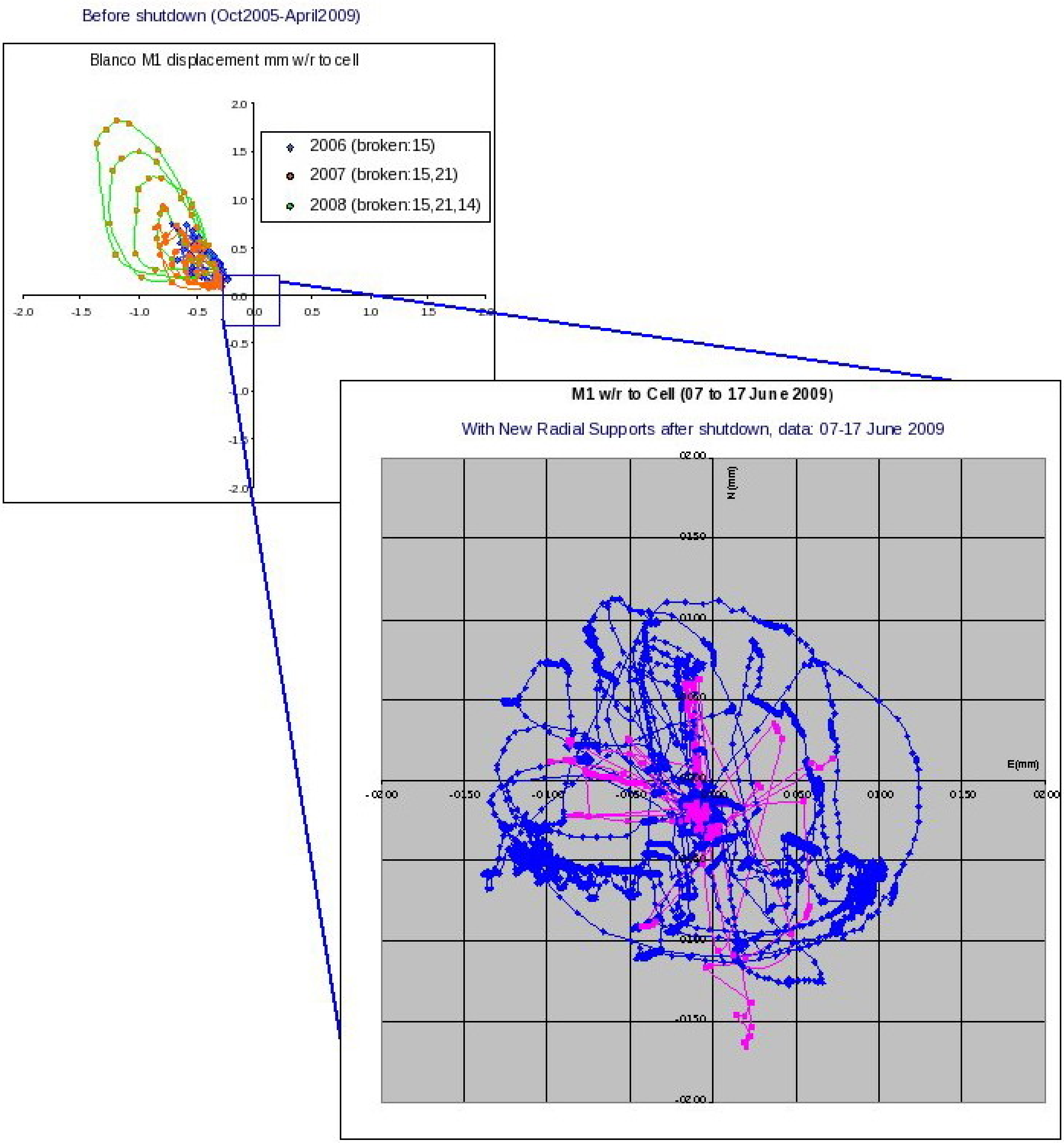
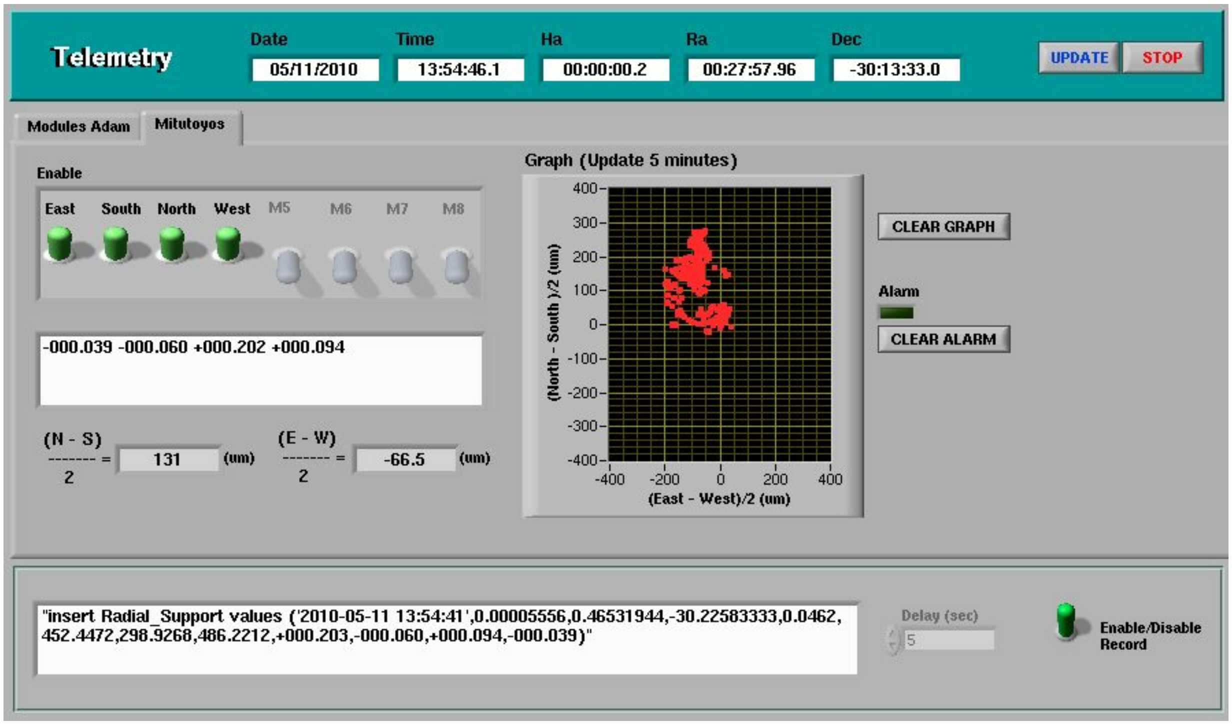


