Optical design of an UV–camera for a Ritchey–Chretien space telescope

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ABSTRACT

A study for the optical design of an UV–imaging camera is briefly reported. We emphasize the guidelines that drove the design choices adopted, as trade–off between optical quality and efficiency. Optical solutions for an additional long focal length channel are also given.

This study is performed in the framework of the SUV project, a 170cm Ritchey–Chretien space telescope to be made with the collaboration of Russia, Ukraine, Italy and Germany.

1. INTRODUCTION

In order to finalize the design of an imaging camera for a multi purpose space telescope in the UV wavelength region a number of scientific and technical requirements are to be met. Some of the performances offered by the camera depends upon technical aspects linked to the telescope and/or the spacecraft (for example the resolution, driven by the optical quality of the telescope and by the spacecraft jitter). Other aspects are strictly depending from the camera design itself, mainly the Field of View (FoV hereafter) and the resolution.

As a baseline we assume to obtain a corrected, unvignetted camera's FoV$\approx 5'$.

A high throughput of the camera can be assured by a minimum number of reflections, while refractive elements are to be avoided. The chromatic aberrations arising from MgF and LiF (essentially the only glasses suitable for such a task) are in fact a not obvious problem to overcome. Moreover the degradation of the refracting material in the space environment make their use very problematic when a long-life mission is considered.

Another crucial point is the choice of the equivalent F/ ratio on the detector. State–of–the–art of the UV detectors[1,2,3] imposes maximum physical sizes of the order of few *cm* and pixel size of 15 to 25 μm It is clear that a wide FoV can be obtained loosing in spatial resolution and viceversa.

A general problem arises from the accommodation of many instruments (spectrographs, photometers, and others) in the focal plane. In fact, because optical performances degradates with the distance from the main optical axes, all instruments should be placed as close as possible to the optical axis. In the (special) case of an imaging camera we point out that any folding mirror, placed *before* the focal plane position, will introduce shadowing and vignetting over a significant region of the FoV left to the other instruments (typically spectrographs entrance slits). Because significant loss of throughput in these instruments has to be avoided, a number of constraints on the optical design are imposed.

In this paper we analyze different optical designs for an imaging camera to be implemented in a UV space telescope. Both optical and general mechanical constraints have been considered.

The study was performed in the framework of the Spectrum–UV (SUV hereafter) mission[4,5] (see Fig.1), a general purpose Ultraviolet Observatory to be launched by Russia in mid 1997. The plan is to carry in a 7 days, highly elliptical orbit a 170–cm aperture telescope for imaging and spectroscopy in the 912 Å to 4000 Å range. A cluster of 20–cm to 50–cm multilayer coated telescopes, for observation in the EUV and XUV is coaligned with the main telescope.

An advanced feasibility study of the mission is being carried on by an international team which includes scientists from Canada, Germany, Italy, Russia and Ukraine. The prime instrument of the SUV payload is a 170–cm aperture, diffraction limited Ritchey–Chretien (RC hereafter) telescope (T–170) for imaging and spectroscopy. Its nominal parameters are given[6] in Tab.1.

The overall expected quality on the focal plane, due to the convolution of the expected manufacturing accuracy[7] of the optics (polishing) and guiding error is about 0.3" for the 80% of the light concentration. The fine tracking is performed via rotation of the secondary mirror around its neutral point.

In the following we describe the design of the imaging camera (a moderately wide FoV camera) together with an

