A NEW OPTICAL SOLUTION FOR VST INCLUDING AN ADC CORRECTOR

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1. Introduction

In this document an upgrade of the optical design for the VST is presented. Respect to the previous one, this solution takes into account a possible ADC (Atmospherical Dispersion Compensator) design for atmospherical correction from U to I bands (330 ÷ 900 nm). This ADC would permit to observe the whole spectral range of targets at zenith distances as large as 60°, reducing losses due to atmospheric dispersion.

In order to achieve the desired image quality for the system, the optical parameters of the mirrors and corrector were reoptimized together with those for the ADC. The rays of curvature of the lenses were normalized to DIN tables 58166.

Taking into account atmospheric refraction and inserting an ADC in the optical design, some aberrations are introduced, so the optical quality is reduced. In U and I bands which are the extreme ones, percentual energy meets scientific requirements in 17 μm and 20 μm, instead than in 15 μm.

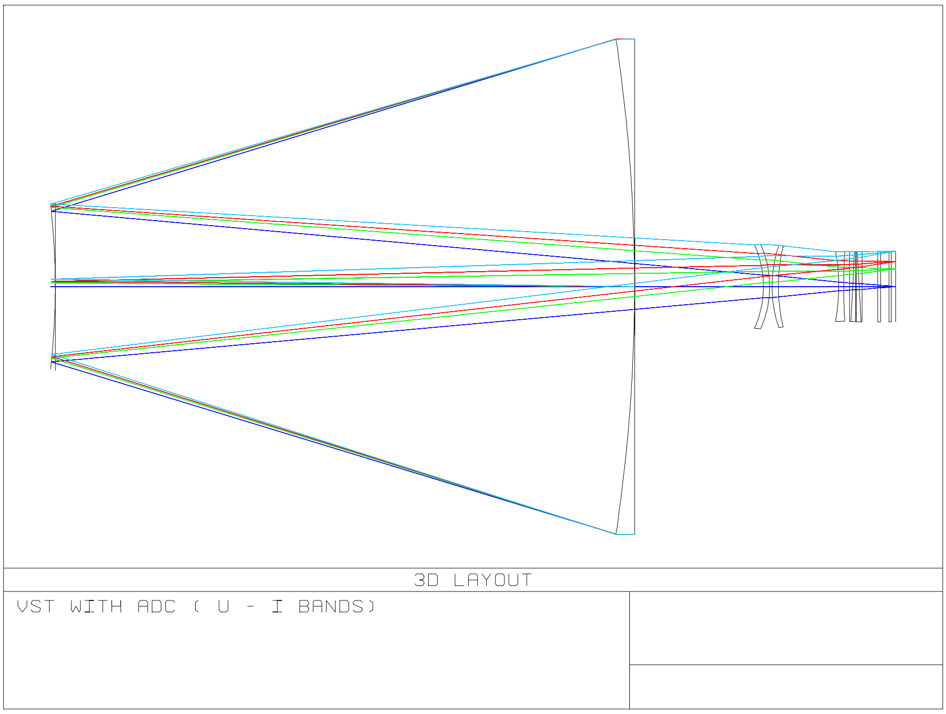
The ADC is made with two doublet prisms, with flat entrance and exit surfaces and is inserted between the last lens of the corrector and the filter.

The two doublets are used counter rotating for stars at different zenith distance. To simulate the effect of atmospheric refraction, a special surface which models the atmosphere at different zenith angles was utilized in ray tracing.

This solution was optimized for wavelenghts at which there were the highest combination of filters (Wide Field Camera filters) and CCD efficiencies. These wavelenghts were weighted proportionally to the efficiencies, in order to increase also the optical quality in U and I bands.

2. Optical layout

In Figure 2-1 the new optical layout for the VST is reported. It is modified respect to the last solution presented at Zeiss in February. An ADC corrector was inserted between the last lens of the camera and the filter, in order to correct the atmospherical dispersion on the image plane. The parameters of the mirrors and lenses were reoptimized together with those of the ADC, to satisfy the constraints on the image quality.



The new main nominal optical characteristics are reported in Table 2-1. The design was optimized in the spectral range between 330 nm and 900nm, taking into account the different efficiencies for filters and CCD in U ÷I bands. Respect to the previous design, the distance between M1 and M2 is reduced of about 35 mm, M2 diameter is incremented of 3%, the distance of the camera from M1 vertex is incremented of 62 mm. The first lens thickness is reduced of about 9 mm, and the filter has a thickness which varies for each band in order to obtain the best focus for the spot. The full camera thickness is reduced of 20 mm, so adding the ADC which has a thickness of 60 mm, there is a total increment for thickness of 40 mm.

VST MAIN NOMINAL OPTICAL DATA	
Main optical data for the full system	
Optical configuration	Modified Ritchey Chretien
Free Entrance Diameter	2500 mm
F/#	5.75
Angular field of view	1° x 1°
Linear field of view diameter	363.6 mm
Distance between M1 and M2	2922.5 mm
Image scale	0.21"/pixel
Focal plane CCD mosaic	16 k x 16 k
CCD pixel size	15 µm x 15 µm
Wavelenght range	330 ÷ 900 nm
Distance between M1 and camera	650 mm
Back focal distance	1317.5 mm
Overall lenght	4240 mm
Primary Mirror parameters	
Outer Diameter	2500 mm
Inner Diameter	550
Ray of curvature	-8360.6 mm
Conic constant K1	-1.13651
Focal distance	-4180.3mm
f/number	1.67
thickness	11 cm
Secondary Mirror parameters	
Diameter	833.5 mm
Ray of curvature	-3586.7 mm
Conic constant K2	-4.77021
Focal distance	1793.3 mm
f/number	2.15
thickness	13 cm

Table 2-1 VST main nominal optical data

3. Camera and ADC

The camera consists of only three spherical lenses, made of Silica as in the last design. The rays of curvature and thicknesses of the lenses were reoptimized together with the telescope parameters and those of an atmospheric dispersion compensator. Table 2-2 provides the optical data for camera, ADC, filter and dewar window. The rays of curvature of the lenses are normalized to DIN tables 58166.

An ADC for secondary focus, made of two doublet prism, with flat entrance and exit surfaces was designed. Each doublet is compound with two opposed prisms, made of UBK7 and LLF6, having the same mean refractive index and hence the same prism angles (3°). So the outer surfaces are parallel and normal to the optical axis. The ADC was designed to correct up to 60° zenith angle for all bands. and in U band it

The two doublet prisms are used counter rotating, with a variable relative orientation to tune for stars at different zenith distance. They provide the maximum dispersion, when the two doublets are aligned with their dispersion directions parallel and in opposition to that of the atmosphere, and the minimum where they are antiparallel (the doublet prisms are rotated of 90° in opposite sense).

Different thicknesses of the filters were chosen for best focussing in each band.

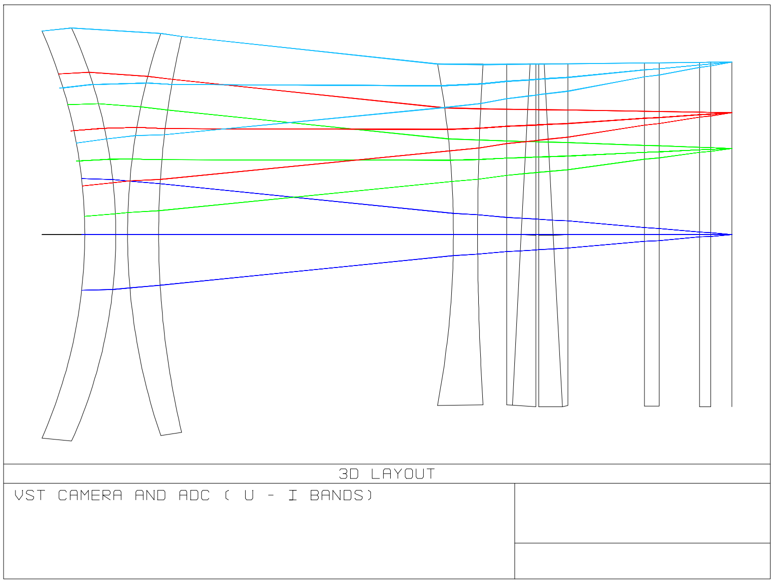


Figure 3 – 1 VST camera and ADC in the configuration of minimum dispersion

OPTICAL DATA FOR CAMERA, ADC, FILTER AND DEWAR WINDOW							
Element	Prism angle	R1	R2	Material	Diameter	Thickness	Air thickness
L1	0°	-523.3 mm	-523.3 mm	Silica	420.6 mm 426.5 mm	32 mm	12.2 mm
L2	0°	649.4 mm	891.2 mm	Silica	415.2 mm 408.9 mm	32 mm	304 mm
L3	0°	-957.7 mm	2738.4 m	Silica	353.1 mm 351.8 mm	25 mm	30 mm
ADC S1 (First prism)	0°	Infinity		UBK7	352.24 mm	15 mm	0 mm
ADC S2 (First prism)	3°	Infinity		LLF6	352.44 mm	15 mm	3 mm
ADC S3 (Second prism)	0°	Infinity		UBK7	352.7 mm	15 mm	0 mm
ADC S4 (Second prism)	-3°	Infinity		LLF6	352.9 mm	15 mm	79.2 mm
Filter (U band)		Infinity	Infinity	Silica	354.4 mm 354.6 mm	15.095 mm	41.8 mm
Filter (B band)		Infinity	Infinity	Silica	354.5 mm 354.5 mm	14.977 mm	41.8 mm
Filter (VR band)		Infinity	Infinity	Silica	354.6 mm 354.8 mm	14.97 mm	41.8 mm
Filter (I band)		Infinity	Infinity	Silica	354.7 mm 354.9 mm	15.01 mm	41.8 mm
Dewar window		Infinity	Infinity	Silica	355.6 mm 355.8 mm	11.3 mm	22 mm