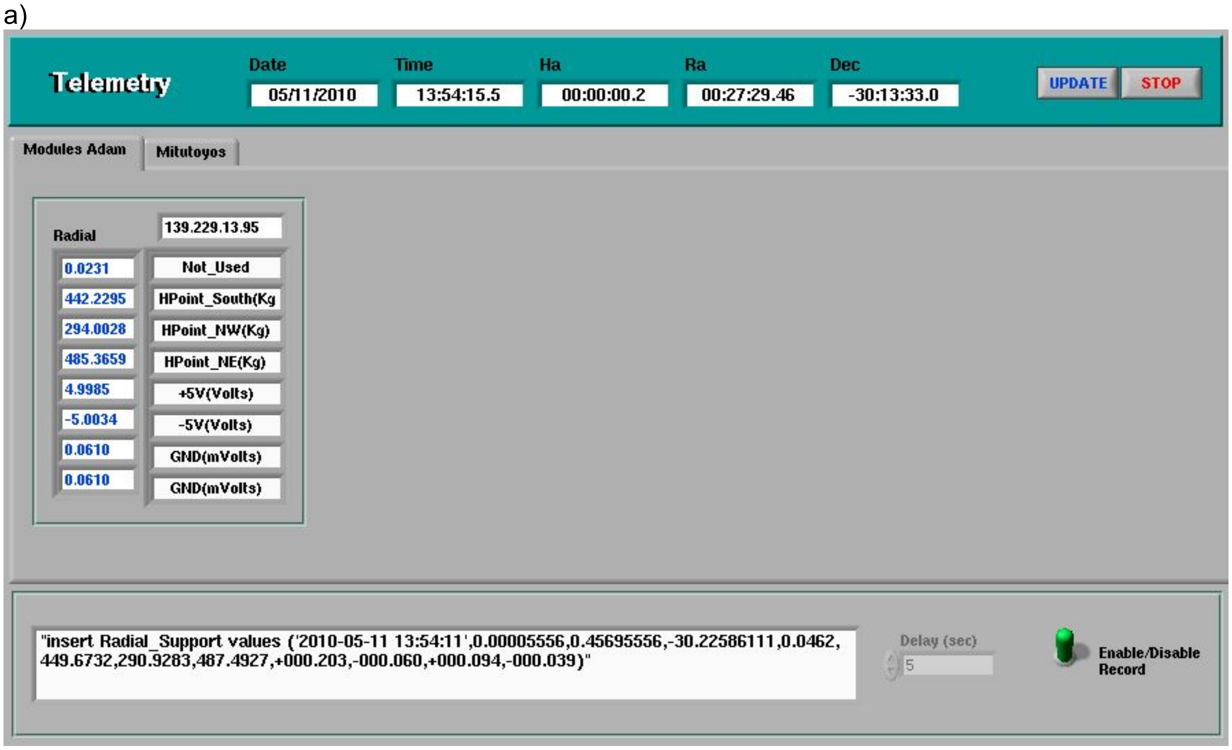
Fig.2. Blanco M1 displacement w/r to cell while moving the telescope to all possible positions.

