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HISTORY OF DOCUMENT CHANGES

Issue	Date	Change Description
Verison 1.0	Aug 30th, 2019	Initial Issue

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List of Abbreviations

AO	Adaptive optics
MCAO	Multi-conjugate adaptive optics
GAOS	GREGOR adaptive optics system
GREGOR	is not an acronym
DM (DM1 … DM5)	Deformable mirror(s)
EST	European Solar Telescope
TT	Tip-tilt (agile) mirror
F1, F2, F3, F4, F5	designations for the focal planes of GREGOR
Mxx	designation for a mirror in the GREGOR optics

1. Scope

This document describes the opto-mechanical layout for the prototype multi-conjugate adaptive optics system for the European Solar Telescope which is to be installed at the GREGOR solar telescope of KIS at the Teide Observatory of the Instituto Astrofísica de Canarias (IAC) in Tenerife, Spain.

The purpose of the prototype MCAO system is to test and verify a scaled-down version of the baseline design for the EST MCAO system. The EST design consists of a total of five deformable mirrors (DMs), one DM at a conjugate of the entrance pupil, four DMs with conjugates along the line of sight at various distances within the Earth's atmosphere. The combination of five DMs requires a well-developed wave front sensing and control strategy, which must be verified before the preliminary design of the EST MCAO system can be completed. The prototype will serve as a testbed for developing and verifying wave front sensing and control concepts which will be developed within the WP 7.

2. Applicable and Reference Documents

NUMBER	AUTHOR AND TITLE
REF 1	Berkefeld et al., "The GREGOR Adaptive Optics System", AN (2012)

3. Requirements

The prototype shall be integrated into the existing adaptive optics system at the GREGOR solar telescope (GAOS), which involves a single deformable mirror at a transferred pupil in the optical path of the telescope which is common for all instruments. The optical elements of GAOS are mounted on a separate optical bench which has been specified to accommodate also an MCAO system and which therefore is very large, approximately 4.5 by 1.2m (**Figure 1**). The prototype shall also restore the original position and plate scale of the F4 focus which follows GAOS. A description of GAOS is found in **Ref 1.**
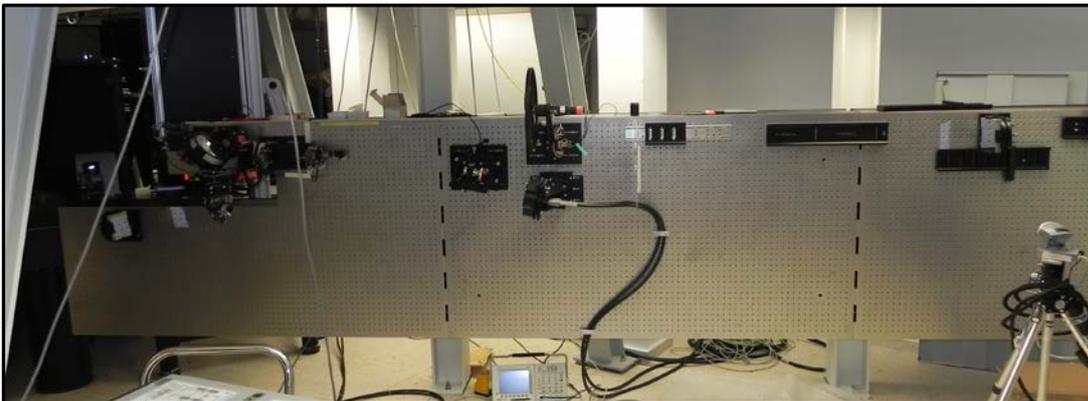
Figure 1. Adaptive Optics bench of GREGOR.

In order to represent the EST MCAO design, the prototype shall provide four deformable mirrors at conjugates along the line-of-sight of the telescope which cover the expected altitude distribution of turbulence in the earth's atmosphere that must be compensated. The compensated field shall be 1 minute of arc.

4. Interfaces

4.1 Optical interface to GAOS

The prototype interfaces to the existing adaptive optics system which follows the tertiary telescope focus F3 and consists of a collimating mirror which reproduces a transferred pupil, an agile flat mirror (TT) to compensate wavefront tip-tilt, a deformable mirror (DM1), a camera mirror which reproduces the F3 focal plane at F4, and a motor-controlled flat mirror which redirects the beam towards the desired focus station. A beam splitter which follows DM1 diverts light to the wavefront sensor.

Collimator and camera mirrors are obliquely illuminated, which gives rise to static astigmatism if they were rotationally symmetric (spherical) mirrors. At the time of this writing, both mirrors are toroidal mirrors. They will be replaced by off-axis paraboloid mirrors in order to improve the overall optical performance. The characteristics of the collimator and camera mirrors are shown in Table 1.

FUNCTION	FORM	CURVATURE RADIUS	DIMENSION
COLLIMATOR	toric	3850 mm x 3821.3 mm	120 mm x 120 mm
	paraboloid	3960 mm, decenter 277 mm	120 mm dia.
CAMERA	toric	3612 mm x 3600 mm	120 mm x 120 mm
	paraboloid	3960 mm, decenter 277 mm	120 mm dia.

Table 1 GAOS optics characteristics.

The prototype MCAO system will be integrated into the GAOS optical train after the collimator mirror and before the motorized flat mirror in front of F4.

The prototype MCAO system will provide for optical feeds for two wavefront sensors, one immediately following the existing DM1, the other one following all deformable mirrors.

4.2 Mechanical Interface

The prototype will be installed on the GAOS optical bench in the area below the TT / DM1 complex and the current camera / redirection mirrors. Off-the-shelf standard mounting elements will be used as all optical elements will be catalogue items.

5. Design Description

5.1 General Considerations

The function of the MCAO system requires an accessible section in the optical path where conjugates of the desired atmospheric layers have dimensions which are compatible with high altitude deformable mirrors. For reasons of cost and reduced complexity, all four deformable mirrors (DM2, DM3, DM4, DM5) shall be identical. The base line is an ALPAO DM192 which has an optical area of 22 mm.

The optical volume of interest is close to a focal plane. The volume of layer conjugates close to F3 covers the axial back focal range between 140 mm (25 km) to 1800 mm (2 km) towards the collimator mirror. The prototype will use the volume which follows the focal plane that is produced by the GAOS camera mirror.
An optical element close to that focal plane (M16) with a focal length of 1000 mm generates a volume where the angles of the paraxial chief and marginal rays have opposite signs, while their heights are similar and have the same sign. This creates a bundle of light which maintains a nearly constant diameter for the required field of view. The proper choice of the focal length of that element determines the diameter which is adapted to the diameters of DM2 – DM5.

A second optical element (M17) with a focal length of 850 mm after the array of deformable mirrors reproduces the original F4 at its original position, which now becomes F5.

Figure 2 shows the heights of paraxial rays from F3 to F5 along the unfolded optical axis.

Figure 2. Paraxial ray diagrams for the MCAO setup for toric collimator/camera mirrors (top) and for paraboloids (bottom). The red box marks the volume for DM2 – DM5.

Both optical elements can be mirrors with optical power, or lenses. Mirrors require oblique illumination in order to avoid vignetting. This means that they must be aspheric in order to limit static optical aberrations, which makes them very expensive and difficult to obtain. Lenses are catalogue items and are used on-axis so they do not suffer from obliquity, but they introduce chromatic focus shifts. For the purposes of prototyping, these deficits are acceptable.