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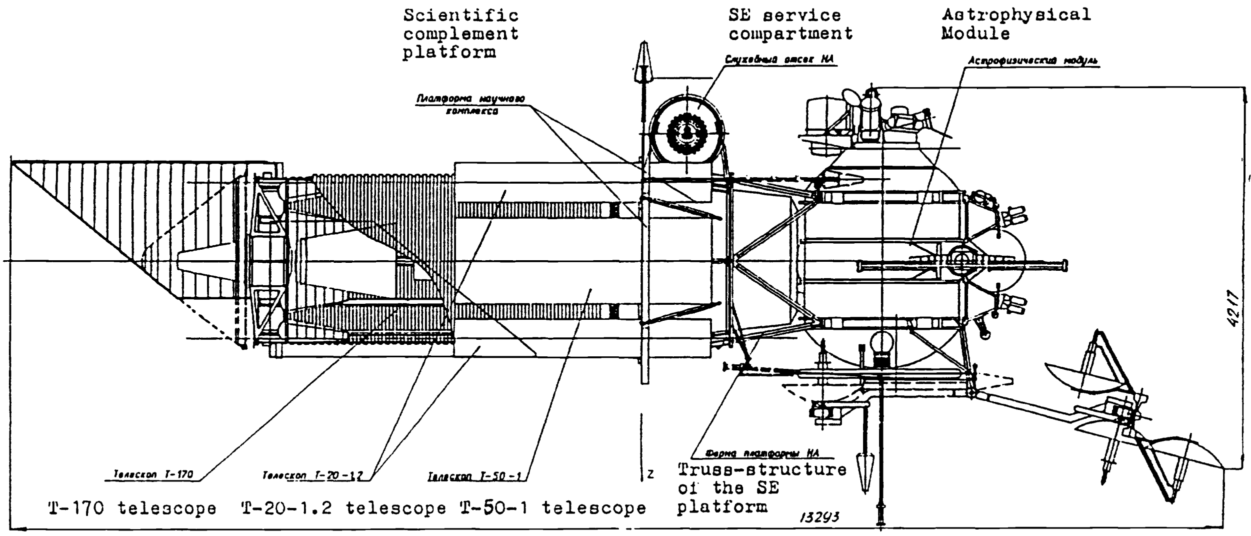

Figure 1: Side view of the SUV spacecraft configuration.

Primary Mirror	
Diameter	1700 ± 2 mm
Focal Ratio	F/2.8
Curvature Radius	-9333 ± 10 mm
Conical Coefficient	1.050237 ± 0.005
Secondary Mirror	
Diameter	500 ± 0.5 mm
Curvature Radius	-3216 ± 5 mm
Conical Coefficient	3.612442
Overall Parameters	
EFL	17000mm
Plate Scale	12.13 arcsec$\cdot$mm^{-1}
Mirrors Separation	3500 ± 10 mm
Focal Extraction	750 ± 2 mm
Focal Plane Curvature	1270 mm
Central Obstruction	0.47

Table 1: Nominal optical parameters of the T–170 telescope.

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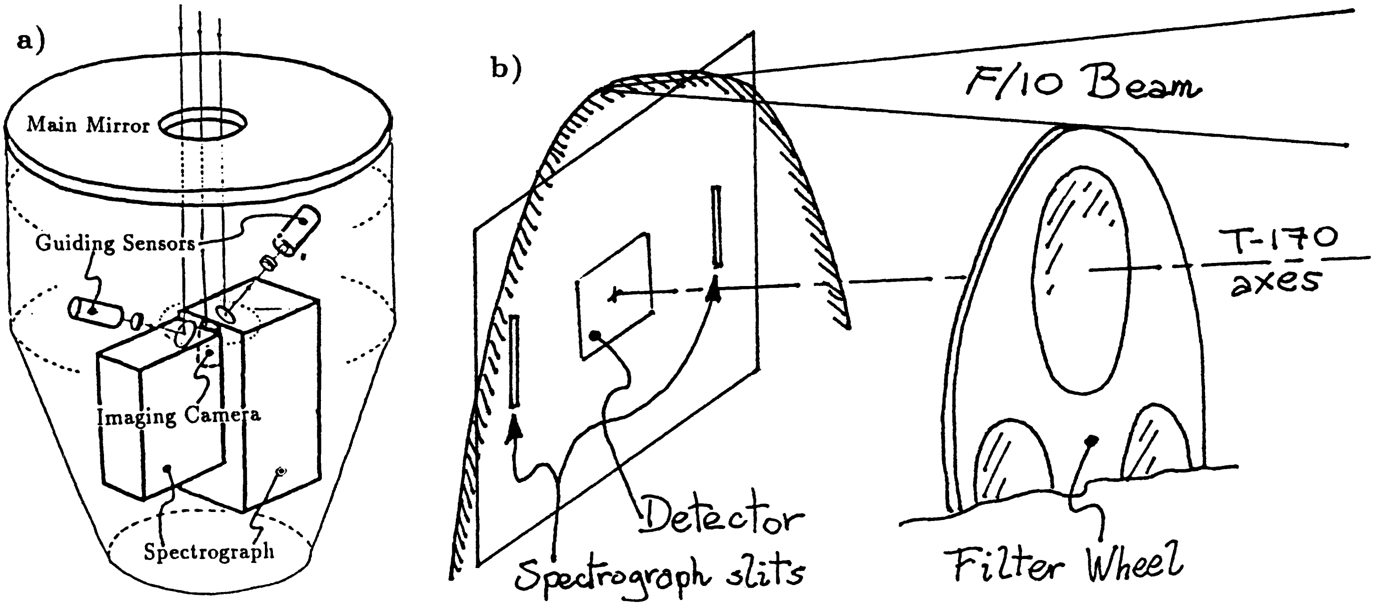