A Telemetry logging system was implemented (2) to keep track of the M1-related opto-mechanic Telescope parameters, like M1 radial displacement w/r to cell (Mitutoyos), axial hard-points load cells (Adam modules) and in the future, axial actuators voltages (Mamacs).

Figure 3 are pictures of the Telemetry GUI showing the actual position of the Blanco main mirror in its cell during, roughly, the first week of May2010 (a) and the hard-points load in Kg at the time of the grab (b).



a)



(b)

Fig.3.The Blanco M1 telemetry GUI.

4.- Coma:

Figure 3 shows the top-ring plus serrurier flexure w/r to M1 (3) as the telescope is moved over the same sky-map grid shown in Figure 1. The top-ring flexure is measured with a laser projector attached to the main mirror and a CCD camera attached to the PF corrector unit.

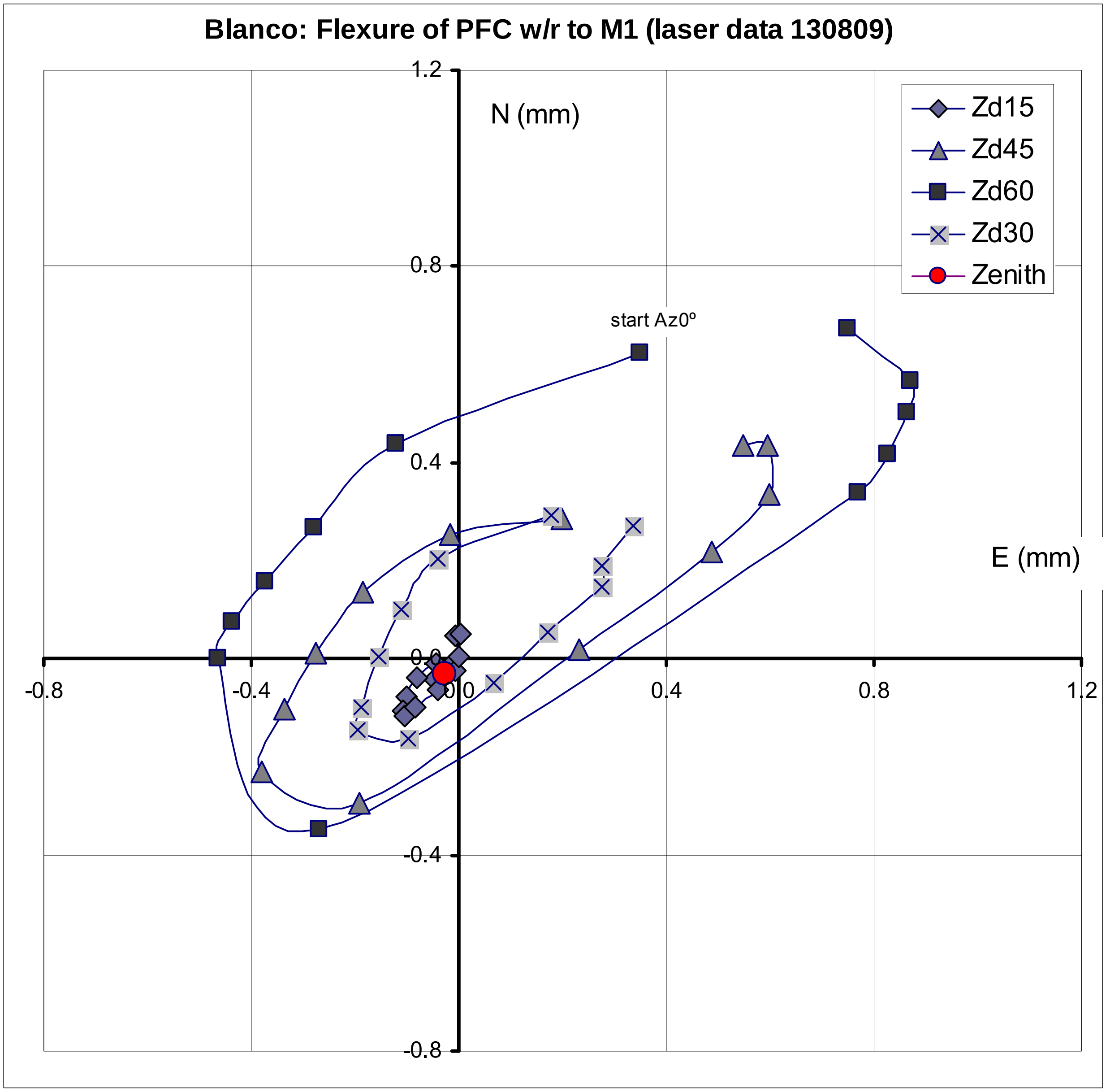


Fig.4. The Blanco top-ring displacement w/r to M.