Table 2-2 VST optical data for camera, ADC, filter and dewar window

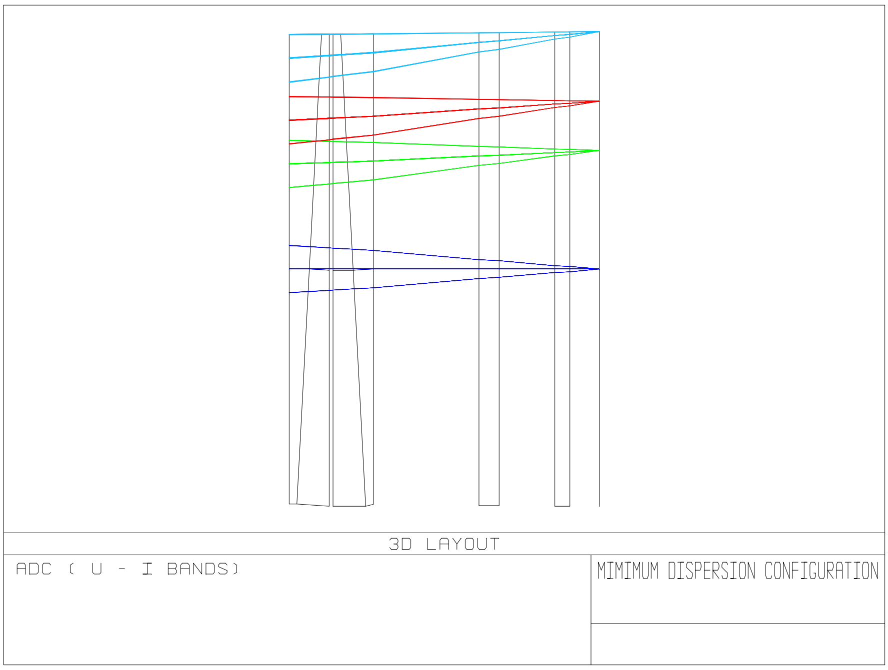


Figure 3- 2 ADC in the configuration of minimum dispersion

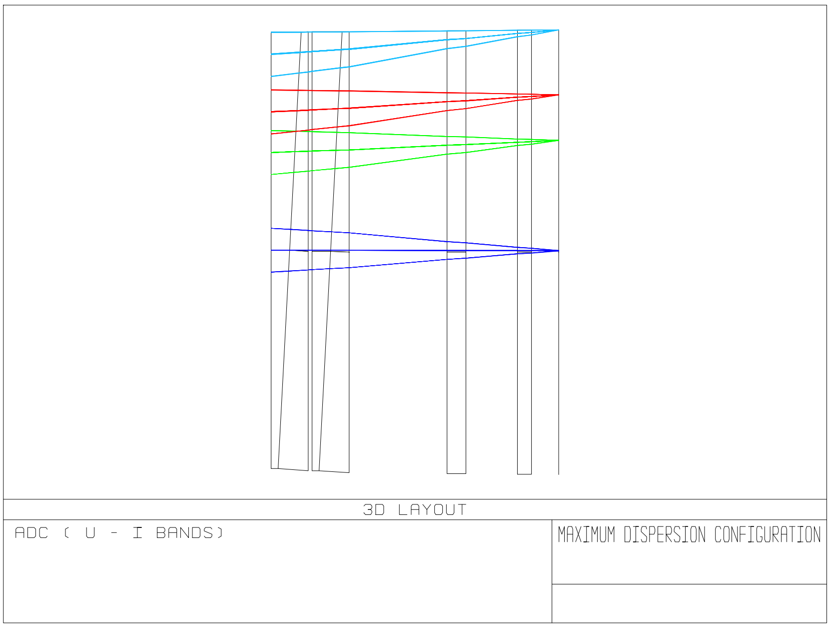


Figure 3-3 ADC in maximum dispersion configuration for atmosphere compensation

4. Study of atmospherical dispersion and image quality for U band

The atmospherical index of refraction changes more rapidly at shorter wavelenghts, hence differential refraction is higher in U band. The ADC corrector designed corrects well in U band until 68°. The atmospherical parameters values utilized for atmosphere refraction simulation are reported in Table 4-1.

They represent typical climate and geographical data measured at Paranal. In Table 4-2 the atmospheric dispersion values in U band are reported, for the different fields of view. In figure 4-1 the spot diagrams at zenith corresponding to minimum dispersion are reported. Figure 4-2 shows the longitudinal dispersion on the image plane for a maximum observing angle of 68°. Spot diagrams for the ADC configuration of maximum dispersion, for atmosphere compensation at 68°are shown in Figure 4-3. In Figure 4-4 the curves for Encircled Energy fraction versus distance from the centroid of the spot are reported. The relative percentual values, enclosed respectively in 15 μm and 18 μm , normalized to diffraction limit are given in Table 4-3. In this band, the image quality with the ADC corrector inserted is reduced respect to the other bands and to the solution without atmospheric refraction and ADC. 80% of energy at least is met in 20 μm.
In figure 4-5 MTF until Nyquist frequency is reported. Minimum MTF until Nyquist frequency is 47%. In Figure 4-6 field curvature and percentual distortion curves are shown for the different fields of view.

Maximum field curvature is 0.12 mm at the edge of the field for λ=0.334 μm and the maximum distortion is 0.17% at the edge of the field.

Latitude	Height above sea level	Ambient Temperature (°K)	Pressure (mbar)	Relative humidity
24.6258°	2635 m	273	750	10%

Table 4-1 Parameters values used for the atmospherical refraction model

Field of view angular radius (deg)	Atmospherical dispersion diameter (μm) for z=68°	Atmospherical dispersion diameter (arcsec) for z=68°
0	107.2	1.5
0.3535	130.9	1.8
0.4999	132.2	1.85
0.707	109.3	1.53

Table 4-2 Atmospherical dispersion values in U band on the image plane for the different fields of view