Figure 2: **a**): The direct camera; **b**): Its corresponding vignetting over the spectrographs entrance slits.

high–resolution channel using the same detector of the main camera. In the first case a nearly 1:1 coupling with the telescope is assumed as guideline, while for the second option a magnification factor of 10 is to be provided.

2. THE OPTICAL DESIGN

We investigated four different schemes for the optical design: from a simpler direct camera to a class of solutions using two relay mirrors. The final choice will depend on the performance of different schemes and on the basis of vignetting over the other instruments in the focal plane.

We recall that the optical quality of the main telescope on a flat surface (when the proper focussing strategies are taken into account) allows a 8′ FoV (less than 0.1" blur at the edge of the field).

2.1. A direct camera

The simplest solution consists of an on–axis *direct camera* at the focal plane of the telescope (Fig.2a). This is very efficient (maximum throughput) and allows accurate photopolarimetry because uses only optics with revolution symmetry. Actually only FOC and HSP, both onboard HST, are able to perform a moderately accurate photopolarimetry in the UV. This solution, however, conflicts with the presence in the focal plane of other instruments (mainly spectrographs).

The very limited space left directly at the focal plane implies in fact to built such a device very small.

In order to establish the minimum size available, we performed an analysis[8] of the vignetting over the spectrographs slits introduced by the filter wheels (see Fig.2b).

Both few, large sized, wheels and many small sized wheels were considered. Assuming realistic figures for the overall number of filters needed, a minimum vignetting over the focal plane of $\approx 5\times$FoV is obtained.

In the current baseline of the focal plane accommodation the spectrographs slits are placed 10′ off–axis. This imposes a limit to the camera's FoV of about 2′ which is too low for many scientific observations.

2.2. An on–axis folded camera

To overcome the mechanical problems of the direct camera an on–axis flat folding mirror (see Fig.3a) becomes an