Three configurations were studied in detail using the OSLO optical design software. Two configurations use the existing toric optics for M12 and M15, the third implements the paraboloids. One toric configuration has toric mirrors for M16 and M17, the other one two catalogue lenses. The parabola configuration has toric M16 and M17; the difference for lenses would be marginal.

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5.2 Toric M12 and M15, all mirrors
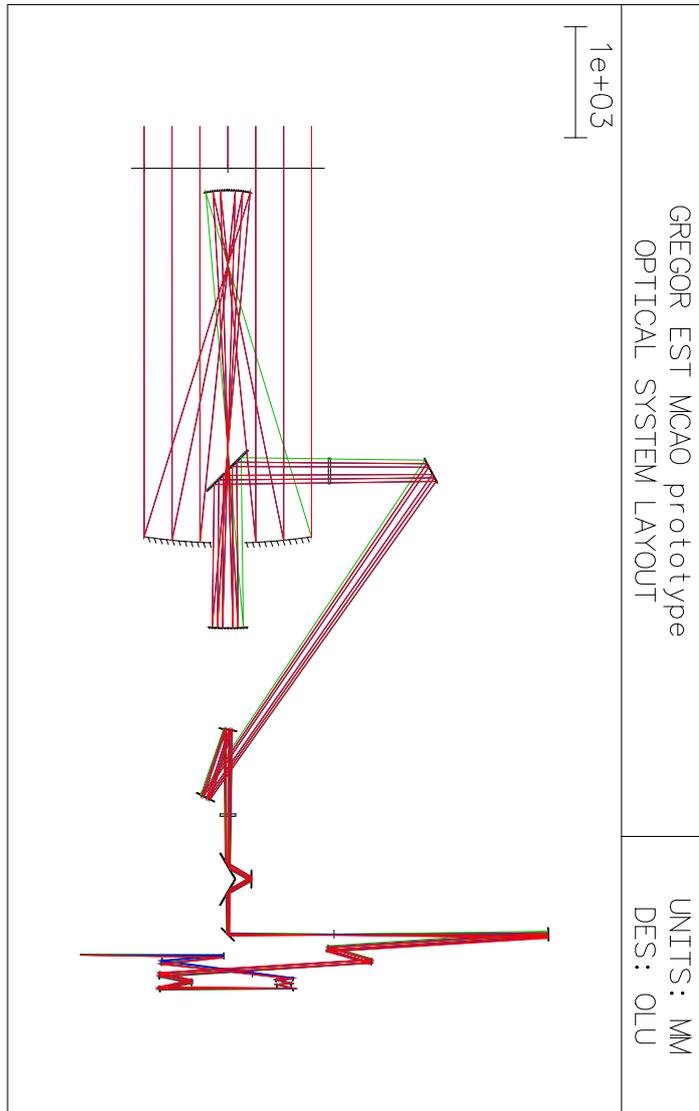
Figure 3. GREGOR optical design with all toric mirrors in the AO/MCAO train.

Figure 3 shows the overall optical design f the GREGOR telescope with the adaptive optics system at the bottom. Figure 4 shows the AO optical train alone.

The inclusion of the four specified high-altitude deformable mirrors and the requirements for F5 positioning makes it necessary to fold the beam with two additional flat reflective surfaces which follow M15. One of the surfaces here can be a beamsplitter for a wavefront sensor for the pupil conjugate DM1. The four high-altitude deformable mirrors are arranged in a trombone which, if shifted en-bloc, permits adjusting the distances of the compensated layers.

Figure 5, Figure 6 and Figure 7 show wavefront error maps, spot diagrams across the field and through the focus and point spread functions. They reflect the entire telescope optical train and demonstrate the high quality of the optical design. Table A in the appendix presents the characteristics of the optical design including the telescope.
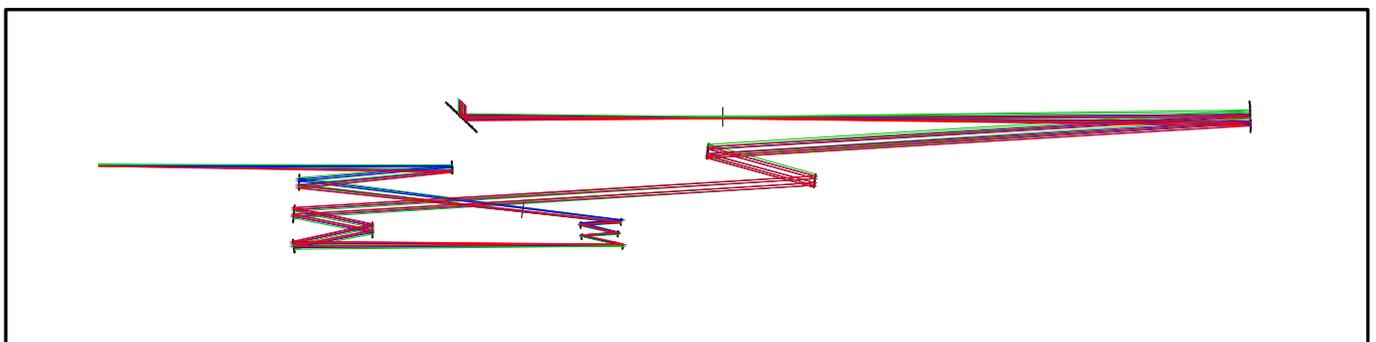
Figure 4. Layout of the EST MCAO prototype with toric M12 / M15, and toric M16 / M17.
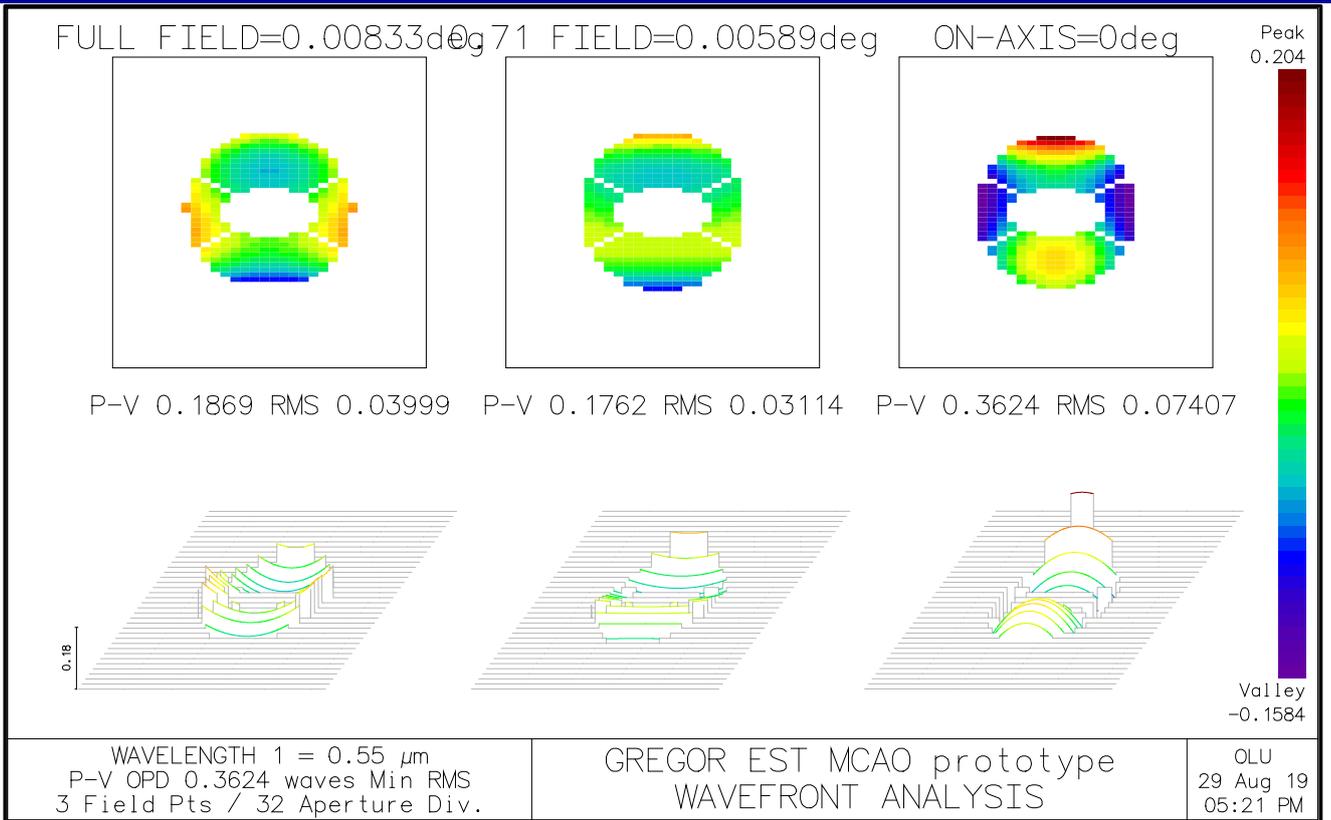
Figure 5. Wave front error map