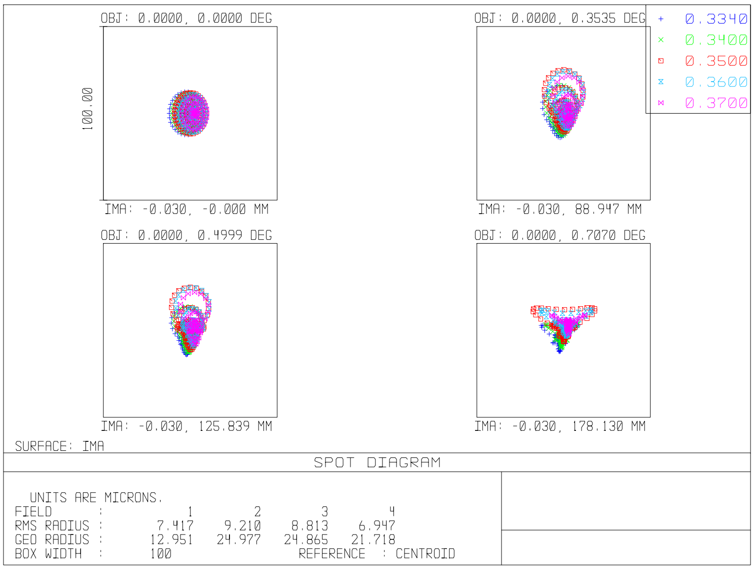


Figure 4-1 Spot at zenith with ADC compensation for U band

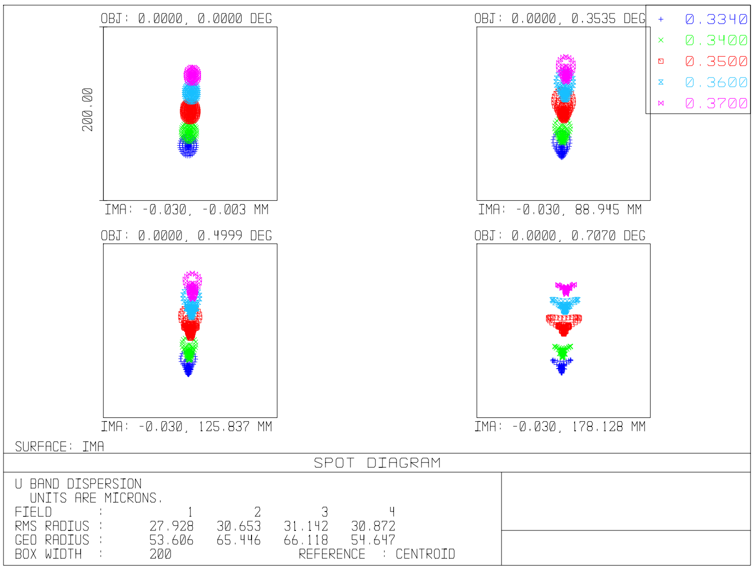


Figure 4-2 Spot diagram with atmospherical dispersion at 68° in U band

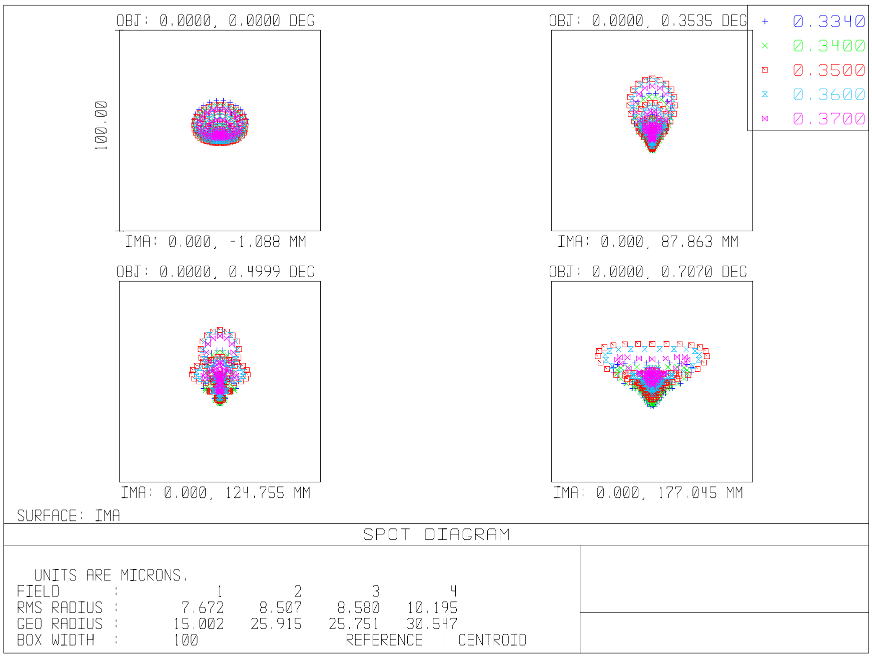


Figure 4-3 Spot on the image plane with ADC compensation (maximum dispersion configuration at 68°) in U band

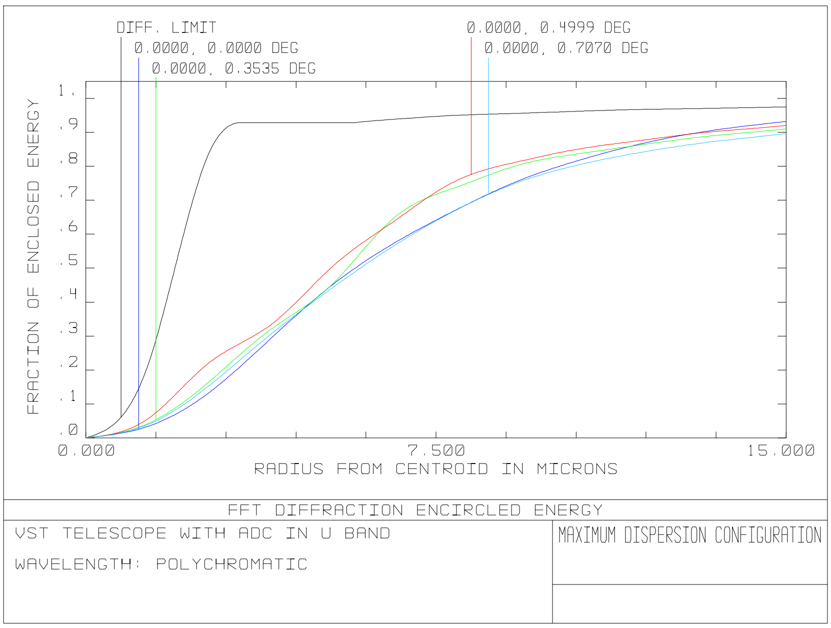


Figure 4-4 Encircled Energy in U band

Field of view angular radius (deg)	EE % enclosed in 15 µm	EE % enclosed in 18 µm
0	75 %	83 %
0.3535	77 %	84 %
0.4999	77 %	84 %
0.707	75 %	81 %

Table 4-3 Encircled Energy in U band enclosed in 15 µm and 18 µm

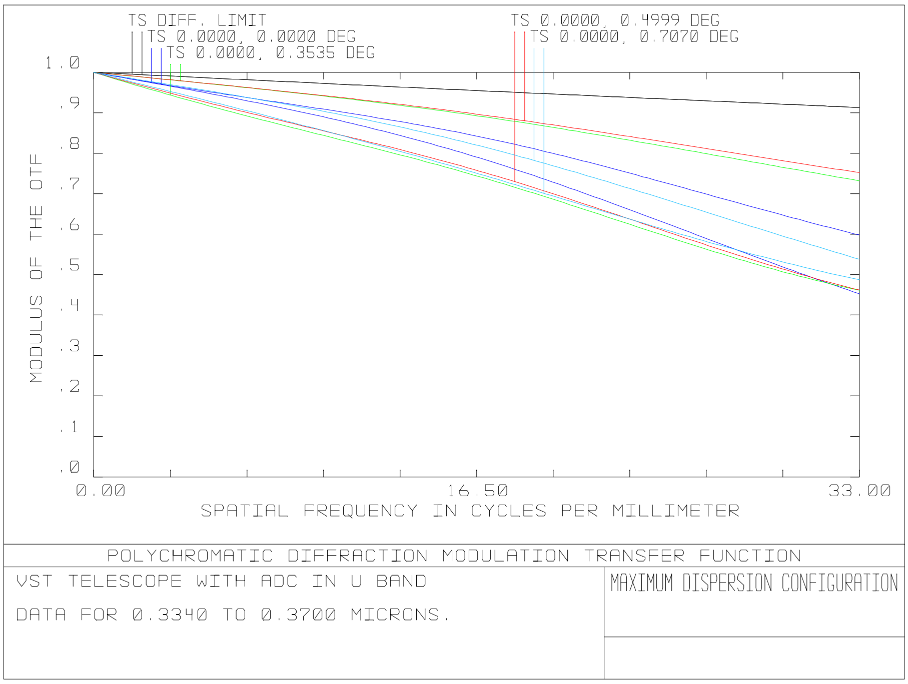


Figure 4-5 MTF in U band. Minimum MTF until Nyquist frequency is 47%.