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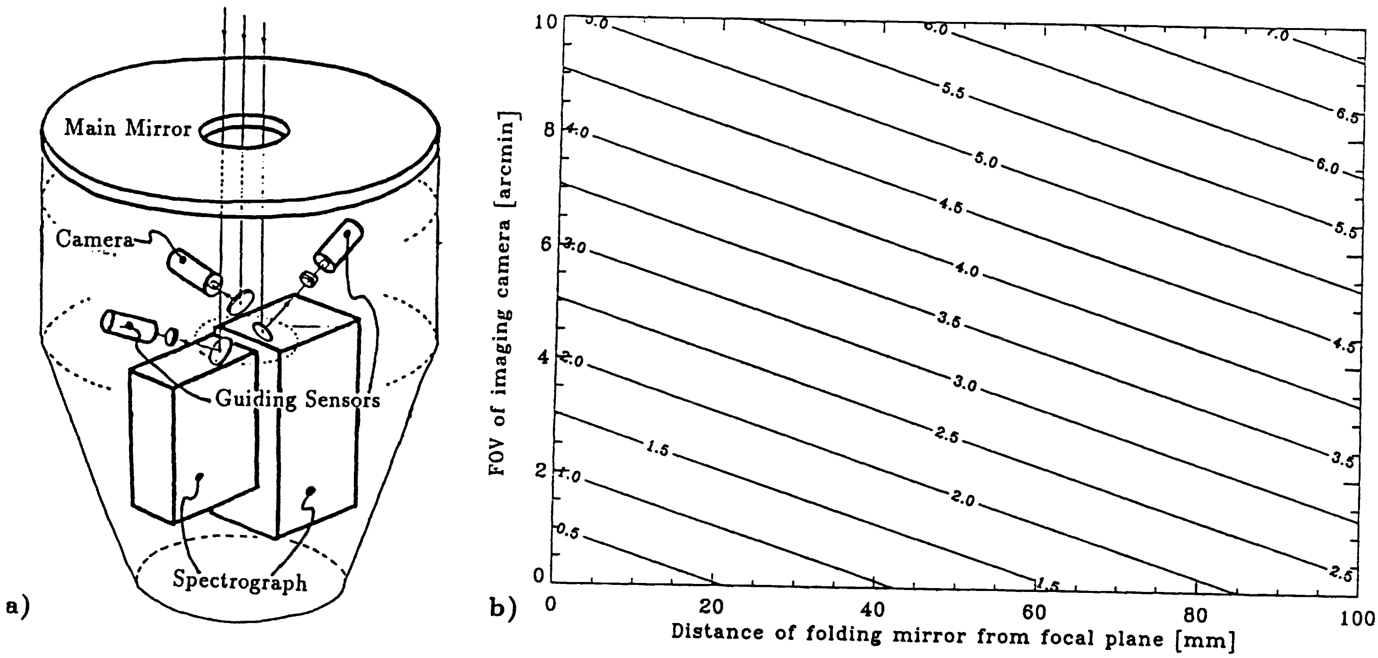

Figure 3: **a**): The on–axis, one folding mirror, camera; **b**): The relationship between the camera's FoV and the mechanical clearance for various unvignetted off–axis on the spectrographs focal plane.

attractive solution[9]. The optical quality is clearly identical to the previous case.

However, if one deals with the requirements of mechanical clearance from the folder to the detector (in order to allow enough space for filters, shutters, calibration lamps and eventually low disperser devices like grisms) some balancing between the camera's FoV and the vignetting over the spectrographs focal plane is to be made.

As it can be seen from Fig.3b only very limited mechanical space is left when the scientific requirements are met. On the other hand, the option to move the entrance slits far away from the optical axes translates into a lower throughput of the spectrographs.

2.3. A two mirrors camera

In the previous schemes no solutions exists to realize a 5′ FoV camera without affecting the throughput of the spectrographs. The problem with the above schemes is essentially due to the presence of some elements (mirrors or filter wheels) well before the focal plane. To avoid this problem we have considered optical schemes using two mirrors[10].

In this option a small mirror is place close to the focal plane and reimaging onto the detector is performed via a relay mirror (see Fig.4a). The main task of M3 is to control the field curvature, while the one of M4 is to correct the spherical aberration. No obvious way to reduce astigmatism is found. Some solutions were deeply investigated (see Fig.4b) but their performances were not satisfactory over the required FoV. One of the better solutions offers a blur of 0.83 arcsec at the edge of a 3′ FoV. Because of poor optical performances this solution was rejected.