Figure 6. Spot Diagram.
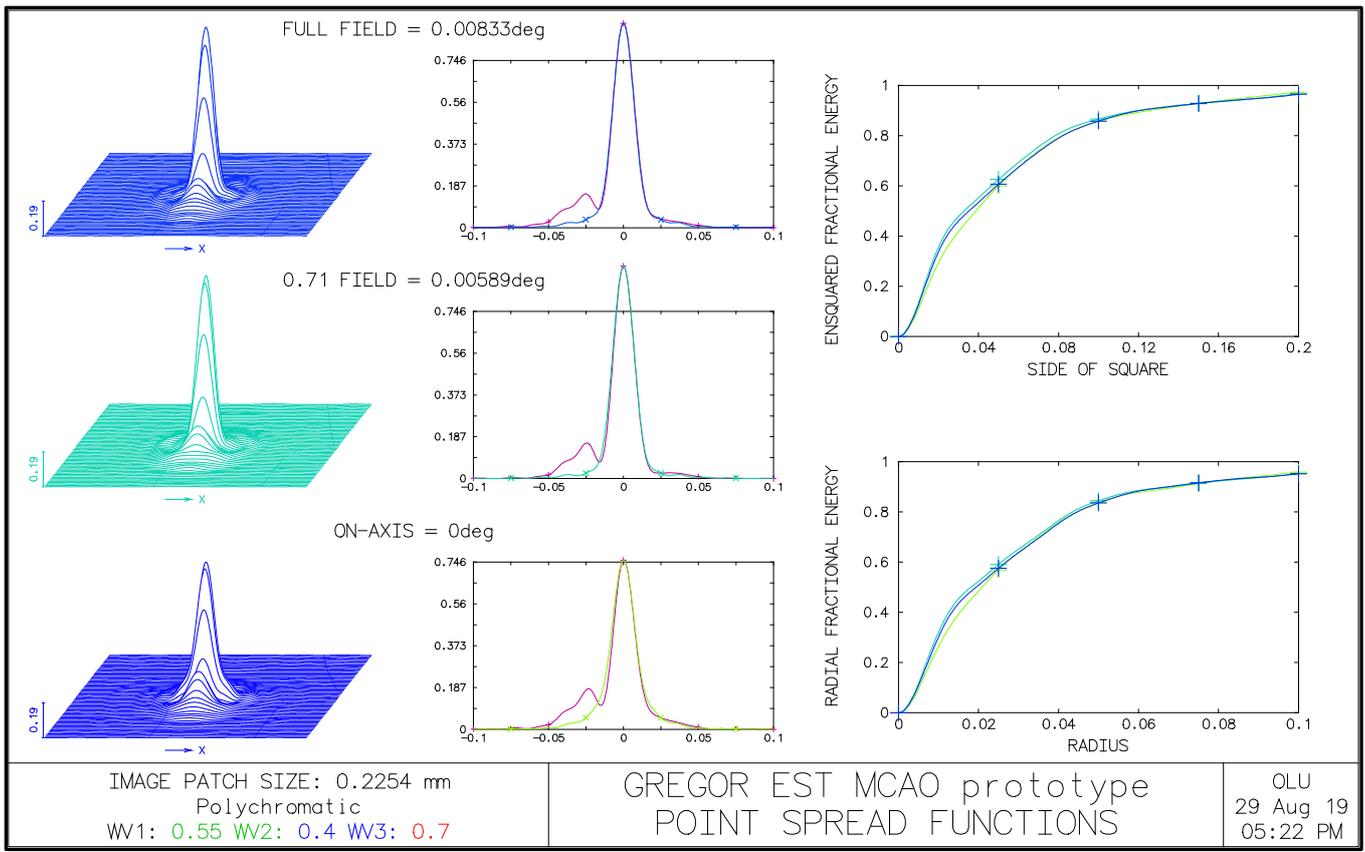
Figure 7. Point spread function and encircled energy

5.3 Toric M12 and M15, lenses for M16 and M17

Figure 8 shows the optical layout for the design with lenses. Here, a flat mirror is introduced directly after DM1. This surface can be configured as a beamsplitter for a CAO wavefront sensor. The folded beam illuminates M15, which is followed by a f=1000mm catalogue lens which stands in for M16. The stack of high-altitude DMs can also be adapted to different conjugate altitudes by a bulk shift. A second flat surface, which can be a beamsplitter for a wide-field wavefront sensor, directs the beam through a catalogue f=850mm lens towards F5.
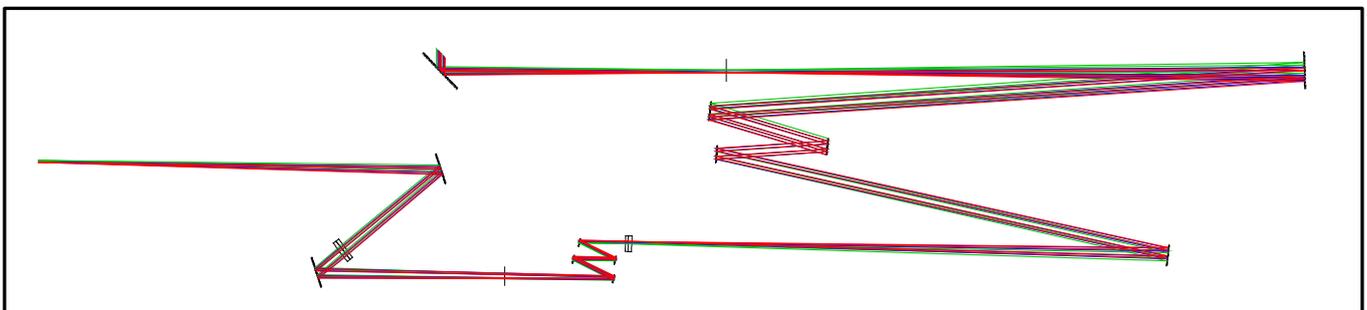
Figure 8. Toric mirrors and lenses optical layout.

