Two-mirror planetary camera with an off-Rowland UV spectrograph for the Rosetta space mission

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ABSTRACT

An all-reflective, unobstructed and unvignetted optical design for a wide field of view (12° squared) camera is described. The camera is obtained by two sections of conical surfaces and allows an efficient stray light rejection, in order to detect faint gaseous features in the neighborhood of the comet nucleus against its bright body. Very good optical performances are obtained with a 2048 × 2048 CCD array detector allowing more than 90% of the encircled energy into a single 12 μm squared pixel over the whole detector area. Distortion is kept to a few percent allowing a backup operation of this camera for navigation purposes.

Also an add-on option of an off-Rowland quasi-stigmatic spectrograph is described. The optical design is such that this spectrograph is feeded by a plane mirror mounted on the camera filter wheel, and the spectrum is sent on the same CCD detector of the imaging mode in a similar way. Thus a very low resource additional spectroscopic option is obtained. This channel mounts a 4° length entrance slit, and permits to obtain a very good spectral and spatial resolution.

Keywords: Optical Design, Planetary Sensing, UV Spectroscopy.

1 INTRODUCTION

Rosetta[1] is a cornerstone mission of European Space Agency (ESA) to be launched in 2003, devoted to the approaching, orbital mapping and subsequent delivery of two landers, around a periodical comet: the target should namely be the Wirtanen P/1991 XVI comet, to be reached in 2011, but it still has to be confirmed.

In this framework we have been involved in the definition of a Wide Angle Camera (WAC hereafter) for the mapping of the comet surface and for the detection of gaseous streams from the cometary nucleus surface. Some possible optical designs have already been studied and previously described[2,3] and they are relative to a camera which had to satisfy the original scientific requirements described in Tab. 1: the best optical solution that we found for this camera was an off-axis section of a three mirror, unobstructed, concentric system.

Since these first preliminary studies, a lot of other work has been done because of the change of a number

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Focal length	80 mm
Effective F/	3.2
Field of View	18° × 18°
Detector size	2048 × 2048 pixels
Pixel size	12 μm × 12 μm
Mechanical clearance	$\geq$ 50 mm
Geometrical Encircled Energy	$\geq$ 80% in one pixel
Spectral range	140-1000 nm (all-reflective solution)
Stray light rejection	$\geq$ two bounces

Table 1: Original scientific requirements of the WAC.

of scientific constraints, becoming more and more clear with the definition of the instrument. So, the definition of the final camera design is still in development and in this paper we want to show how the relaxation of some constraints has been translated into a very different approach of the optical design.

2 RELAXING TOLERANCES VERSUS REDUCTION OF THE OPTICAL ELEMENTS

Some of the scientific rationales that have driven the optical design of this planetary camera have remained unchanged during the study phase of the imaging facility. But the elusive nature of the cometary nucleus (ground based images are usually by far too poor to give any surface detail, and the only reliable images are the ones of the Halley's comet given by the HMC in the Giotto mission during its fly-by like approach) makes very difficult to give any firm statement about what is really expected by such a mission.

Two of the most important driving points, that is the wavelength coverage and the contrast attainable, appear to be very clear and on a sounder scientific basis. Thus, the choice of an all-reflective, unobstructed optical solution becomes a mandatory one: in fact the 10^4 requested contrast ratio between the nucleus limb illuminated by the sunlight and the faint gas emission rules out any sort of refractive and/or obstructed design.

However other important requirements from the optical point of view like the corrected, unvignetted Field of View (FoV) and the focal ratio of the camera, fixed at the very beginning of the study at some given figures, have been gradually changed during the several meetings that took place on the subject.

From an initial 18° × 18° FoV a more modest 12° × 12° one (on the same 2048 × 2048 pixel CCD) has finally been selected. Moreover, the recognition that the nucleus of the comet choosen as the target (namely the Wirtanen comet) was smaller than what was currently believed led to a twofold effects: the need of orbiting at larger distance to avoid navigation problems and the decrease of the apparent size of the comet itself. The focal ratio of the camera also increased from F/3.2 to F/4.8. In this case, the driving parameter was the minimum exposure time, a factor which depends on a number of aspects, including the attitude of the spacecraft (in order to reduce blurring of the image during exposure) and the full well of the CCD detector adopted at the focal plane.