2.4. An off–axis folded camera

To solve both mechanical and optical problems found in the above optical schemes, two paths can be followed:

- To allow for a larger number of mirrors, in order to correct for astigmatism, but with the introduction of much more mechanical problems and one more reflection;
- To discard the assumption of having the camera on–axis.

The second solution is clearly the more efficient. In fact one has to take care that in this case the detector can be

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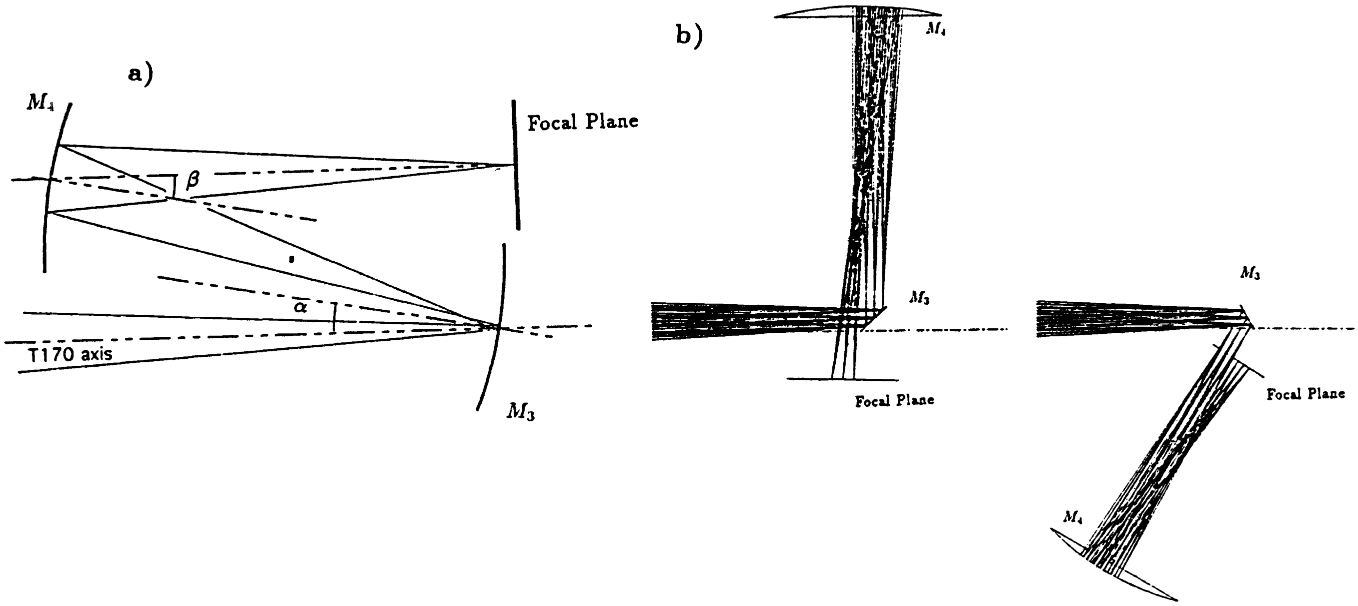

Figure 4: **a)**: The concept for the two mirrors camera; **b)**: The investigated solutions.

properly tilted in order to partially compensate the little defocussing due to the curvature of the FoV. The maximum blurring over the whole FoV of 6′ is ≈ 0.1".

3. A LONG FOCAL LENGTH CHANNEL

In spite of the diameter of the main telescope, that could, in principle, offer spatial resolution comparable with the one offered by HST, the expected image quality is of the order of 0.3".

It is also clear that any efforts to get much higher resolution from the telescope is in conflict with the wide FoV requirement. Nevertheless it is to be hoped that a non-vanishing MTF be available at resolutions of diffraction limit level, that is 0.06" at 500*nm*. In order to be able to retrieve, at least for a small number of well selected targets, such a spatial information[11,12,13,14] an option for a long (F/100) focal length channel has been taken into account.