Figures 9 to 11 show wavefront, spot diagram and point spread function analyses. The characteristics of the optical design are shown in the Appendix, Table B.

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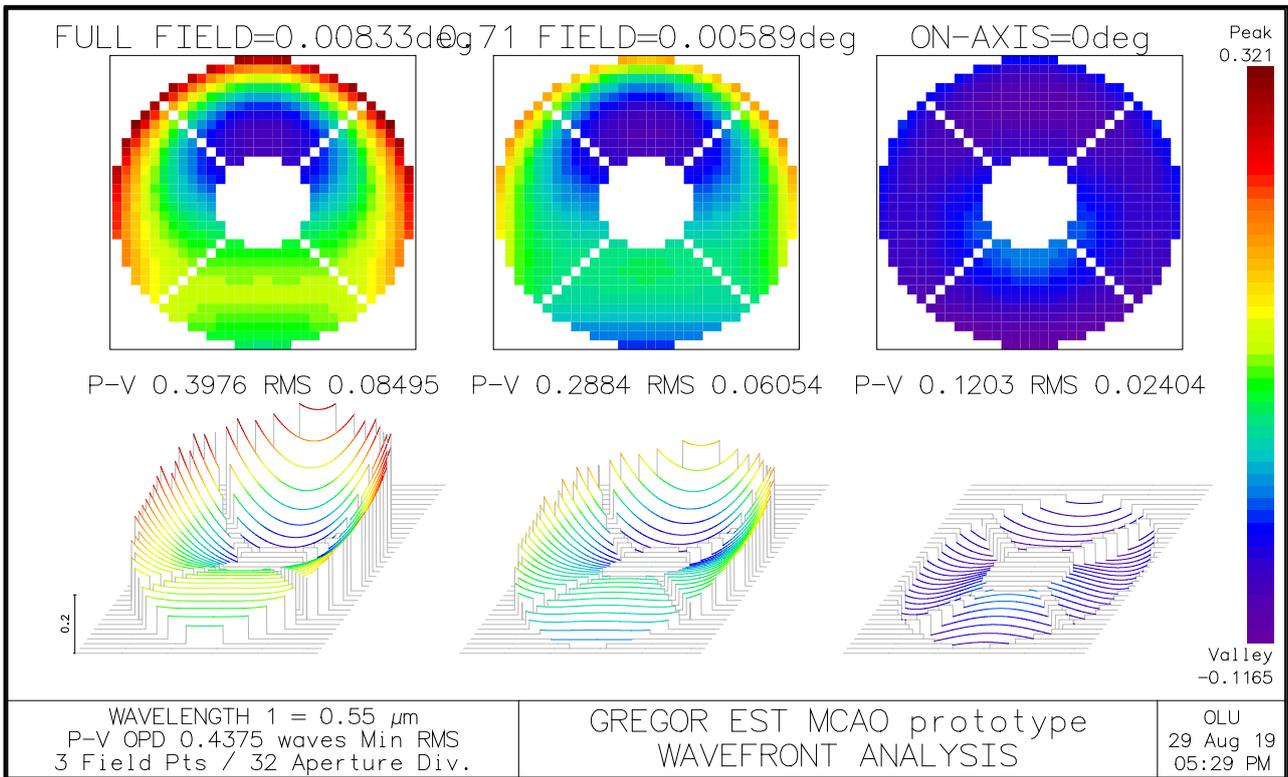
Figure 9. Wave front error maps for toric mirrors and lenses optical layout.

Figure 10. Spot diagrams for toric mirrors and lenses optical layout
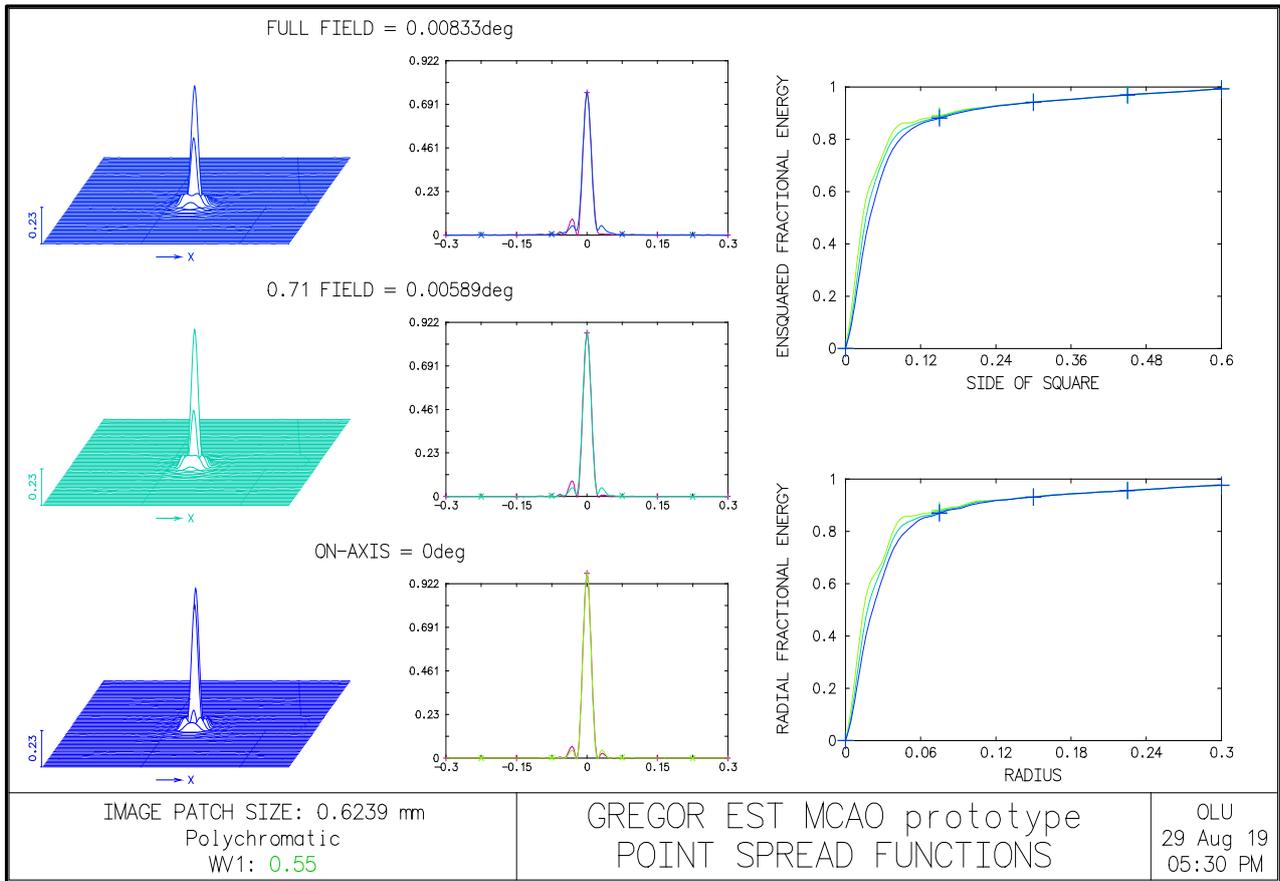
Figure 11. Point spread functions for toric mirrors and lenses optical layout

5.4 Parabolic M12 and M15, toric M16 and M17

Figure 12 shows the optical layout with parabolas for the collimator and camera mirrors. This configuration is very similar to the configuration with toric mirrors instead of the parabolae and also contains two additional flat reflective surfaces, one of which could be a beamsplitter for a DM1 wave front sensor.