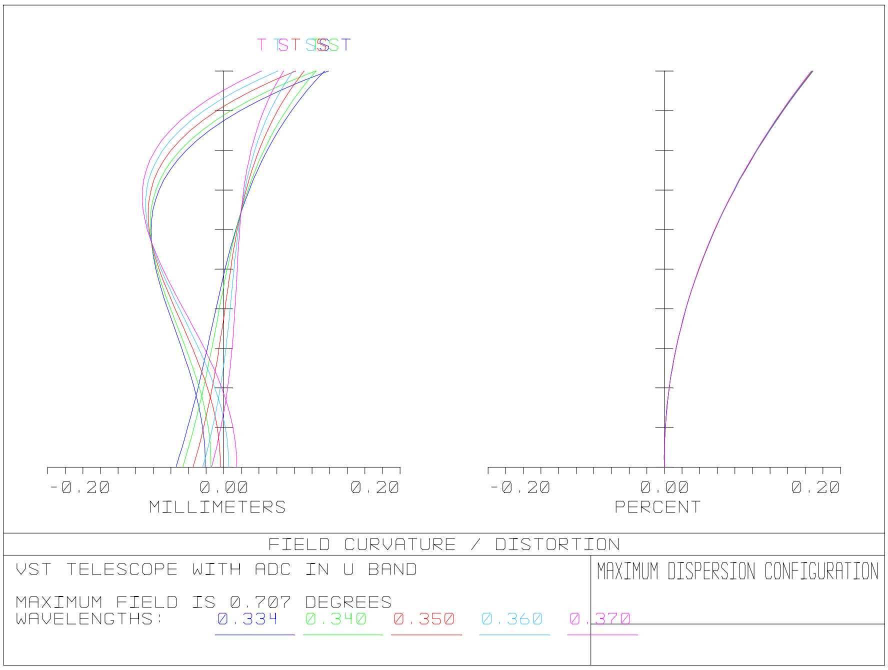


Figure 4-6 Field curvature and distortion in U band. Maximum field curvature is 0.12 mm at the edge of the field for λ=0.334 µm and the maximum distortion is 0.17% at the edge of the field.

5. B band

In B band, the image, quality also with the ADC corrector inserted is much higher than for the other bands. In Table 5-1 the atmospheric dispersion values in B band are reported, for the different fields of view. In figure 5-1 the spot diagrams at zenith corresponding to minimum dispersion are reported. Figure 5-2 shows the longitudinal dispersion on the image plane, for a maximum observing angle of 60°. Spot diagrams for the ADC configuration of maximum dispersion, for atmosphere compensation at 60° are shown in Figure 5-3. In Figure 5-4 the curves for Encircled Energy fraction versus distance from the centroid of the spot are reported. The relative percentual values enclosed in 15 µm, normalized to diffraction limit are given in Table 5-2. In figure 5-5 MTF until Nyquist frequency is reported. Minimum MTF until Nyquist frequency is 55%. In Figure 5-6 field curvature and percentual distortion curves are shown for the different fields of view.

Maximum field curvature is 0.11 mm and the maximum distortion is 0.17% at the edge of the field.

Field of view angular radius (deg)	Atmospherical dispersion diameter (µm) for z=60°	Atmospherical dispersion diameter (arcsec) for z=60°
0	75.06	1.05
0.3535	89.2	1.25
0.4999	96	1.34
0.707	91	1.27

Table 5-1 Atmospherical dispersion values in B band on the image plane for the different fields of view

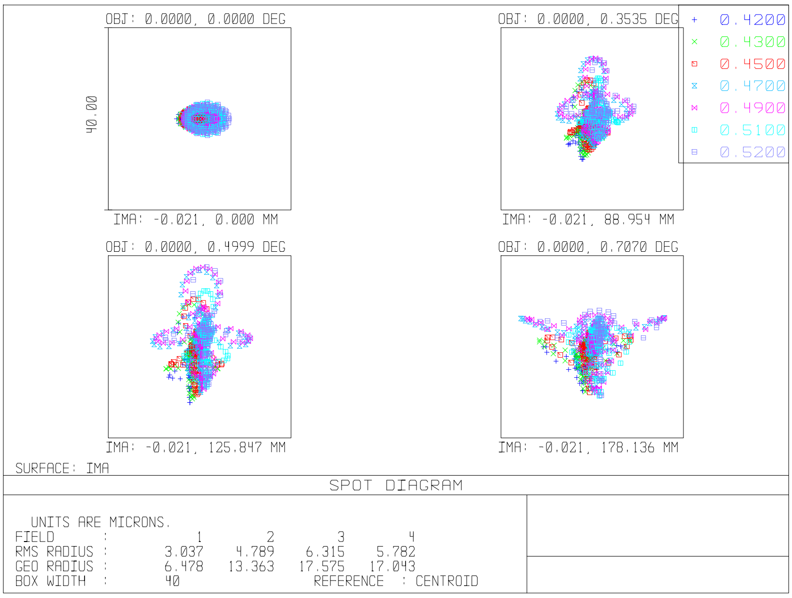


Figure 5-1 Spot at zenith with ADC compensation for B band

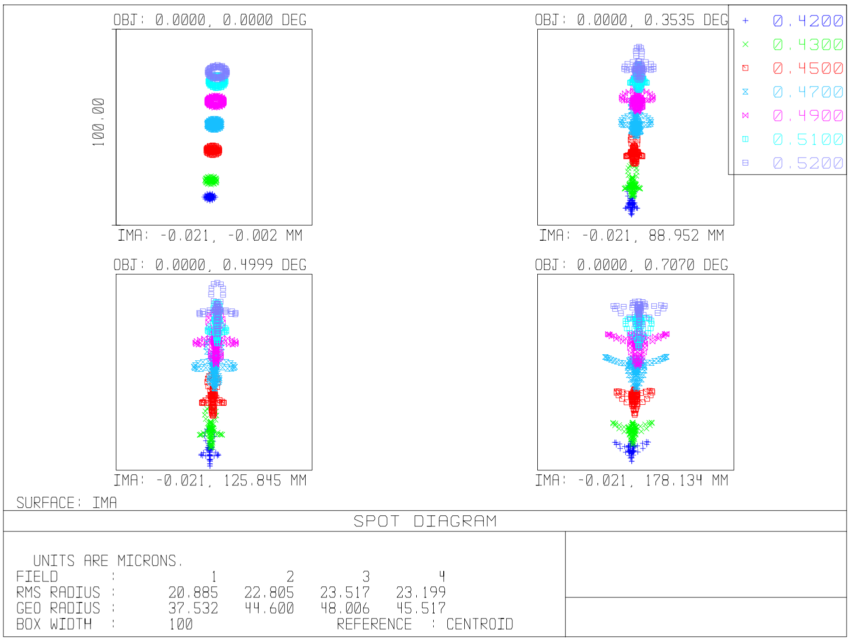


Figure 5-2 Spot diagram with atmospherical dispersion at 60° in B band

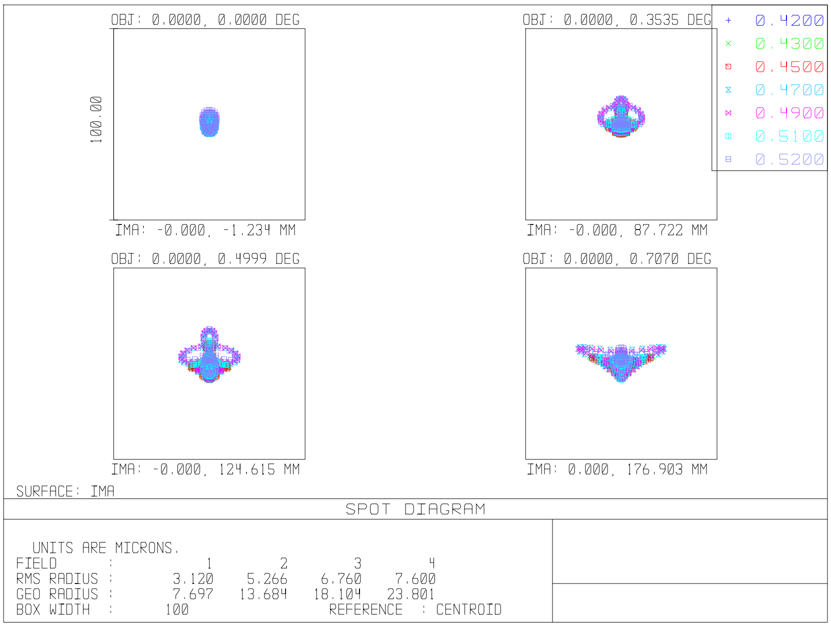


Figure 5-3 Spot on the image plane with ADC compensation (maximum dispersion configuration at 60°) in B band