The main constraint, from the optical point of view, is to use the same detector of the F/10 camera and a minimum number of moving elements (like additional shutters, mirrors, and so on) for obvious safety reasons.

Two main schemes are given and discussed: a *skewed* long arm option in which light is reimaged via an elliptical mirror, and a small all–reflective magnifier to be arranged in the filter wheels. Both schemes are intended to cover a FoV of 10" to 20".

3.1. A long arm F/100 option for the camera

A solution for a dual F/10+F/100 camera was proposed by Popov[15] and subsequently modified by Ragazzoni and Falomo[16]. It consists essentially in a pair of flat folding mirrors, each covering the F/10 and F/100 fields, see Fig.5a. The F/100 beam is formed by a concave mirror (allowing the formation of an *auxiliary* focal plane, where a finger could be accommodated) and reaches the same detector of the F/10 arm via two holes in the folding mirrors. A pair of shutter will select the used arm.

The position of the two mirrors with respect to the T–170 optical axis has to be decided taking into account:

- Optical performances on the F/10 arm (strongly dependent upon the distance of the F/10 channel axis from the T–170 one;
- Optical performances on the F/100 arm (practically independent from the distance of the F/100 channel axis from the T–170 one if proper off–axis astigmatism correction and a limited field of view are adopted);

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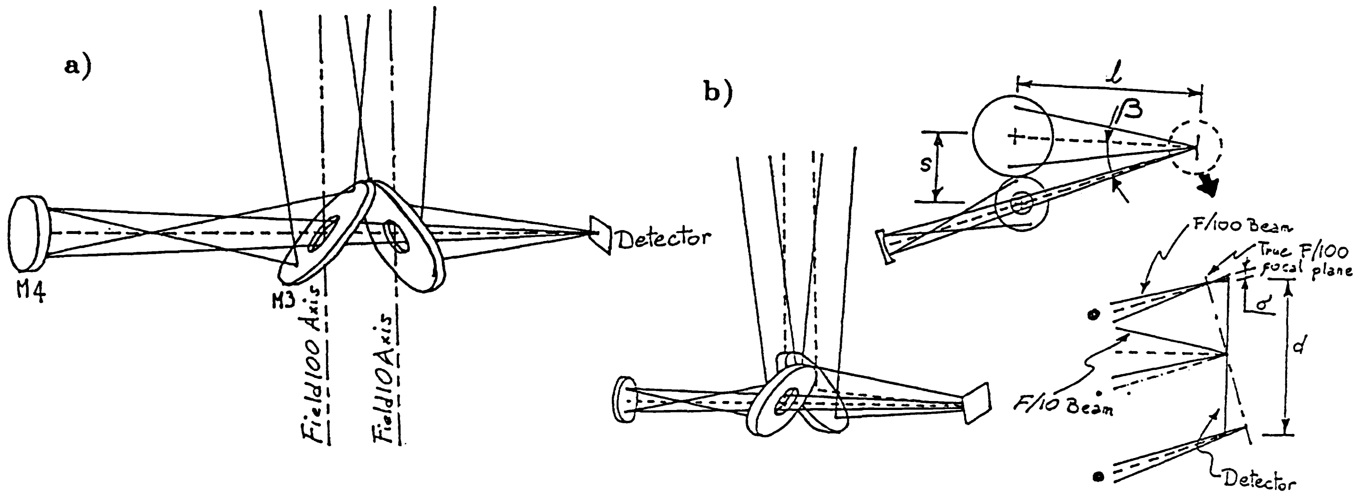

Figure 5: **a)**: An F/100 channel passing *through* the folding mirror of the F/10 arm; **b)**: A skewed version without any hole in the F/10 folding mirror.

- Vignetting upon the other instruments on the focal plane (namely the slits for the spectrographs).

The overall optical configuration requires 4 reflections and allows the feasibility of a coronographic mode. Regarding this last aspect we note that where an auxiliary focal plane is obtained, the light goes through twice, that is the introduction of a finger translates into a partial (probably strongly FoV–dependent) vignetting. This drawback could be overcome arranging a coronographic spot placed on a transparent plate which could also incorporate an apodhizing mask.