Table C in the appendix presents the optical design characteristics for this configuration.

Figure 12. Parabolic and toric mirrors optical layout.

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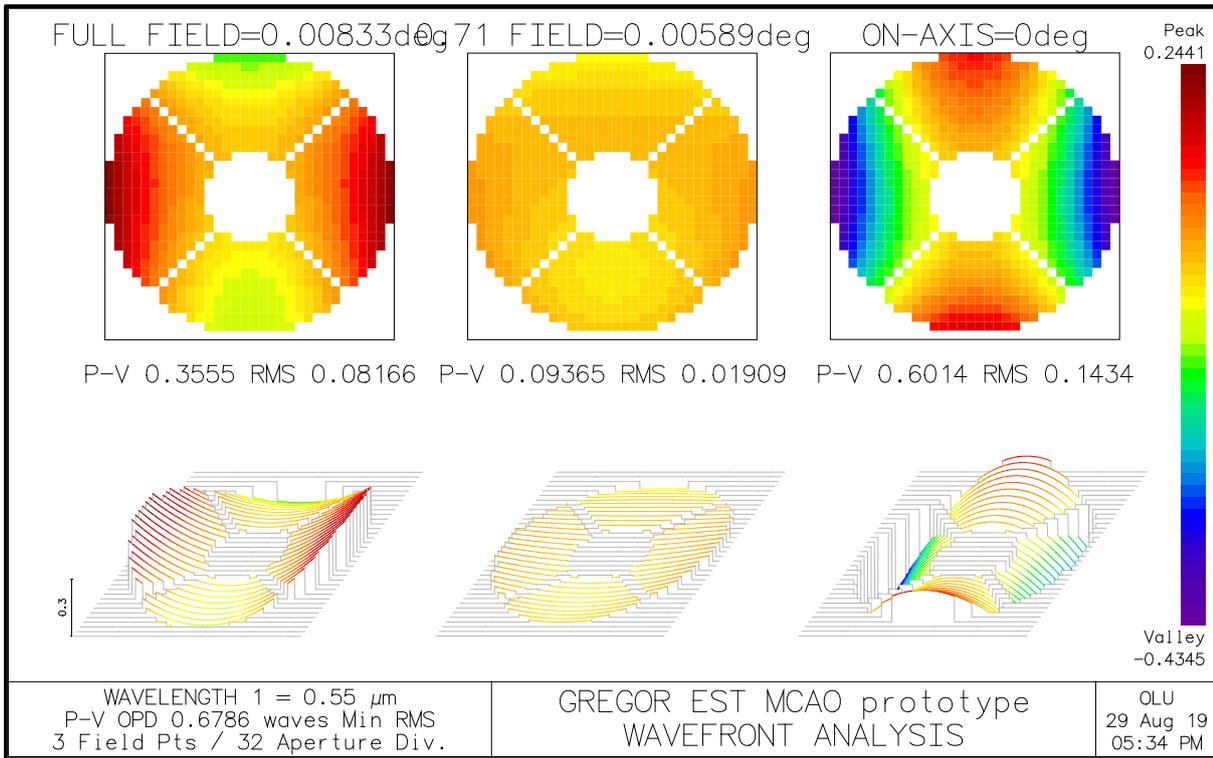
Figure 13. Wave front error maps for arabolic and toric mirrors optical layout.
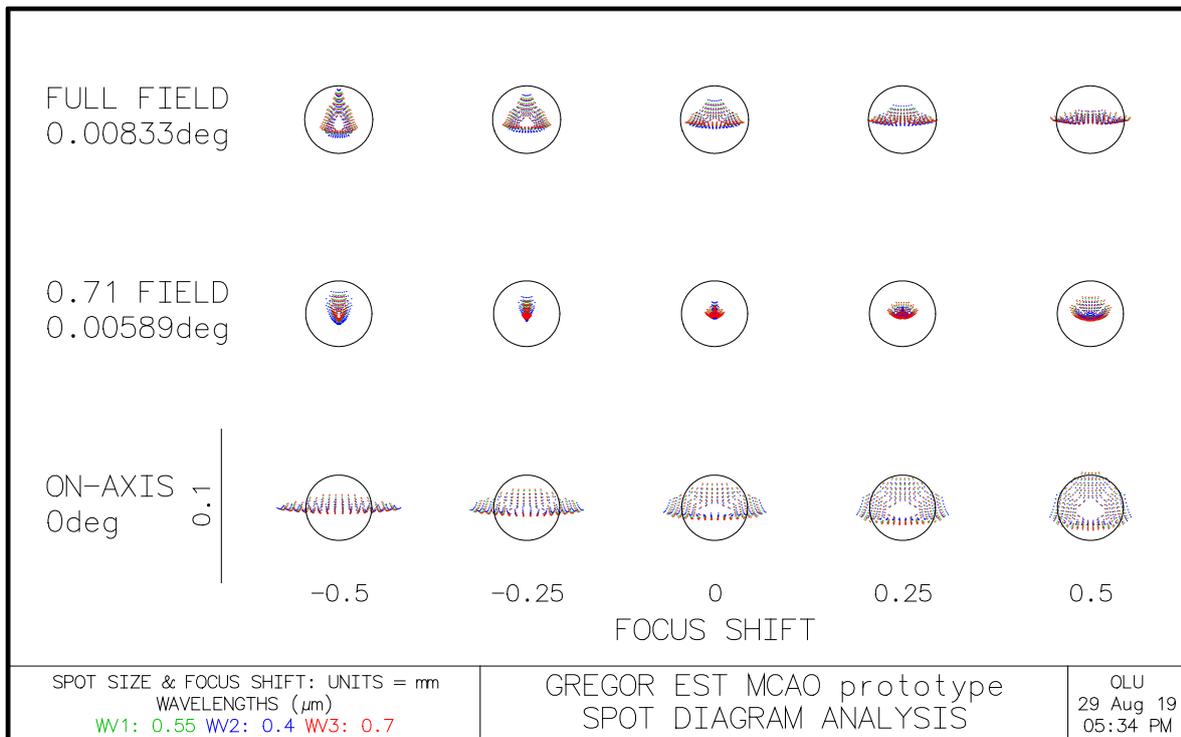
Figure 14. Spot diagrams for parabolic and toric mirrors optical layout.