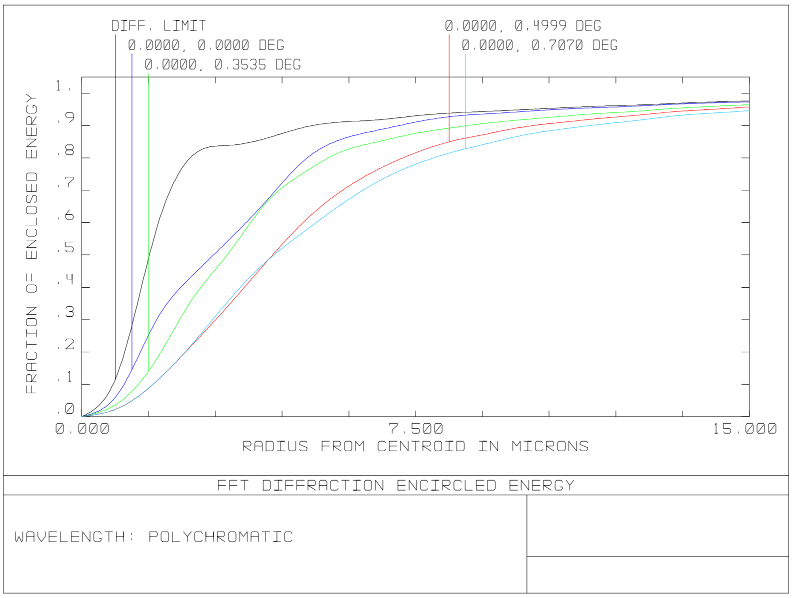


Figure 5-4 Encircled Energy in B band

Field of view angular radius (deg)	EE % enclosed in 15 µm
0	98 %
0.3535	94 %
0.4999	84 %
0.707	89 %

Table 5-2 Encircled Energy in B band enclosed in 15 µm

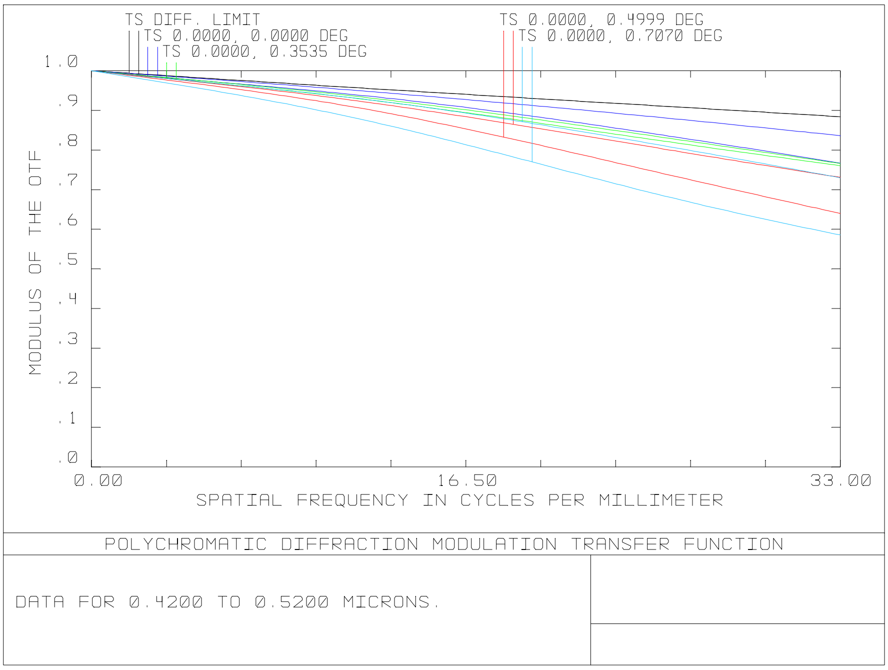


Figure 5-5 MTF in B band. Minimum MTF until Nyquist frequency is 55%.

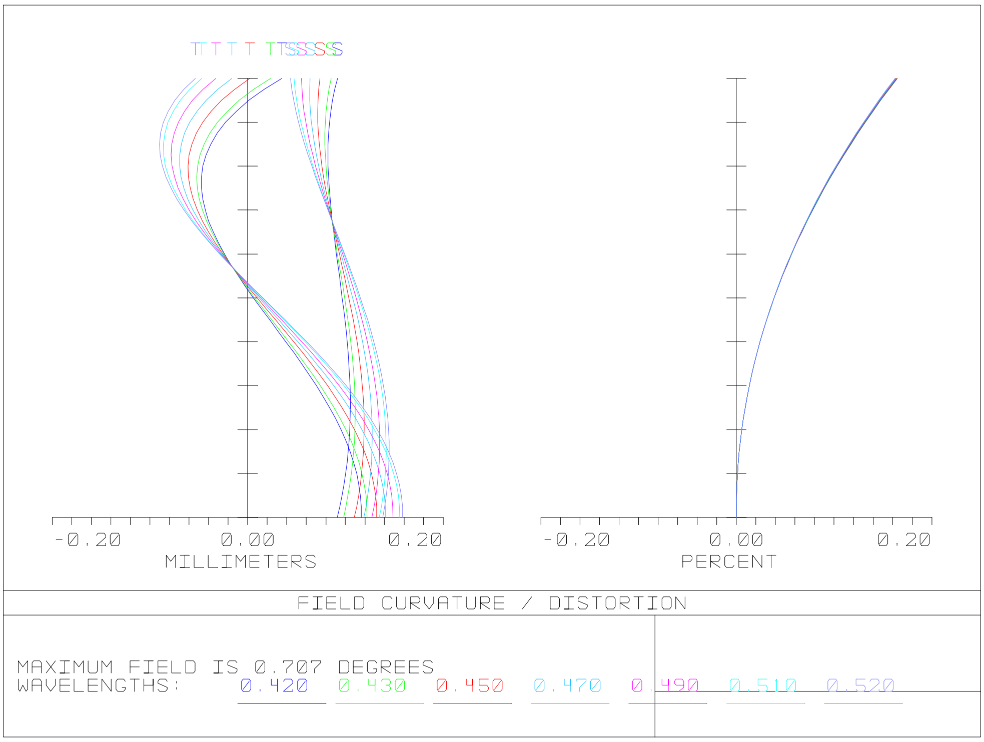


Figure 5-6 Field curvature and distortion in B band. Maximum field curvature is 0.11 mm and maximum distortion is 0.17 % at the edge of the field.

6. VR bands

The optical design is optimized for VR bands, since filter which will be utilized in this range is the same for both. Scientific requirement for image quality is met in 17 µm in this bands with the ADC corrector. In Table 6-1 the atmospheric dispersion values in VR bands are reported, for the different fields of view. In figure 6-1 the spot diagrams at zenith corresponding to minimum dispersion are reported. Figure 6-2 shows the longitudinal dispersion on the image plane, for a maximum observing angle of 60°. Spot diagrams for the ADC configuration of maximum dispersion, for atmosphere compensation at 60° are shown in Figure 6-3. In Figure 6-4 the curves for Encircled Energy fraction versus distance from the centroid of the spot are reported. The relative percentual values enclosed respectively in 15 µm and 17 µm, normalized to diffraction limit are given in Table 6-2. In figure 6-5 MTF until Nyquist frequency is reported. Minimum MTF until Nyquist frequency is 44%. In Figure 6-6 field curvature and percentual distortion curves are shown for the different fields of view.Maximum field curvature is 0.2 mm and the maximum distortion is 0.16% at the edge of the field.

Field of view angular radius (deg)	Atmospherical dispersion diameter (µm) for z=60°	Atmospherical dispersion diameter (arcsec) for z=60°
0	56.5	0.79
0.3535	56	0.78
0.4999	68.9	0.97
0.707	64.3	0.9

Table 5-1 Atmospherical dispersion values in VR bands on the image plane for the different fields of view