The measured coma wavefront data (3) has been transformed to PF displacement in mm needed to correct the coma. Given that the laser flexure measurement is set to zero at Zenith, the all-sky average coma vector has been subtracted to all the data, leaving the residual coma quite close to zero at zenith as expected. There is some discrepancy in amplitude of the measured coma magnitudes respect to the corresponding flexure magnitudes (~1.7 times for numbers in the order of 1mm), nevertheless the direction, sign and overall shape of the coma map is consistent with the measured top-ring flexure. Moreover and in spite of the discrepancy in amplitude, if **F** and **C** are the measured top-ring flexure and coma vectors respectively, the correlation error is: E = **|C–-F|** = 0.07 +/- 0.03 Arcsec over all the skymap. The target value of coma wavefront is 0.1Arcsec or 0.714um of wavefront OPD at the edge of the pupil (or 0.595mm displacement between primary mirror and top-ring) and the conversion factor used to move back and forth from wavefront-of-coma to millimeters-of PF-translation is: 1.2(umWF/mmPFtranslation). The rule for the direction is: "move the PFC towards the coma vector point" (4).

Figure 5 shows the measured coma vector points with telescope at Zd=60° and moving in Az from 0° though 330° on the skymap grid of Figure 1. Superimposed is an ellipse fitted to the corresponding top-ring flexure (amplified by 1.7).