.
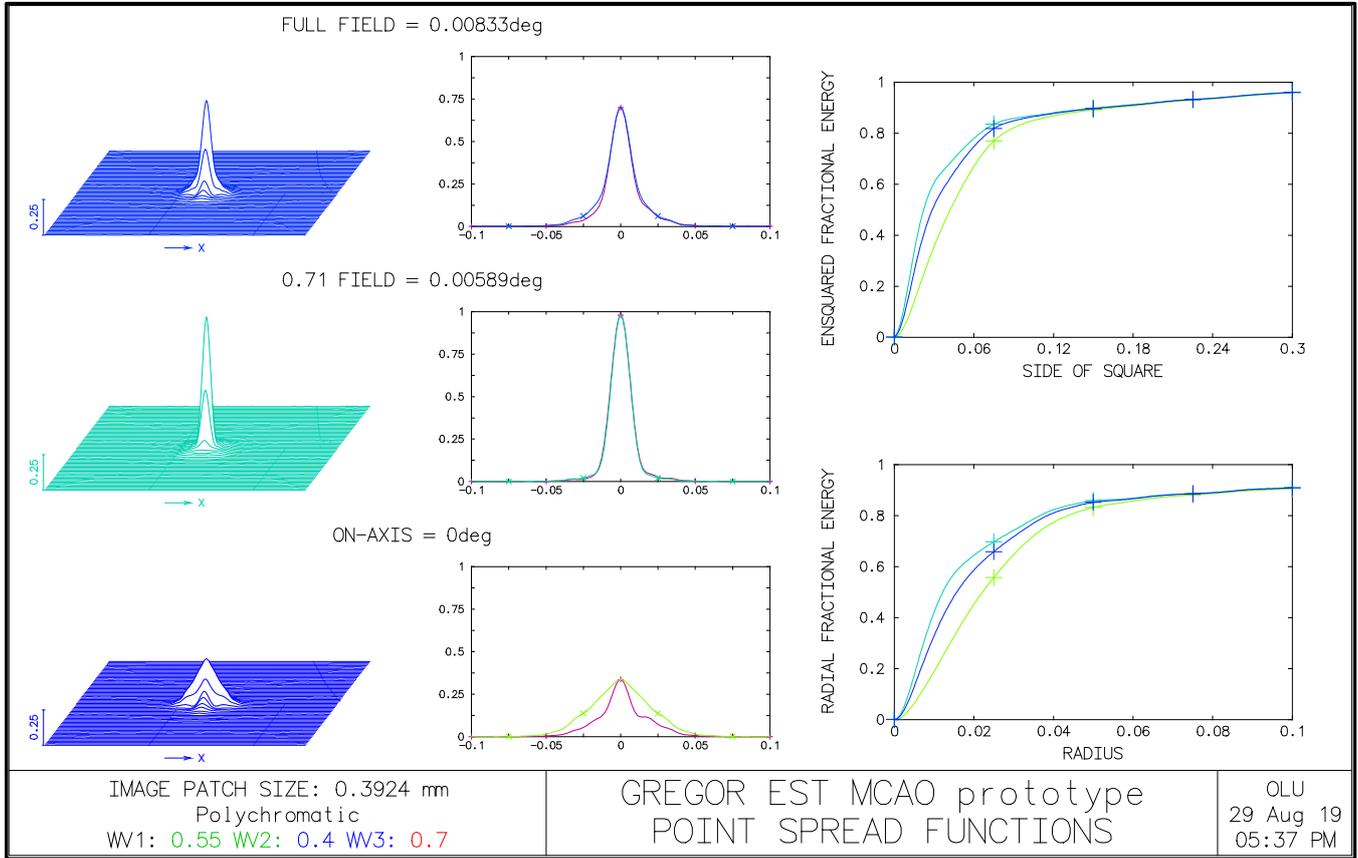
Figure 15. Point spread functions for parabolic and toric mirrors optical layout.

6. Appendix

6.1 Table A

*LENS DATA
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GREGOR EST MCAO prototype
```

SRF	RADIUS	THICKNESS	APERTURE RADIUS		GLASS	SPE	NOTE
OBJ	--	1.0000e+20	1.4544e+16		AIR		
1	--	1.0000e+07	3.6589e+03	S	AIR		
2	--	5.0000e+06	2.2044e+03	S	AIR		
3	--	3.0000e+06	1.4772e+03	S	AIR		
4	--	2.0000e+06	1.0409e+03	S	AIR		
AST	--	3.3780e+03	750.000000	ASKX	AIR		M2 Spider
6	-5.0150e+03	-2.5075e+03	750.491308	SKX	REFL_HATCH	*	M1
7	--	-668.700000	38.500000		AIR		F1 Feldblende
8	1.0388e+03	620.934700	215.000000	K	REFL_HATCH	*	M2 Fangspiegel
9	--	1.7053e+03	146.890000		AIR		Pupille
10	--	1.6146e+03	64.790000		AIR		F2
11	-2.7970e+03	-1.4146e+03	180.000000	K	REFL_HATCH	*	M3
12	--	900.000000	120.973815	SX	REFL_HATCH	*	M4
13	--	20.000000	115.000000	K	BK7	C	Fenster
14	--	87.251320	108.000000		AIR		
15	--	807.748700	106.870000		AIR		Pupille
16	--	-3.5642e+03	125.000000	K	REFL_HATCH	*	M5
17	--	637.000000	90.000000	K	REFL_HATCH	*	M6
18	--	-758.000000	80.000000	K	REFL_HATCH	*	M7
19	--	-20.000000	70.000000	K	BK7	C	Fenster
20	--	-447.000000	45.030000		AIR		
21	--	240.000000	135.000000	K	REFL_HATCH	*	M8 (Rotator 1)
22	--	-240.000000	80.000000	K	REFL_HATCH	*	M9 (Rotator 2)
23	--	377.000000	135.000000	K	REFL_HATCH	*	M10 (Rotator3)
24	--	-950.000000	80.000000	K	REFL_HATCH	*	M11
25	--	-1.9200e+03	20.000000	X	AIR		F3
26	3.8498e+03	1.9780e+03	60.000000	K	REFL_HATCH	*	M12
27	--	-404.550471	S 30.000000	K	REFL_HATCH	*	M13 (Tip-Tilt)

28	--	1.9000e+03	25.589017 SK	REFL_HATCH	*	M14 (DM)
29	-3.6120e+03	-292.000000	33.751944 SK	REFL_HATCH	*	M15
30	--	292.000000 P	29.549332 S	REFL_HATCH	*	
31	--	-1.1964e+03 P	25.346721 S	REFL_HATCH	*	
32	2.0000e+03	28.987385 S	8.127454 SK	REFL_HATCH	*	M16
33	--	123.130000	7.474659 SK	AIR		F4 int
34	--	-130.370000	8.295611 SK	REFL_HATCH	*	DM5 (20 km)
35	--	138.080000	9.164835 SK	REFL_HATCH	*	DM4 (8 km)
36	--	-146.500000	10.085465 S	REFL_HATCH	*	DM3 (4km)
37	--	361.120000	11.062234 S	REFL_HATCH	*	DM2 (2 km)
38	--	820.000000	13.469952 SKX	AIR		Pupil
39	-1.8000e+03	-558.570000	31.241657 S	REFL_HATCH	*	Reimager
40	--	1.2851e+03 V	24.431017 S	REFL_HATCH	*	
IMS	--	--	20.950000			F4

*SURFACE NOTES