These variations, however, becomes smoothly clear from a meeting to another, leading us to *tune* our current optical design rather than to re-design at each time a new optical concept. It is clear that an optical design able to meet the requirements for a given FoV and for a given F/ratio is also able to meet less stringent specifications, by cutting down the input pupil, and by cutting down the off-axis angles of the incoming rays. So, as a side effect, a number of problems linked with the original designs appeared to be more and more relaxed. One can list some of them:

manufacturability: the deviation of the mirrors from an osculating sphere becomes gradually lower and the feasibility of the mirrors used in the optical design correspondingly becomes easier;

baffling: since the FoV is shrinked, more room is allowed between the light beams coming from the mirrors and so more space becomes available for the baffling structures;

distortion: both the F/ ratio increasing and the FoV reduction positively affect this parameter;

encircled energy: mainly the F/ ratio increasing usually translates in a larger encircled energy into a given pixel size;

tolerancing: as a consequence of all the items here reported, a substantial relaxation of the optical tolerances can be derived.

However, during the relaxation of the constraint parameters, a natural question arose: *is it possible to drop one of the optical elements ?* In the classical Seidel-term approach it is assumed that each optical element controls a single Seidel distortion: thus, since coma, for example, is a typical field dependent term, it can be assumed that the elimination (or the great reduction) of a large FoV requirement reduces the need for a coma off-axis control and by consequence the optical element controlling it. However the correction of the Seidel's aberrations could be distributed among all the optical components and sometimes it is not clear which component has to be dropped. In all these cases, the need for a new design, or a new optical concept, is reached.

In the off-axis design, like the all reflecting and unobstructed ones, the problem is even more complicated: while it is clear that a pupil is located on one of the optical elements (usually not on the first surface) it is difficult to trace, even from a qualitative point of view, other answers. But as the F/ ratio increase translates into lower FoV independent aberrations, it is natural to think that such a case will produce as an effect to make the pupil optical elements simpler (that is, for example, changing it from an aspheric to a spherical one).

2.1 The case of WAC: from three to two mirrors

As a direct consequence of this qualitative approach and considering the original three mirror design[3] (a negative power first element, a nearly zero power secondary element, where the pupil is located, and a final third element with positive power) one can consider the following possibilities for the reduction from 3 to 2 mirrors:

1. to drop the first mirror (in this way the WAC design drops to an all-reflective Schmidt camera);
2. to drop the second mirror and to locate the stop somewhere in between the first (negative) and the second and last (positive) mirror;
3. to drop the third mirror and to co-add the power on the second and last mirror that becomes in this way a positive power element.

The first option leads to a well studied design, unable for our case, to satisfy the requirements and it is no longer considered here. The second one is just the starting configuration from which we produced the design for the 3 mirror camera: in fact we initially designed a relatively poor 2 mirror configuration with an intermediate pupil stop where, later, we added a correcting element. This option has been studied and several ray-tracing simulations have been run, but unfortunately the obtained optical performances were not really satisfactory. So, after a remarkable amount of ray-tracing optimization work, and including various stages of global optimization, the winning choice was the third one.

3 WAC OPTICAL CONFIGURATION

Following the previous considerations about the optical design constraints, the configuration shown in Fig. 1 has been obtained. The parameters of the optics are summarized in Tab. 2.

The system consists of two conic mirrors. The primary (M1) is an off-axis convex section of an oblate ellipsoid decentered with respect to the optical axis of 35 mm and its shape is squared (52×52 mm^2). It provides the