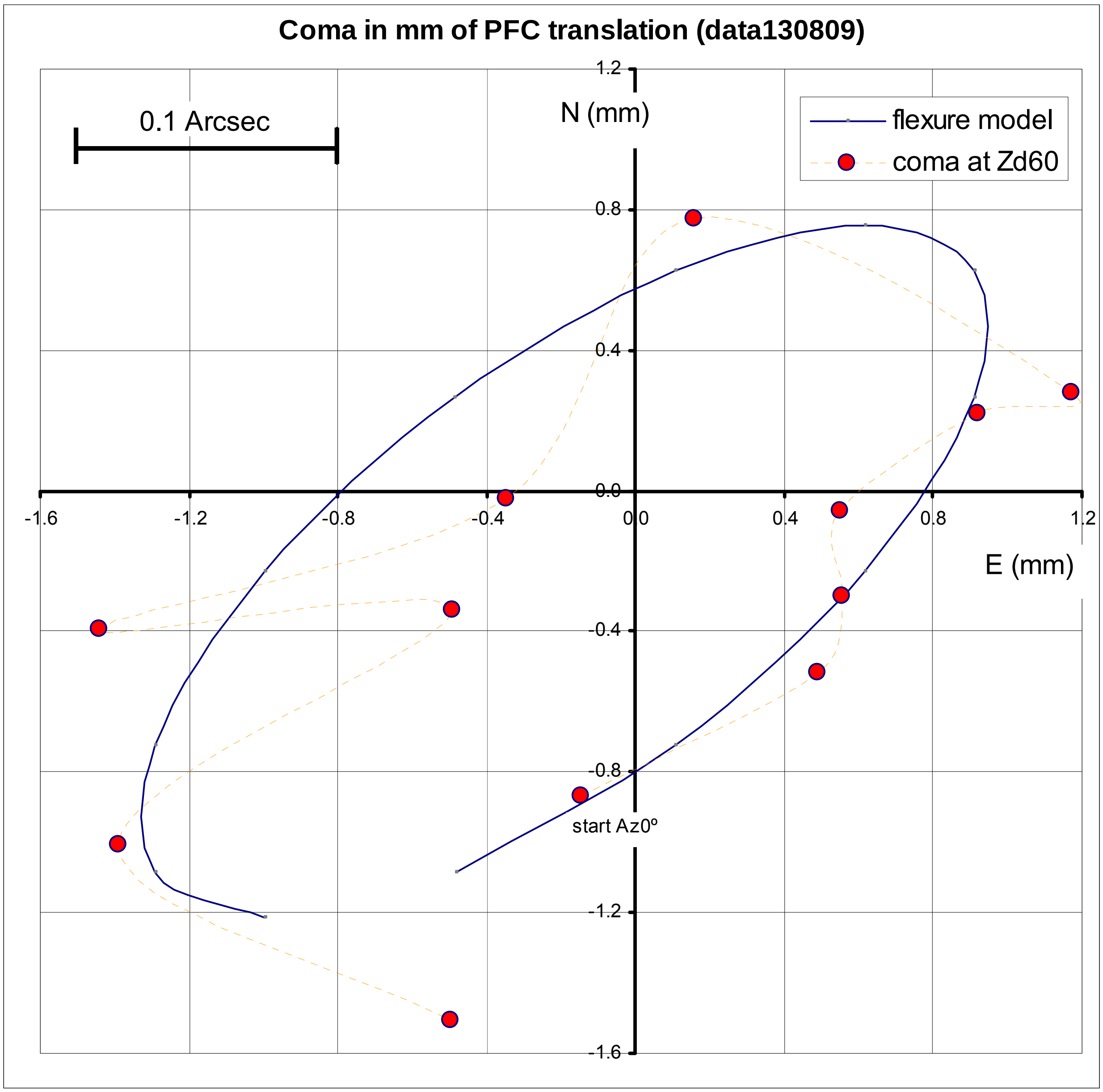


Fig.5. The PF Coma map at Zd60°.

A PF Coma look-up table (LUT) from Hartmann data would look like the one shown in Table 1 where red means coma > 0.1 arcsec. But the coma-to-flexure matching found above, suggests that a LUT based on an analytical model of the top-ring flexure would correct the coma to < 0.1Arcsec all over the sky.

PF Coma LUT Aug2009						(Mag. Target 714nm)				
Az	OPD Mag. nm					Az Ang Deg				
Zd	0	15	30	45	60	0	15	30	45	60
0	31	37	551	550	880	262	252	3	343	351
30	31	367	380	463	713	262	267	29	26	43
60	31	504	719	728	628	262	231	302	76	62
90	31	456	687	724	554	262	204	120	104	84
120	31	678	218	675	945	262	102	226	138	104
150	31	628	385	1010	1206	262	152	71	129	103
180	31	506	482	853	791	262	174	180	161	169
210	31	273	915	740	349	262	185	168	178	274
240	31	406	369	347	1495	262	191	104	296	285
270	31	115	498	891	600	262	117	226	307	304
300	31	160	524	984	1716	262	164	266	295	306
330	31	191	122	1019	1588	262	185	355	320	342
360	31	37	551	550	880	262	252	3	343	351

Table 1. The Coma LUT.

This, or a similar, Coma LUT could be applied to the Decam Hexapods and should correct the Blanco coma due to top-ring and serrurier flexure. Any small coma residual measured in real time by Donut could be corrected by applying a tweak correction at the corresponding telescope position.

5.- Astigmatism, Trefoil and Quadratic:

The residual Spherical inherent to the Telescope plus PFC is 0.27+/-0.05arcsec and cannot be corrected by the active system because it consumes all the dynamic range, or power, of the actuators. Coma, due mainly to top-ring flexure and of magnitude 0.1+/-0.05arcsec, cannot for the moment be corrected over all the sky. So the only data that can give information on Blanco Image Quality evolution are the mirror figure aberration terms that can be corrected i.e. Astigmatism, Trefoil and Quadratic. The mirror function, which is controlled by the mirror program (4map), is a polynomial expansion in the so-called quasi-Zernike base:

$$W(r, \theta) = A11\cos(1*\theta) + A02r^2\cos(0*\theta) + A04r^4\cos(0*\theta) + A13r^3\cos(1*\theta - \Phi1) + A22r^2\cos(2*\theta - \Phi2) + A33r^3\cos(3*\theta - \Phi3) + A44r^4\cos(4*\theta - \Phi4).$$

The wave-front sensors results and the correction imputs to 4map, are expresed in the format of a phasor vector, i.e. an Amplitude (Anm) and a Phase angle (Φn). There are four sets of corrections that can be applied to the Blanco telescope to minimize aberrations:

1) Baseline Corrections (basePF.par and baseF8.par) are constant term arrays.
2) Look-up tables (LUT) are corrections actively applied to M1as a function of telescope orientation. For any given telescope position, 4map finds the four surrounding sky-map grid points and determines the aberration correcting vector to be applied, by making a linear combination of the four aberration vectors in each sky-map point, weighted by the distance of each point to the actual position of the telescope. LUTs for correcting astigmatism, trefoil and quadratic are applied to M1 and are different for PF and F8 configurations, and a coma correction LUT can be applied to M2 tilt in F8 Cassegrain focus configuration.
3) Tweak corrections can be applied to M1 to do small adjustments to the astigmatic features, or to M2 tilt to adjust coma at certain positions on the sky. The tweak corrections, as all the others, add vectorially to the underlying correction but is activated only at the telescope position it was applied at. It can also be turned off (recomended) when not needed any more.