```
 1   20 km above telescope
 2   10 km above telescope
 3   5 km above telescope
 4   2 km above telescope
 5   M2 Spider
 6   M1
 7   F1 Feldblende
 8   M2 Fangspiegel
 9   Pupille
10   F2
11   M3
12   M4
13   Fenster
15   Pupille
16   M5
17   M6
18   M7
19   Fenster
21   M8 (Rotator 1)
22   M9 (Rotator 2)
23   M10 (Rotator3)
24   M11
25   F3
26   M12
27   M13 (Tip-Tilt)
28   M14 (DM)
29   M15
32   M16
33   F4 int
34   DM5 (20 km)
35   DM4 (8 km)
36   DM3 (4km)
37   DM2 (2 km)
38   Pupil
39   Reimager
41   F4
```

```
*CONIC AND POLYNOMIAL ASPHERIC DATA
 SRF      CC        AD           AE           AF           AG
  6    -1.0000e+00  --           --           --           --
  8    -3.0630e-01  --           --           --           --
 11    -5.3767e-01  --           --           --           --


*TILT/DECENTER DATA
 12      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   45.000000    TLB     --      TLC     --
 16      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   27.787200    TLB     --      TLC     --
 17      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    8.063500    TLB     --      TLC     --
 18      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    9.149400    TLB     --      TLC     --
 21      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA  -60.000000    TLB     --      TLC     --
 22      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   30.000000    TLB     --      TLC     --
 23      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA  -60.000000    TLB     --      TLC     --
 24      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA  -45.000000    TLB     --      TLC     --
 26      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    1.900000    TLB     --      TLC     --
 27      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA  -10.000000    TLB     --      TLC     --
 28      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   10.000000    TLB     --      TLC     --
 29      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -8.000000    TLB     --      TLC     --
 30      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   12.200000    TLB     --      TLC     --
 31      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -6.100000    TLB     --      TLC     --
 32      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -7.050000    TLB     --      TLC     --
 34      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    9.390000    TLB     --      TLC     --
 35      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -9.390000    TLB     --      TLC     --
 36      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    9.390000    TLB     --      TLC     --
 37      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -6.000000    TLB     --      TLC     --
 39      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA    6.500000    TLB     --      TLC     --
 40      DT    1    DCX      --         DCY     --      DCZ     --
         BEN        TLA   -3.125000    TLB     --      TLC     --


*SURFACE TAG DATA
 26      CVX      0.000262
 29      CVX     -0.000278
 32      CVX      0.018511
 39      CVX     -0.000563
```

6.2 Table B

*LENS DATA
```
GREGOR EST MCAO prototype
```

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	1.0000e+20	1.4544e+16	AIR		
AST	--	3.3780e+03	750.000000 ASKX	AIR		M2 Spider
2	-5.0150e+03	-2.5075e+03	750.491308 SKX	REFL_HATCH	*	M1
3	--	-668.700000	38.500000	AIR		F1 Feldblende
4	1.0388e+03	620.934700	215.000000 K	REFL_HATCH	*	M2 Fangspiegel
5	--	1.7053e+03	146.890000	AIR		Pupille
6	--	1.6146e+03	64.790000	AIR		F2
7	-2.7970e+03	-1.4146e+03	180.000000 K	REFL_HATCH	*	M3
8	--	900.000000	120.973815 SX	REFL_HATCH	*	M4
9	--	20.000000	115.000000 K	BK7 C		Fenster
10	--	87.251320	108.000000	AIR		
11	--	807.748700	106.870000	AIR		Pupille
12	--	-3.5642e+03	125.000000 K	REFL_HATCH	*	M5
13	--	637.000000	90.000000 K	REFL_HATCH	*	M6
14	--	-758.000000	80.000000 K	REFL_HATCH	*	M7
15	--	-20.000000	70.000000 K	BK7 C		Fenster
16	--	-447.000000	45.030000	AIR		
17	--	240.000000	135.000000 K	REFL_HATCH	*	M8 (Rotator 1)
18	--	-240.000000	80.000000 K	REFL_HATCH	*	M9 (Rotator 2)
19	--	377.000000	135.000000 K	REFL_HATCH	*	M10 (Rotator3)
20	--	-950.000000	80.000000 K	REFL_HATCH	*	M11
21	--	-1.9200e+03	20.000000 X	AIR		F3
22	3.8498e+03	1.9780e+03	60.000000 K	REFL_HATCH	*	M12
23	--	-404.550471 S	30.000000 K	REFL_HATCH	*	M13 (Tip-Tilt)
24	--	367.480000	25.589017 SK	REFL_HATCH	*	M14 (DM)
25	--	-1.5325e+03 P	27.167813 S	REFL_HATCH	*	Folding_1
26	3.6120e+03	1.7804e+03	33.751944 SK	REFL_HATCH	*	M15
27	--	--	8.127454 S	AIR		
28	--	--	8.127454 S	AIR		
29	528.520000	12.500000	25.000000	S-BSL7 C		322313000

```
30      -456.430000      9.000000     25.000000         S-TIM22 C
31      -2.0833e+03     29.200000     25.000000              AIR

32          --         123.130000     10.000000              AIR     F4 int

33          --        -130.370000     12.000000 K   REFL_HATCH   * DM5 (20 km)

34          --         138.080000     12.000000 K   REFL_HATCH   * DM4 (8 km)

35          --        -146.500000     12.000000     REFL_HATCH   * DM3 (4km)

36          --         361.120000     12.000000     REFL_HATCH   * DM2 (2 km)

37          --         624.500000     13.560202 SKX      AIR        Pupil

38          --        -100.000000     50.000000     REFL_HATCH   * Folding_2

39      -497.210000     -13.080000    37.280000           N-BK7 C
40       345.820000      -0.100000    37.280000 P          AIR

41       344.200000     -10.160000    37.280000 P       N-SF2 C
42       1.2279e+03    -403.600000    37.280000 P          AIR

43          --          1.3351e+03 V  50.000000     REFL_HATCH   *

IMS         --          1.433717      20.950000                      F4
```

*SURFACE NOTES
```
 1    M2 Spider
 2    M1
 3    F1 Feldblende
 4    M2 Fangspiegel
 5    Pupille
 6    F2
 7    M3
 8    M4
 9    Fenster
11    Pupille
12    M5
13    M6
14    M7
15    Fenster
17    M8 (Rotator 1)
18    M9 (Rotator 2)
19    M10 (Rotator3)
20    M11
21    F3
22    M12
23    M13 (Tip-Tilt)
24    M14 (DM)
25    Folding_1
26    M15
29    322313000
32    F4 int
33    DM5 (20 km)
34    DM4 (8 km)
35    DM3 (4km)
36    DM2 (2 km)
37    Pupil
38    Folding_2
44    F4
```

*CONIC AND POLYNOMIAL ASPHERIC DATA
```
SRF      CC          AD          AE          AF          AG
 2    -1.0000e+00     --          --          --          --
```

```
 4    -3.0630e-01      --          --          --          --
 7    -5.3767e-01      --          --          --          --