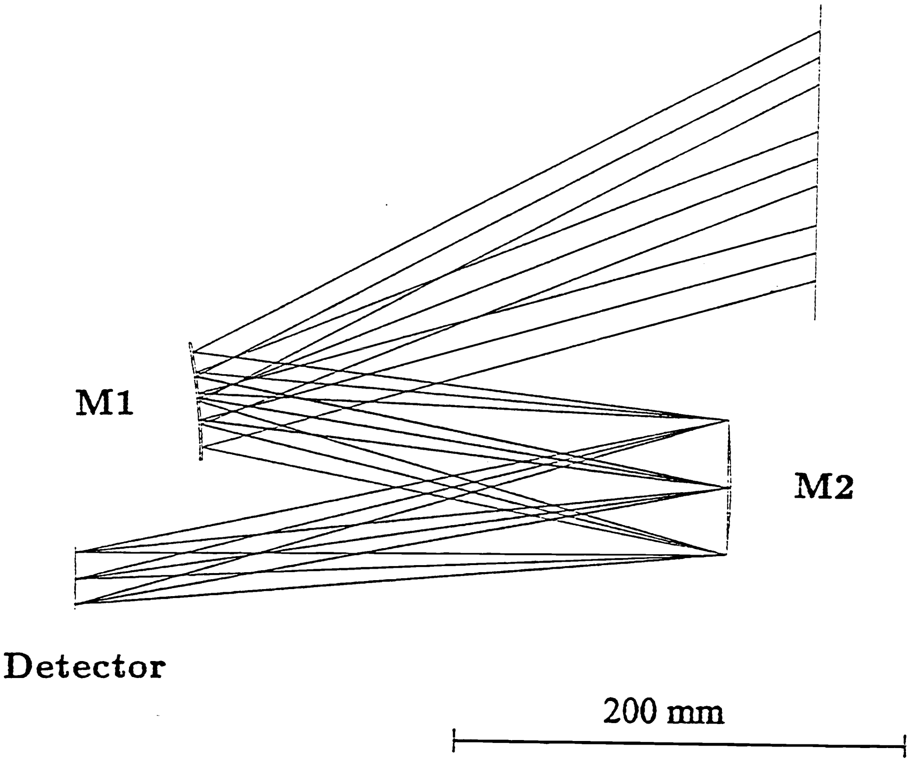

Figure 1: Schematic drawing of the WAC optical design.

	M1	M2
Mirror figure	convex oblate ellipsoid (off-axis section)	convex oblate ellipsoid (on-axis section)
Mirror shape	squared	circular
Mirror size	52×52 mm^2	$\phi = 60.3$ mm
Mirror area	27.0 cm^2	28.6 cm^2
Decentering	35 mm	—
Conic constant	5.39	0.17

Table 2: Mirror parameters of the WAC two mirror optical design.

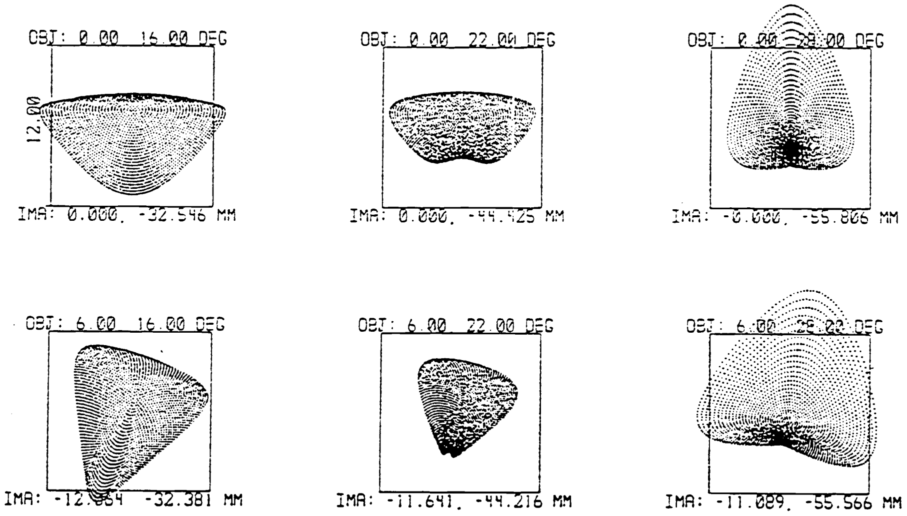

Figure 2: Performances of the WAC: spot diagrams for sources in half of the FoV.

collection of the light incoming from the astronomical target at an angle of 22° with respect to the mirrors common axis, and sends it onto the secondary mirror (M2) that is the real entrance pupil. The secondary mirror is an on-axis concave oblate ellipsoid of circular shape ($\phi = 60$ mm) which focuses the light on a plane placed behind M1; the distance between the focal plane and M1 is forced to be 55 mm, in order to satisfy some mechanical contraints. Finally, the focal plane is slightly tilted ($\approx 0.55°$) with respect to the mirror axis perpendicular plane, so obtaining a sensible improvement of the optical performances.

The strong conicity of M1 (≈ 5.4) imposes a particular care for the optical manufacturing of this mirror. The deviation from the best fit sphere is about 90 μm at the upper edge of the surface and for the interferometric testing of this mirror the introduction of a null lens set becomes strongly necessary. The M2 conicity is on the other hand very low (≈ 0.17) and no problem can arise for the procurement of this component.

This optical configuration provides the 90% of the Geometrical Encircled Energy within a single pixel (12 μm squared) over the whole FoV, fully satisfying the nominal 80% requirement: the obtained spot diagrams are shown in Fig. 2. Moreover, also the geometrical distortion of the camera has been evaluated obtaining a value of about 4%: since this is a relatively low value, it also possible to think to a backup operation way of this camera for navigation purposes.