At PF the current Baseline corrections as well as the “small corretions” Ast. LUT and Tref. LUT are shown in Tables 2. The Quad.LUT is zero. Note that, as shown in Table 1, the first five collumns are Amplitude in nm and the second five are angles in degree. Rows are Zd and collumns are Az from N to W.

PF Baseline (basePF.par)			
term		Ampl.(A)	angle(Φ)
Ast.	(b2)	369	76
tref.	(b3)	0	0
quad.	(b4)	0	0

PF Astigmatism LUT (4map2pf.cof):

* Ast.LUT built on data 13Aug2009. corrected 110510.
*hartmann data shows no convection streams.

40	294	528	337	460	236	268	316	266	282
40	0	476	533	527	236	243	316	279	279
40	391	163	363	437	236	271	279	288	279
40	171	267	305	401	236	304	325	268	278
40	310	110	413	186	236	247	217	277	262
40	263	177	65	349	236	247	248	260	280
40	0	0	60	457	236	279	271	227	259
40	97	0	0	112	236	282	235	284	389
40	235	0	0	191	236	223	296	291	294
40	163	75	199	271	236	272	273	312	366
40	193	41	147	377	236	258	281	307	339
40	37	343	111	443	236	276	295	307	333
40	294	528	337	460	236	268	316	266	282

PF Trefoil LUT (4map3pf.cof):

*tref LUT on hartmann data taken 130809.corrected 110510.

0	0	0	0	109	332	354	347	351	348
0	0	0	0	74	332	330	331	357	353
0	0	0	0	54	332	343	341	337	334
0	0	0	20	43	332	399	357	349	340
0	0	0	54	0	332	373	466	353	331
0	0	0	0	110	332	388	319	371	355
0	0	0	0	36	332	356	363	339	361
0	0	0	0	171	332	319	371	336	364
0	0	0	0	0	332	340	496	331	335
0	19	0	19	109	332	311	299	346	345
0	0	0	0	121	332	345	322	327	346
0	0	0	0	59	332	310	319	345	350
0	0	0	0	109	332	354	347	351	348

Table 2. PF baseline and LUTs.

After the Blanco main mirror support upgrade was finished mid-2009, much work has been done in testing and characterizing an active system that was behaving in new ways. At big corrections (>500nm), the active sytem responds well. The response factor is ~1. i.e. the output measured by the WFS equals the imput aberration. But for small corrections the system needed to be characterized in order to be able to tune it. Four important calibrations were done for small corrections:

1.- Active system resolution: ~226nm for astigmatism and ~52nm for trefoil.
2.- Amplitude response factors measured: ~0.8 for astigmatism and ~0.9 for trefoil.
3.- Angular response error: ~38Deg for astigmatism and ~25Deg for trefoil.
4.- The phase angle transformation from WFS output to 4map input is, for astigmatism: $\Phi'=(\Phi/2+90)*2=\Phi+180$, for trefoil: $\Phi'=(\Phi/3+60)*3=\Phi+180$ and for quadratic: $\Phi'=(\Phi/4+45)*4=\Phi+180$.

Finally, to avoid introducing noise given that this correction regime is close to the resolution of the system, the LUTs values are filtered using the following criteria:

Define **k** as skymap position #k, LUT**k** as the aberration correction value at that position, **Target** as the target opd value for each term as given in Table 3 and **Resk** as the residual aberration amplitude at the skymap position k with baseline correction applied, then:

LUT**k** = IF(**Resk< Target**, 0, **Resk- Target)** (if residual<target value=0, else value=the difference).

The first results with the above PF corrections are shown in Table 3.

All sky average	astig	ang	tref.	ang	quad	ang	Total
d80 (amplitude in nm of opd)	320	54	121	166	106	159	
d80 arcsec	0.11	54	0.05	166	0.04	159	0.12
Stdev arcsec	0.04	24	0.02	20	0.02	23	0.05
p-v arcsec	0.15		0.06		0.08		0.18
Target:opd in nm (0.1Arcsec)	303		256		238		

Table 3. Blanco M1 mirror residuals at PF.

Figure 6 shows the evolution of the PF IQ (5,6), where the Total d80 in Arcseconds is the square root of the quadratic sum of the three astigmatic terms.
The telescope has always been corrected as best as possible over the observing sky and that is seen in the Average values and Stdev, but the psf stability seems better represented by the P-V value over the sky-map.