The principal problem of this solution is the vignetting introduced by the hole in the F/10 folding mirror.

From a detailed calculation it clearly appears that an acceptable value for the size of the hole is of the order of $10mm$ corresponding to a FoV in the F/100 arms of $\approx$ 10 arcsec. A larger value will produce large vignetting in the F/10 camera while a smaller value will restrict substantially the FoV in the F/100 channel without significantly improve the vignetting of the F/10 camera.

Moreover, the folding mirrors of the camera will introduces noticeable vignetting on the focal instrument plane. A detailed calculation can be performed only after all parameters have been fixed.

A slightly different version from the last one is its *skewed* version, sketched in Fig.5b.

In this configuration the F/10 folding mirror does not need to have a hole therefore leaving untouched its performances. An angle β approximately equal to:

$$\beta \approx \frac{s}{l} \tag{1}$$

is experienced between F/10 and F/100 folded beams. This translates into a tilt of the true F/100 focal plane, producing at the edges of the d–sized detector a further blurring σ (defined as the diameter of the light–beam in the stigmatic approximation) of the order of:

$$\sigma \approx \beta \frac{d}{2} \times \frac{1}{100} \tag{2}$$

Using typical values for the various parameters a negligible value of $\sigma \approx 16\mu m \approx 0.019$", to be compared with diffraction–limited performances of the order of 0.06", is obtained.

3.2. An all reflective magnifier

A very attractive option to implement a long (F/100) channel is to introduce a pair of spherical mirrors in the filter wheels[17,18]. The solution found (see Fig.6) is quite satisfactory over a FoV of approx 20". Vignetting is plotted in Fig.7a and optical performances (better than 0.1" over the whole FoV) are shown in Fig.7b.

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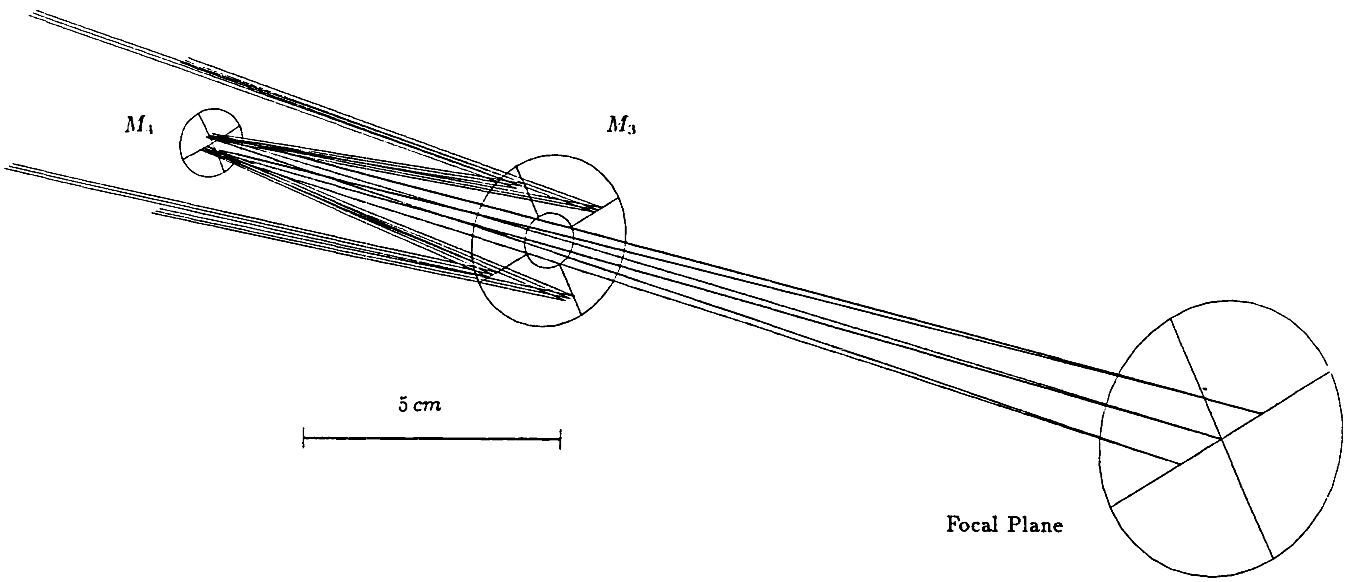