Finally, this optical system is not telecentric and this aspect must be taken in account when the positioning of the camera filter wheel has to be considered: in fact, the filters must be placed perpendicularly to the principal ray in order to avoid degradation of the image optical quality.

4 THE ADD-ON SPECTROSCOPIC CHANNEL

The possibility of having an ultraviolet spectroscopic channel on the WAC was already described in a previous paper.[3] The general idea is to have a system which is simply an add-on option to the main camera, without interferring with or altering the performances of the latter. By means of this, it could be possible to study some important lines, like the ones produced by CO and CO_2 emitted in the 150-200 nm spectral range, emitted/absorbed mainly by the gases and vapours forming the coma and by the jets out of the nucleus.

In order to do this, several possible concepts have been considered, and the final adopted configuration is to deviate the focused radiation beam going out from the second mirror of the WAC by means of an insertable plane

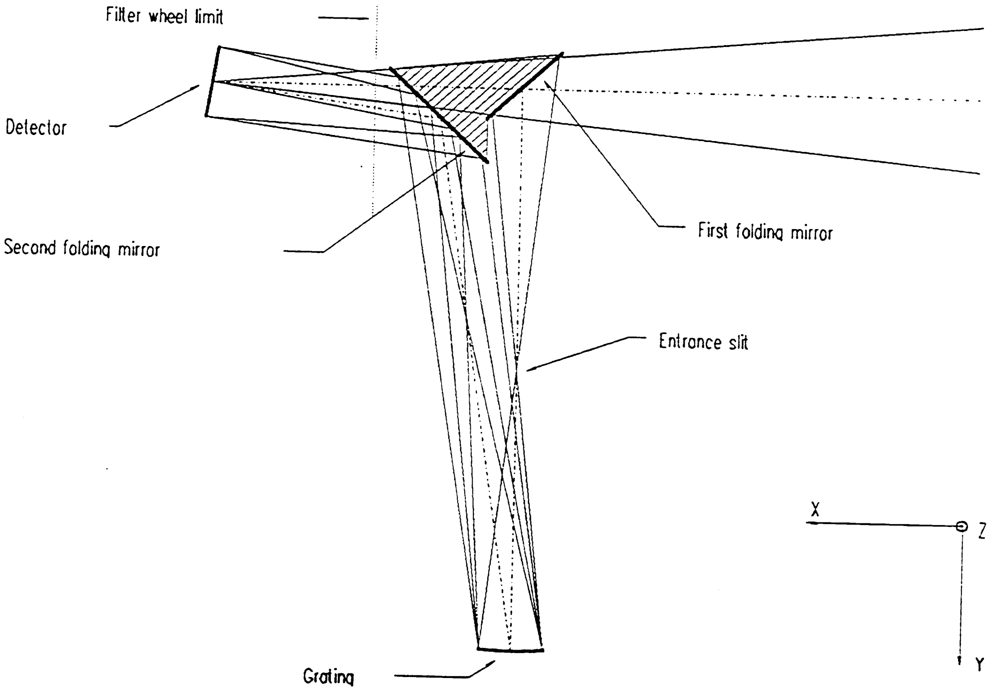

Figure 3: Schematic drawing of the WAC spectroscopic channel optical design.

folding mirror mounted on the filter wheel and to send it on the spectrograph entrance slit, so selecting only a "slice" of the whole FoV; the beam then enters a one element reflection spectrograph and finally the diffracted beam is sent on the camera detector by means of another plane folding mirror, also mounted on the filter wheel. A drawing of this optical configuration is shown in Fig. 3, where only the light beam coming from the second mirror of the WAC is shown for clarity.

The adopted optical concept for the spectrograph is based on the use of a concave toroidal grating, which is a well consolidated configuration to obtain a *quasi*-stigmatic spectrum.[4] Unfortunately, the proposed design with two folding mirrors imposes that the entrance and exit arms of the grating have very different lengths, and this means that it is not possible to work in the so-called on-Rowland configuration, which is the best way to reduce the optical aberrations.[5] So, in order to have the smallest aberrations, the possibility of varying the toroidal shape of the grating has been analysed: it has been obtained that with a furtherly aspherical surface, that is with corrective terms of the y^3 (coma) and yz^2 (astigmatic coma) type (y being the coordinate on the grating surface perpendicular to the ruling and z the one parallel to it) satisfactory results are obtained.