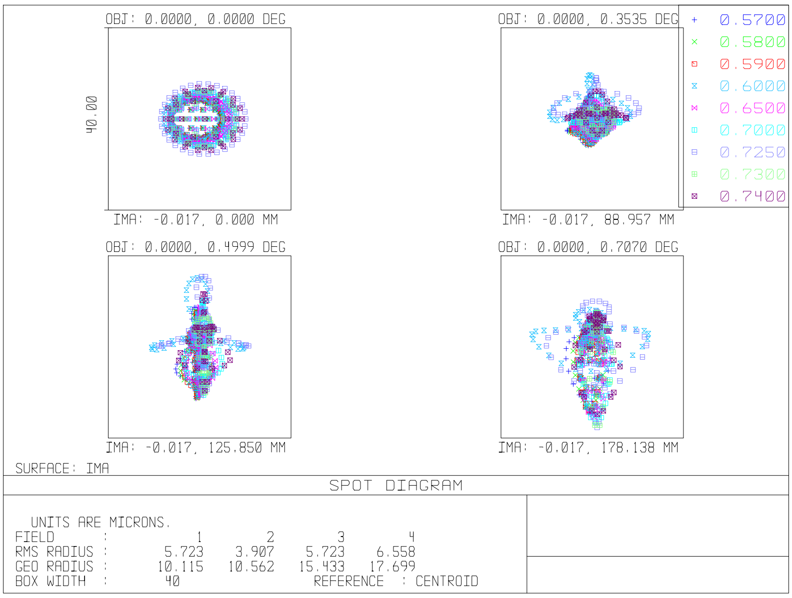


Figure 6-1 Spot at zenith with ADC compensation for VR bands

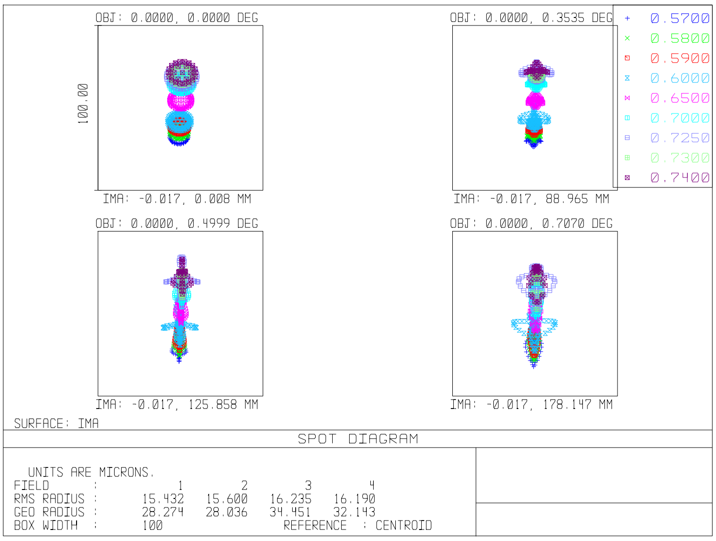


Figure 6-2 Spot diagram with atmospherical dispersion at 60° in VR bands

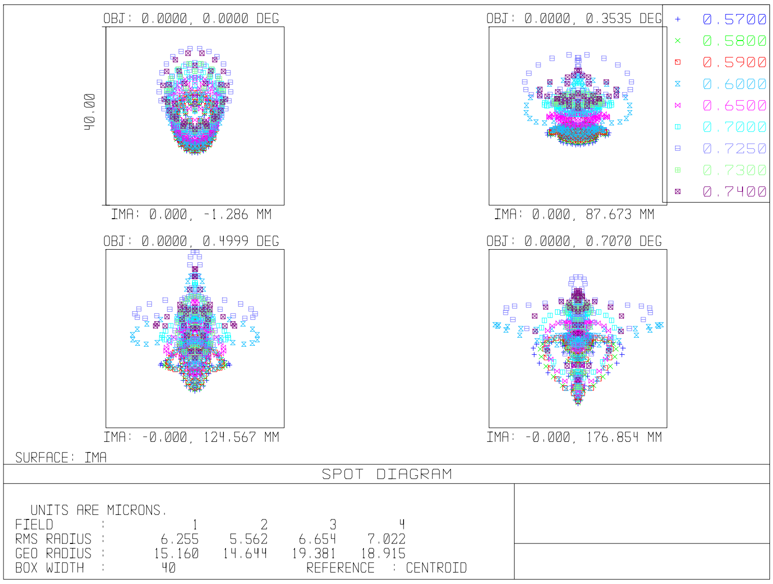


Figure 6-3 Spot on the image plane with ADC compensation (maximum dispersion configuration at 60°) in VR bands

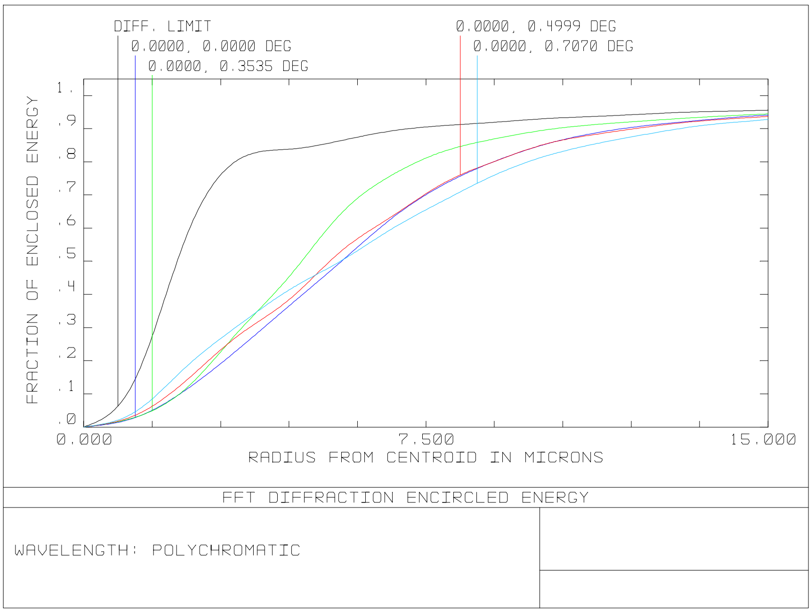


Figure 6-4 Encircled Energy in VR bands

Field of view angular radius (deg)	EE % enclosed in 15 µm	EE % enclosed in 17µm
0	80 %	86 %
0.3535	95 %	97 %
0.4999	83 %	87 %
0.707	79 %	83 %

Table 6-2 Encircled Energy percentual values enclosed in 15 µm and in 17 µm in VR bands

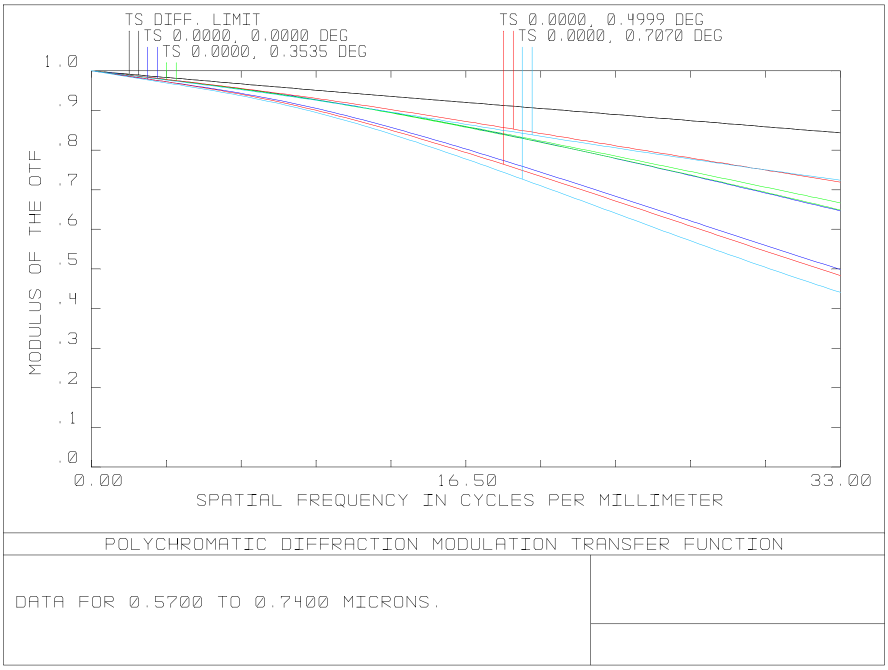


Figure 6-5 MTF in VR bands. Minimum MTF until Nyquist frequency is 44%

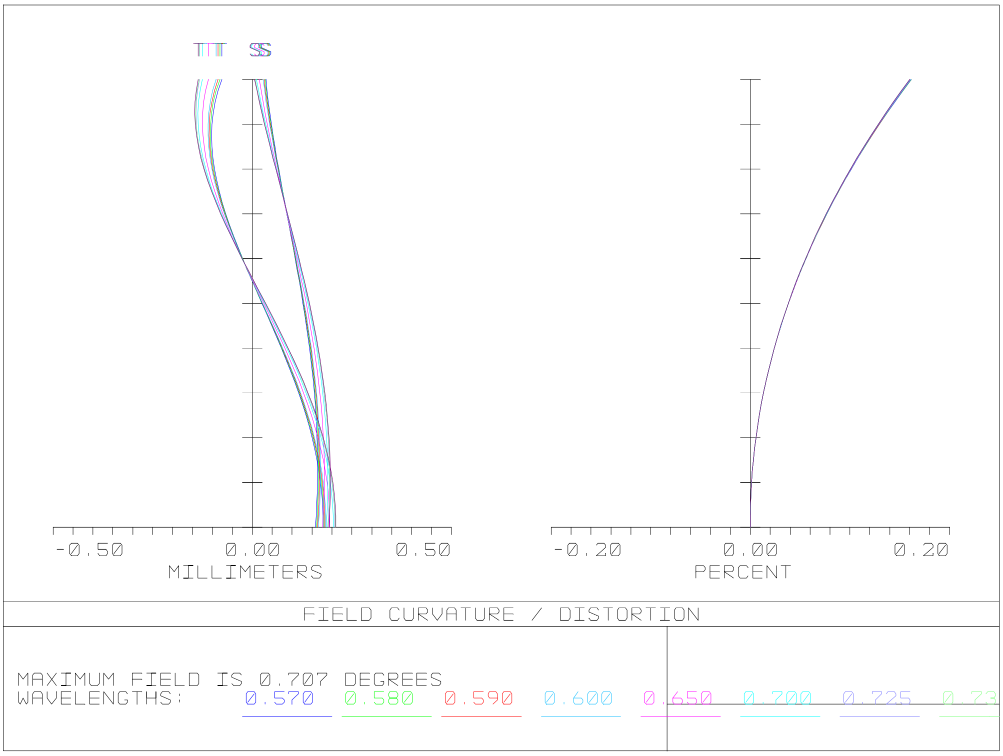


Figure 6-6 Field curvature and distortion in VR bands. Maximum field curvature is 0.2 mm and maximum distortion is 0.16 % at the edge of the field.