*TILT/DECENTER DATA
 8    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  45.000000  TLB    --     TLC    --
12    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  27.787200  TLB    --     TLC    --
13    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA   8.063500  TLB    --     TLC    --
14    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA   9.149400  TLB    --     TLC    --
17    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -60.000000  TLB    --     TLC    --
18    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  30.000000  TLB    --     TLC    --
19    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -60.000000  TLB    --     TLC    --
20    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -45.000000  TLB    --     TLC    --
22    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA   1.900000  TLB    --     TLC    --
23    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -10.000000  TLB    --     TLC    --
24    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  10.000000  TLB    --     TLC    --
25    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  -8.000000  TLB    --     TLC    --
26    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA   5.500000  TLB    --     TLC    --
33    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -12.000000  TLB    --     TLC    --
34    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  12.000000  TLB    --     TLC    --
35    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -12.000000  TLB    --     TLC    --
36    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  12.000000  TLB    --     TLC    --
38    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA  20.000000  TLB    --     TLC    --
43    DT    1    DCX      --     DCY    --     DCZ    --
      BEN        TLA -20.000000  TLB    --     TLC    --


*SURFACE TAG DATA
22    CVX    0.000262
26    CVX    0.000278
```

6.3 Table C

*LENS DATA

GREGOR EST MCAO prototype

SRF	RADIUS	THICKNESS	APERTURE RADIUS		GLASS	SPE	NOTE
OBJ	--	1.0000e+20	1.4544e+16		AIR		
1	--	1.0000e+07	3.6589e+03	S	AIR		
2	--	5.0000e+06	2.2044e+03	S	AIR		
3	--	3.0000e+06	1.4772e+03	S	AIR		
4	--	2.0000e+06	1.0409e+03	S	AIR		
AST	--	3.3780e+03	750.000000	ASKX	AIR		M2 Spider
6	-5.0150e+03	-2.5075e+03	750.491308	SKX	REFL_HATCH	*	M1
7	--	-668.700000	38.500000		AIR		F1 Feldblende
8	1.0388e+03	620.934700	215.000000	K	REFL_HATCH	*	M2 Fangspiegel
9	--	1.7053e+03	146.890000		AIR		Pupille
10	--	1.6146e+03	64.790000		AIR		F2
11	-2.7970e+03	-1.4146e+03	180.000000	K	REFL_HATCH	*	M3
12	--	900.000000	120.973815	SX	REFL_HATCH	*	M4
13	--	20.000000	115.000000	K	BK7	C	Fenster
14	--	87.251320	108.000000		AIR		
15	--	807.748700	106.870000		AIR		Pupille
16	--	-3.5642e+03	125.000000	K	REFL_HATCH	*	M5
17	--	637.000000	90.000000	K	REFL_HATCH	*	M6
18	--	-758.000000	80.000000	K	REFL_HATCH	*	M7
19	--	-20.000000	70.000000	K	BK7	C	Fenster
20	--	-447.000000	45.030000		AIR		
21	--	240.000000	135.000000	K	REFL_HATCH	*	M8 (Rotator 1)
22	--	-240.000000	80.000000	K	REFL_HATCH	*	M9 (Rotator 2)
23	--	377.000000	135.000000	K	REFL_HATCH	*	M10 (Rotator3)
24	--	-950.000000	80.000000	K	REFL_HATCH	*	M11
25	--	-1.9200e+03	20.000000	X	AIR		F3
26	3.9600e+03	1.9780e+03	360.000000	KX	REFL_HATCH	*	M12
27	--	-489.502796 S	30.000000	K	REFL_HATCH	*	M13 (Tip-Tilt)
28	--	1.9800e+03	26.501420	SK	REFL_HATCH	*	M14 (DM)
29	-3.9600e+03 P	-500.000000	400.000000	X	REFL_HATCH	*	M15

```
30        --        200.000000    35.000000      REFL_HATCH    *

31        --       -1.0804e+03    35.000000      REFL_HATCH    *

32    2.0000e+03    205.761300 S  25.000000 K    REFL_HATCH    * M16

33        --        123.130000    20.000000          AIR        F4 int

34        --       -130.370000    12.000000 K    REFL_HATCH    * DM5 (20 km)

35        --        138.080000    12.000000 K    REFL_HATCH    * DM4 (8 km)

36        --       -146.500000    12.000000      REFL_HATCH    * DM3 (4km)

37        --        361.120000    12.000000      REFL_HATCH    * DM2 (2 km)

38        --        820.000000    20.000000          AIR        Pupil

39   -1.8000e+03   -558.570000    40.000000      REFL_HATCH    * Reimager

40        --        1.3157e+03 V  50.000000      REFL_HATCH    *

IMS       --           --         20.950000                     F4
```

*SURFACE NOTES

```
  1    20 km above telescope
  2    10 km above telescope
  3    5 km above telescope
  4    2 km above telescope
  5    M2 Spider
  6    M1
  7    F1 Feldblende
  8    M2 Fangspiegel
  9    Pupille
 10    F2
 11    M3
 12    M4
 13    Fenster
 15    Pupille
 16    M5
 17    M6
 18    M7
 19    Fenster
 21    M8 (Rotator 1)
 22    M9 (Rotator 2)
 23    M10 (Rotator3)
 24    M11
 25    F3
 26    M12
 27    M13 (Tip-Tilt)
 28    M14 (DM)
 29    M15
 32    M16
 33    F4 int
 34    DM5 (20 km)
 35    DM4 (8 km)
 36    DM3 (4km)
 37    DM2 (2 km)
 38    Pupil
 39    Reimager
 41    F4
```

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
6	-1.0000e+00	--	--	--	--

```
 8    -3.0630e-01      --          --          --          --
11    -5.3767e-01      --          --          --          --
26    -1.0000e+00      --          --          --          --
29    -1.0000e+00      --          --          --          --
```

*TILT/DECENTER DATA

```
12    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  45.000000   TLB      --        TLC    --
16    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  27.787200   TLB      --        TLC    --
17    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA   8.063500   TLB      --        TLC    --
18    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA   9.149400   TLB      --        TLC    --
21    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA -60.000000   TLB      --        TLC    --
22    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  30.000000   TLB      --        TLC    --
23    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA -60.000000   TLB      --        TLC    --
24    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA -45.000000   TLB      --        TLC    --
26    DT   1     DCX      --      DCY  277.000000    DCZ    --
      BEN        TLA      --      TLB      --        TLC    --
27    DT   1     DCX      --      DCY      --        DCZ    --
                 TLA      --      TLB      --        TLC    --
28    DT   1     DCX      --      DCY   67.810000    DCZ    --
                 TLA      --      TLB      --        TLC    --
29    DT   1     DCX      --      DCY   -2.300000    DCZ    --
                 TLA      --      TLB      --        TLC    --
30    DT   1     DCX      --      DCY  277.000000    DCZ    --
      BEN        TLA   8.000000   TLB      --        TLC    --
31    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  -8.000000   TLB      --        TLC    --
32    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  -7.050000   TLB      --        TLC    --
34    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA   9.390000   TLB      --        TLC    --
35    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  -9.390000   TLB      --        TLC    --
36    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA   9.390000   TLB      --        TLC    --
37    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  -8.000000   TLB      --        TLC    --
39    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA   8.500000   TLB      --        TLC    --
40    DT   1     DCX      --      DCY      --        DCZ    --
      BEN        TLA  -3.125000   TLB      --        TLC    --
```

*SURFACE TAG DATA

```
39    CVX   -0.000568
```