Another possible solution to reduce the amount of the residual aberrations is to holographically record on the (toroidal) grating surface a ruling pattern produced by the interference of a pair of properly aberrated wavefronts which permits to compensate the aberrations themselves. The optical performances in this case are similar to the ones obtainable by the just described optics.

The geometrical parameters of the proposed spectrograph configuration are summarized in Tab. 3.

The optical performances of this spectrograph are given in Fig. 4: it shows the detector sensitive area and reports on it respectively the values of the spectral and of the spatial resolution. They have been evaluated for a 12 μm × 12 μm slit element source in correspondance of several wavelengths of the spectrum (140 nm, 170 nm, 200 nm, 230 nm, 260 nm, 290 nm and 320 nm) and at different slit heights (0, 15', 30', 1° and 2°).

From an analysis of the reported data, it is evident that the spectrograph is optimal on the equatorial plane

	320 nm	290 nm	260 nm	230 nm	200 nm	170 nm	140 nm
2°	150	150	100	100	100	50	50
1°	300	250	200	200	150	150	100
30'	500	450	400	350	300	250	200
15'	700	650	600	500	500	400	250
0	1000	900	800	700	600	500	350
–15'							
–30'							
–1°							
–2°							

SYMMETRIC

	320 nm	290 nm	260 nm	230 nm	200 nm	170 nm	140 nm
2°	2'40"	2'40"	2'40"	2'40"	2'40"	2'50"	2'50"
1°	1'20"	1'24"	1'24"	1'28"	1'28"	1'28"	1'30"
30'	50"	50"	47"	44"	50"	50"	53"
15'	33"	29"	29"	29"	31"	33"	39"
0	23"	23"	23"	23"	21"	25"	33"
–15'							
–30'							
–1°							
–2°							

SYMMETRIC

Figure 4: Performances of the spectroscopic channel: the detector sensitive area is shown with the position values of the spectral (top) and spatial (bottom) resolution.

Incidence angle	$\alpha = 6.53°$
Stigmatic diffraction angle	$\beta = 1.47°$
Subtended angle on the grating	$\alpha + \beta = 8°$
Entrance arm	$p = 100$ mm
Exit arm	$q = 265$ mm
Magnification ratio	2.65 ($\Rightarrow$ 32 μm squared effective pixel)
Spectral range	140 - 320 nm
Stigmatic wavelength	$\lambda_o = 220$ nm
Grating ruling frequency	$1/d = 400$ grooves/mm
Grating surface	toroidal grating + coma and astigmatic coma corrective terms (or holographycally ruled)
Grating equatorial curvature radius	$R = 146.1$ mm
Grating sagittal curvature radius	$\rho = 144.7$ mm
Aperture	$f/4.8$

Table 3: Parameters of the WAC add-on spectroscopic mode.

of the optics: in fact, here both the spectral and the spatial resolution elements are of the order of three pixels, that is they are limited by the magnification of the entrance slit element size and not by the optical aberrations. The obtained spectral resolution $\lambda/\Delta\lambda$ is of the order of 1000 at the longest wavelengths, decreasing at 400 at the shortest ones; the spatial resolution is about 25" on the whole spectrum. Owing to this particular optical configuration which includes only one focusing element, both the spectral and spatial performances of the spectrograph decrease moving the source along the slit heigth, reducing themselves of about a factor 8 at the detector edges.

A characteristic of this spectroscopic channel is that it will be possible to choose, during the definition of the channel itself, what slice of the FoV is collected by the spectrograph entrance slit: this can be done by suitably selecting the position of both the first folding mirror and of the slit on the camera focal plane reported by the mirror itself. For example it could be better to collect a portion near one edge of the FoV: in fact, in the majority of the cases the camera will see the comet nucleus approximately at the center of the FoV; so to examine the cometary gas, it could be better to send on the spectrograph a portion of the FoV which does not include the nucleus itself.

5 CONCLUSIONS

An all-reflective, unobstructed and unvignetted optical design for a wide angle camera for space application has been described. Very good optical performances are obtained satisfying all the requirements of the Rosetta space mission for approaching a periodical comet. We have also shown how relaxing some scientific requirements a rather different optical configuration can be obtained.

Also the possibility of adding a spectroscopic channel to the camera is described. The optical design is such that this spectrograph does not require additional resources, because it is feeded by a plane mirror mounted on the camera filter wheel, and the spectrum is sent on the same CCD detector of the camera.

Thus, a rather complete and compact solution for a space instrument camera has been obtained: even if it has been designed for a specific application, it can be regarded as a more general purpose camera for planetary exploration, offering the possibility of analysing a wider spectral range than a simple refractive one.

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