7. I band

I band is the more critic one since scientific requirement for image quality is met in 20 µm with the ADC corrector. In Table 7-1 the atmospheric dispersion values in I band are reported, for the different fields of view.In figure 7-1 the spot diagrams at zenith, corresponding to minimum dispersion are reported. Figure 7-2 shows the longitudinal dispersion on the image plane for a maximum observing angle of 60°. Spot diagrams for the ADC configuration of maximum dispersion for atmosphere compensation at 60°are shown in Figure 7-3. In Figure 7-4 the curves for Encircled Energy fraction versus distance from the centroid of the spot are reported. The relative percentual values enclosed respectively in 15 µm and 20 µm, normalized to diffraction limit are given in Table 7-2. In figure 7-5 MTF until Nyquist frequency is reported. Minimum MTF until Nyquist frequency is 36%. In Figure 7-6 field curvature and percentual distortion curves are shown for the different fields of view. Maximum field curvature is 0.2 mm and the maximum distortion is 0.16% at the edge of the field.

Field of view angular radius (deg)	Atmospherical dispersion diameter (µm) for z=60°	Atmospherical dispersion diameter (arcsec) for z=60°
0	16.7	0.23
0.3535	19.06	0.27
0.4999	32.7	0.46
0.707	44.2	0.62

Table 5-1 Atmospherical dispersion values in I band on the image plane for the different fields of view

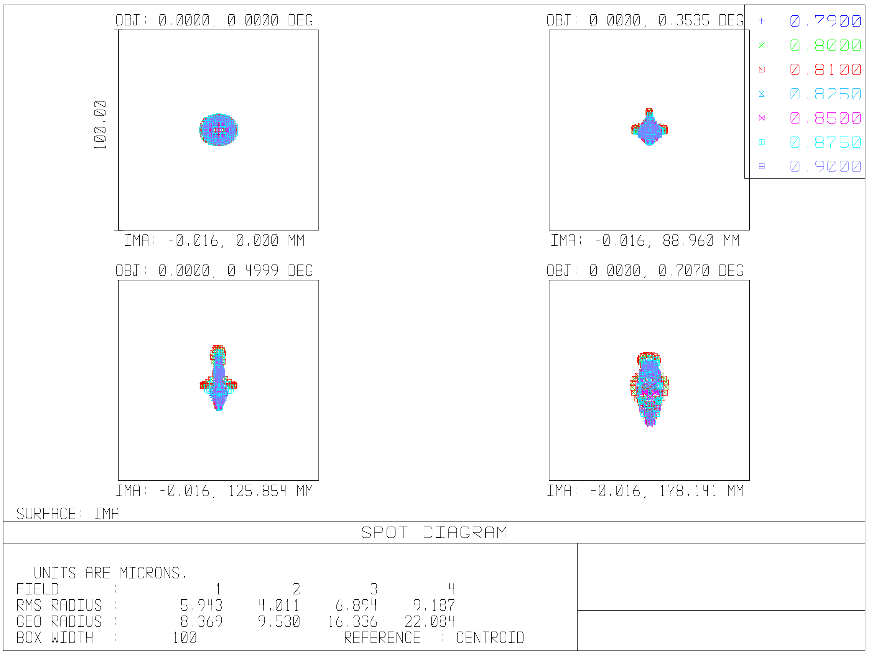


Figure 7-1 Spot at zenith with ADC compensation for I band

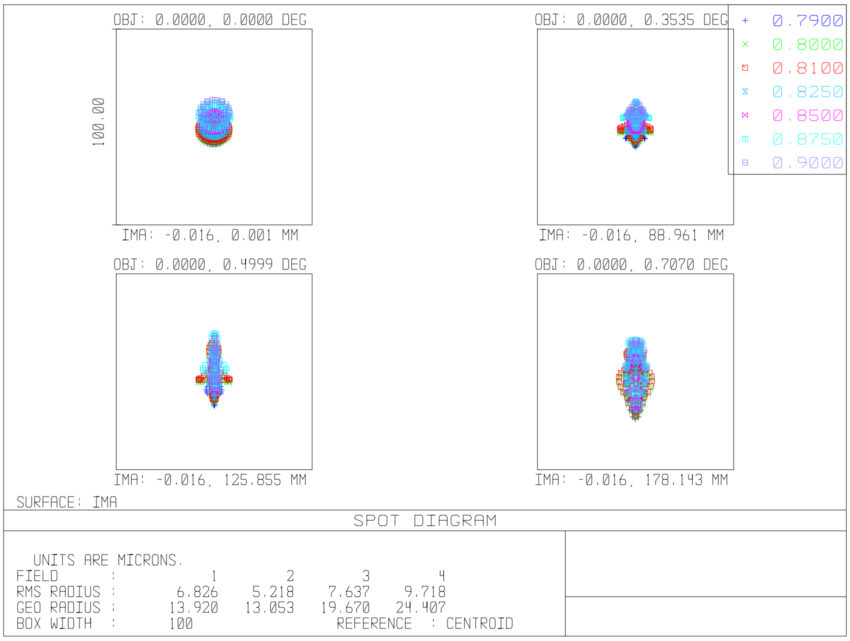


Figure 7-2 Spot diagram with atmospherical dispersion at 60° in I band

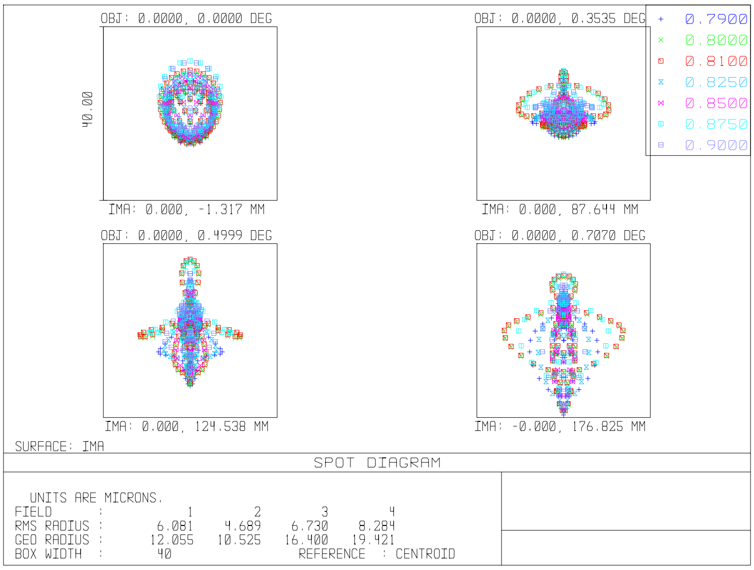


Figure 7-3 Spot on the image plane with ADC compensation (maximum dispersion configuration at 60°) in I band

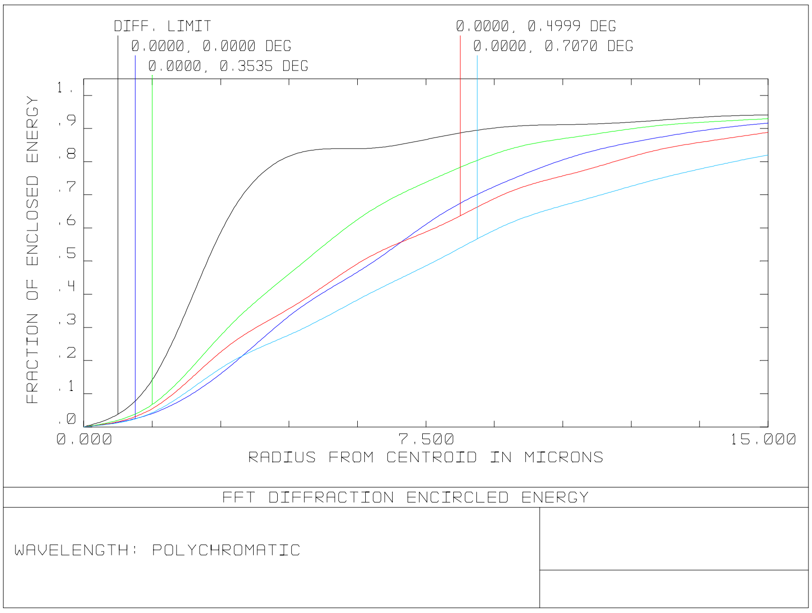


Figure 7-4 Encircled Energy in I band

Field of view angular radius (deg)	EE % enclosed in 15 μm	EE % enclosed in 20 μm
0	79 %	83 %
0.3535	94 %	97 %
0.4999	73 %	90 %
0.707	62 %	81 %