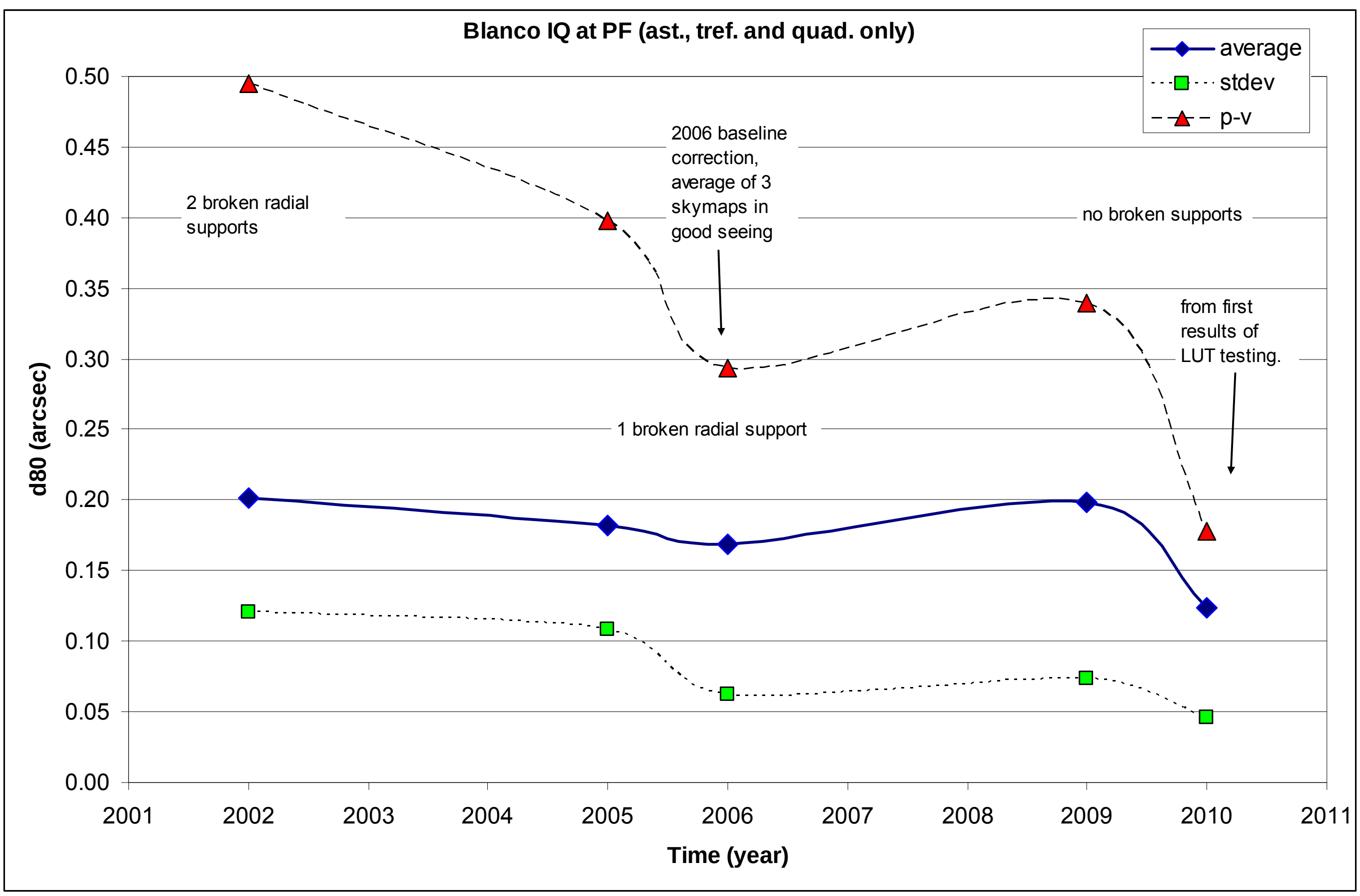


Fig. 6. The evolution of Blanco IQ.

7.- IQ Summary of the PF and the F8 foci:

Table 4 gives the diameter of the d80 star expected at PF where focus is not considered because on the telescope it is removed by focusing. Nevertheless focus stability is very important for IQ. It's under study.

All sky average	foc	spher	coma	ang	astig	ang	tref.	ang	quad	ang	Total d80
d80 (amplitude in nm of opd)	6159	-2488	616	161	320	54	121	166	106	159	
d80 arcsec	5.17	-0.27	0.09	161	0.11	54	0.05	166	0.04	159	0.31
Stdev arcsec	1.49	0.05	0.04		0.04		0.02		0.02		0.08
p-v arcsec	4.97	-0.19	0.15		0.15		0.06		0.08		0.30

Table 4. The PF residual wavefront errors.