Figure 6: The F/100 channel option via a pair of additional reflections.

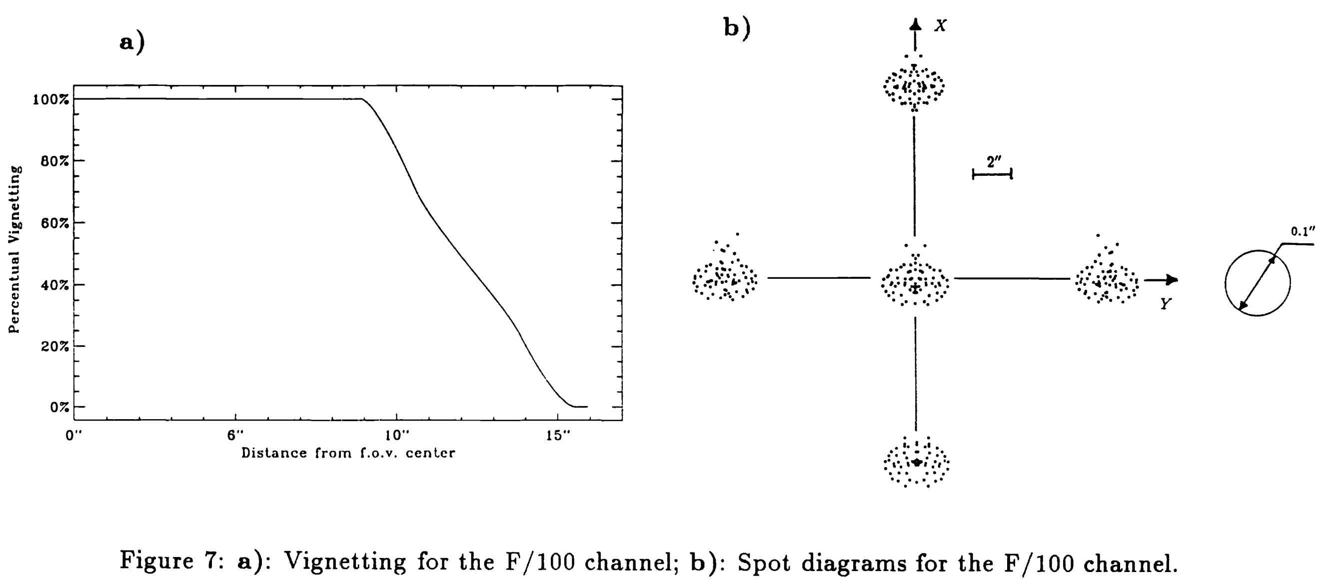

Figure 7: **a)**: Vignetting for the F/100 channel; **b)**: Spot diagrams for the F/100 channel.

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The sensitivity of the optical performances to misplacement or tilting of the two small mirrors is very low, even if some image tilt can occur.

4. CONCLUSIONS

Different optical schemes for an UV imaging camera to cover a $\approx 5'$ FoV have been considered in view of its application in a RC space telescope. Taking into account both optical performances and mechanical/optical constraints, imposed by other instrumentation in the focal plane, it is shown that the best compromise is a single one mirror, off–axis camera.

In addition we demonstrate that the implementation of a long (F/100) channel is possible with the simple insertion of two reflecting optical elements in the filter wheel, thus leaving untouched the capabilities of the main camera.

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