Table 7-2 Encircled Energy percentual values enclosed in 15 μm and in 20 μm in I band

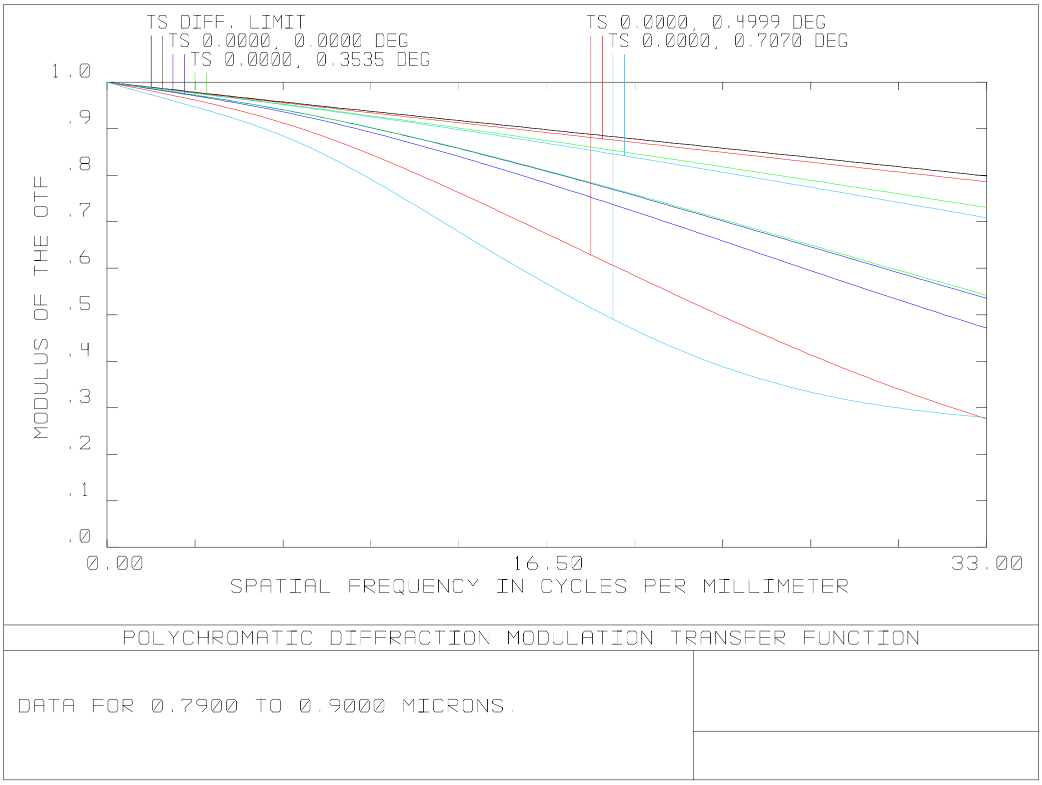


Figure 7-5 MTF in I band. Minimum MTF until Nyquist frequency is 36%

8. Conclusions

The study of this solution, including the ADC corrector, shows a good optical quality in B band, but for the extreme ones there is a degradation respect to the scientific requirements. This is due to the presence of ADC which introduces aberrations by itself. So, if 20 μm for 80% encircled energy in I band and 17 μm in VR bands are acceptable, this solution colud be used to correct atmospherical dispersion obtaining a good final image quality. In Table 8-1 VST main optical data and performance for each band are shown.

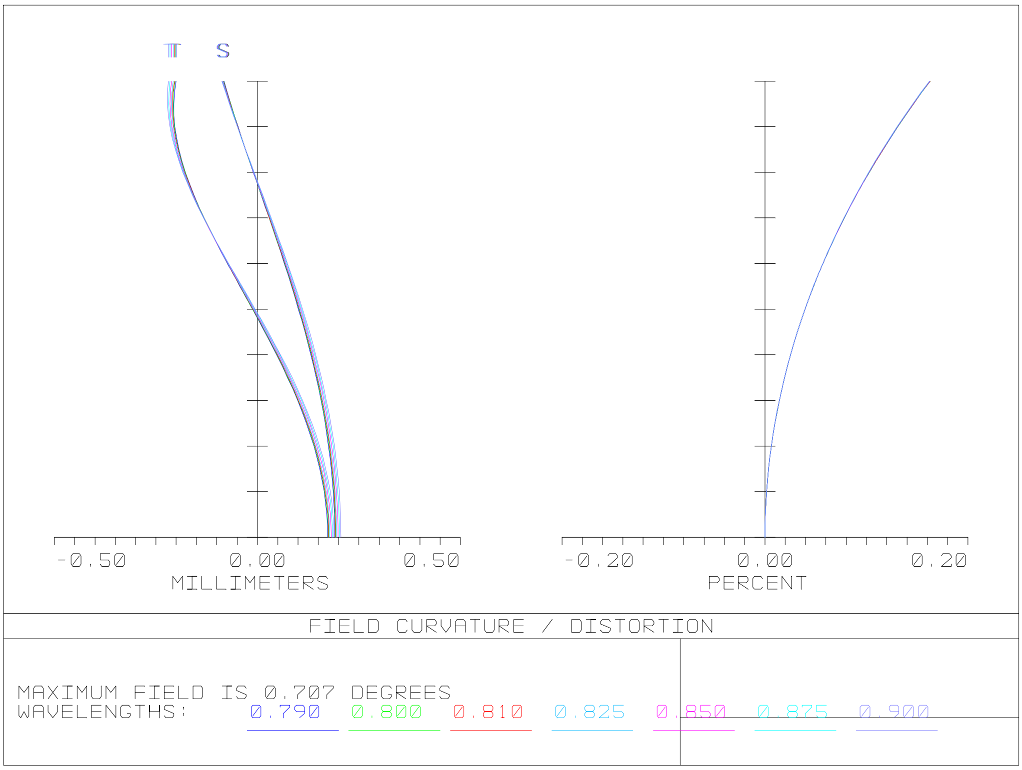


Figure 7-6 Field curvature and distortion in I bands Maximum field curvature is 0.2 mm and maximum distortion is 0.16 % at the edge of the field.

VST MAIN OPTICAL CHARACTERISTICS AND PERFORMANCE FOR EACH BAND	
Optical Configuration	Modified Ritchey Chretien
Main Aperture	2500 mm
Field Of View	1° X 1°
F#	5.76
Equivalenght Focal Lenght	14375 mm
Image Scale	0.21 arcsec/pixel
Spectral Range	U ÷ I bands
Image Plane Corrector	Three spherical lenses made of Silica
Atmospheric Dispersion Corrector (ADC)	Two double prisms made of UBK7 and LLF6
Focal Plane Ccd Mosaic	16 k x 16 k
Ccd Pixel Size	15 µm x 15 µm
OPTICAL PERFORMANCE IN U BAND	
EE% over the whole field of view	more than 80 % in 18 µm
Modulation transfer function until the Nyquist frequency 33 cycles /mm)	over 47 %
Maximum field of curvature	0.11 mm
Maximum distortion	0.174%
OPTICAL PERFORMANCE IN B BAND	
EE% over the whole field of view	more than 84 % in 15 µm
Modulation Transfer function until the Nyquist frequency (33 cycles /mm)	over 55 %
Maximum field of curvature	0.11 mm
Maximum distortion	0.17 %
9. OPTICAL PERFORMANCE IN V, R BANDS	
EE% over the whole field of view	more than 83 % in 17 µm
Modulation Transfer Function until the Nyquist frequency (33 cycles/mm)	over 44 %
Maximum field of curvature:	0.2 mm
Maximum distortion	0.16 %
10. OPTICAL PERFORMANCE IN I BAND	
EE% over the whole field of view	more than 81 % in 20 µm
Modulation Transfer function until the Nyquist frequency (33 cycles /mm)	over 36 %
Maximum field of curvature	0.2 mm
Maximum distortion	0.16 %

Table 8-1 VST main optical characteristics and performance in each band