For the Blanco telescope in the F8 Cassegrain focus configuration, astigmatism, trefoil and quadratic aberrations produced both in the primary and secondary mirrors, can be minimized by baseline plus LUT corrections applied to the axial active support of the primary (M1) and coma is corrected by applying adequate Tilt to the secondary mirror (M2). At F8 the current Baseline corrections are shown in Table 5(c). Two things to be noted here. First, that the F8 baseline is quite different from the PF baseline because it includes the M2 aberrations. Second, that unlike the PF baseline which is very constant throughout years, the F8 baseline varies within a year. This is thought to be related to instabilities in the M2 support system but a good explanation doesn't exist yet. Until the F8 wavefront values are more stable, it makes little sense to built small correction LUTs. So the F8 look-up tables (4map2f8.cof, 4map3f8.cof and 4map4f8.cof) are all zero for now. For similar reasons, M2 instabilities, the coma LUT has never been applied in F8. This instability can be quite critical in the case of active coma correction because each tilt adjustment must simultaneously be accompanied by a telescope re-pointing. A small tilt error can produce an unacceptable image degradation if correction occurs during integration.

F8 Baseline (basef8.par) 03Sept2009

term		Ampl.(nm)	angle(Φ)
Ast.	(b2)	1680	346
tref.	(b3)	560	347
quad.	(b4)	170	171

(a)

F8 Baseline (basef8.par) 30March2010

term		Ampl.(nm)	angle(Φ)
Ast.	(b2)	920	17
tref.	(b3)	550	349
quad.	(b4)	210	179

(b)

F8 Baseline (basef8.par) 27April2010

term		Ampl.(nm)	angle(Φ)
Ast.	(b2)	1385	330
tref.	(b3)	320	347
quad.	(b4)	200	161

(c)

Table 5. The F8 baselines.

The variability of the F8 baselines is shown in Table 6.

term		stdev(nm)
Ast.	(b2)	383
tref.	(b3)	136
quad.	(b4)	21

Table 6. F8 baseline stdev.

The current IQ of Blanco at the F8 focus with the baseline correction in Table 5(**c**) is given in Table 7.

All sky average (vectorial)	foc	coma	ang	spher	astig	ang	tref.	ang	quad	ang	Total d80
d80 (amplitude in um of opd)	7.76	0.42	-147	-2.72	0.41	45	0.08	-45	0.07	-29	
d80 arcsec	6.52	0.06	-147	-0.30	0.14	45	0.03	-45	0.03	-29	0.34
stdev arcsec	0.89	0.05		0.07	0.09		0.05		0.02		0.13

Table 7. The F8 residual wavefront errors.

7.- Conclusions:

1) The Blanco IQ is mainly dominated by spherical aberration. It cannot be corrected but it is stable both in time and with telescope orientation. The spherical aberration at the Blanco PFis -0.27 +/-0.05arcsec (18% variability).

2) The alignment term, coma, will be corrected to less than 0.1arcsec by the Decam hexapod support. The overall coma value at the PF is 0.1 +/- 0.05arcsec (+/-50% variability).
3) The astigmatism, trefoil and quadratic terms are corrected by the main mirror active optics. Each term will be corrected to less than 0.1arcsec and currently at PFthe d80 contribution of the three terms summed in quadrature is around 0.12 +/- 0.05arcsec (+/-42% variability).
4) The F8 baselines show rather strong variations that need to be explained and fixed if possible.
5) During the time a given baseline is valid, the F8 IQ is good. But until the variations are understood the small corrections LUT for F8 will not be implemented.

8.- References:

1) http://www.ctio.noao.edu/telescopes/4m/active4m.html.
Active Optics System 4m Blanco, J.Baldwin, 14 November 1995. (last revised, M.Boccas 3 Feb.2001).
2) M.Warner and O.Estay, Blanco TCS upgrade Team, 2009, CTIO/NOAO, (tb documented).
3) http://www.ctio.noao.edu/telescopes/opteng/Blanco_Optics_summary_2010/PF/flexure and coma/
4) Procedures and Formulae for the adjustment of Telescopes and analysis of their performance, Ray Wilson, 18 June 1980, ESO.
5) PF Hartmann data and F8 Shack-Hartmann data, respectively, in:
http://www.ctio.noao.edu/telescopes/opteng/Blanco_Optics_summary_2010/PF/PF skymaps/
http://www.ctio.noao.edu/telescopes/opteng/Blanco_Optics_summary_2010/F8/F8 skymaps/
6) PF processed data and F8 processed data, respectively, in:
http://www.ctio.noao.edu/telescopes/opteng/Blanco_Optics_summary_2010/PF/PF IQ/
http://www.ctio.noao.edu/telescopes/opteng/Blanco_Optics_summary_2010/F8/F8 IQ/