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Optical design of a compact telescope for the next generation earth observation system

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Abstract—**High resolution earth observing systems need bigger and bigger telescopes. The design of such telescopes is a key element for the satellite design. In order to improve the imaging resolution with minimum impact on the satellite, a big step must be made to improve the compactness of the telescope.**

This paper describes the comparative study of several compact optical designs. This compactness increases drastically the sensitivity of the telescope. The optical designs, their sensitivity, their performances, the need to implement active optics are discussed.

Keywords- optical design ; optical concept ; telescope ; Korsch ; TMA ; catadioptric ; compactness

I. INTRODUCTION

A. Context

High resolution earth observing systems need bigger and bigger telescopes. The design of such telescopes is a key element for the satellite design. In order to improve the imaging resolution with minimum impact on the satellite, a big effort must be made to improve the compactness of the telescope. This will make it possible to keep the agility performances of the satellite and will make the launch less costly. The target is to launch with VEGA.

A high resolution telescope has been developed by CNES (French space agency) for Pleiades satellites. It has been launched on December 2011. CNES is now preparing the next generation optical system. Different studies and technological developments are going on. These activities are named «CXCI». The mission objective is to develop a 30cm resolution system to be launched in 2020-2022.

This optical study is part of CXCI activities lead by CNES. Very different optical designs have been studied. We present a selection of these solutions.

B. Optical requirements

The telescope characteristics are determined by the angular resolution goal, the image sensor hypothesis and the image requirements.

The CXCI concept is a push-broom system. The mission consists in covering a +/- 0.61° field of view with 30 cm ground pixels. The satellite altitude is 700 km. So, the angular resolution is 0.43 microrad.

Different image sensor hypotheses are done. It can be a two-dimensional array of pixels or a time delay and integration (TDI) device. For the two-dimensional array solutions, a 0.2° field of view, following the satellite track, is needed. The different image sensor hypothesis and the associated telescope characteristics are given in the following table:

TABLE I. IMAGE SENSOR HYPOTHESES AND ASSOCIATED TELESCOPE

image sensor	*Image sensor type*	*Pixel size*	*Telescope Clear aperture*	*Telescope F-number*
1	two-dimensional array	5.5 µm	1.5 m	8-8.5
2	two-dimensional array	5.5 µm	1.5 m	5.4
3	TDI device	13 µm	1.5 m	20

The optical MTF specification is to guarantee a 0.25 optical MTF at frequency corresponding to 30 cm on ground.

C. Optical design for CXCI

This paper describes the comparative study of several compact optical designs. Different apertures, from F/5.4 to F/20, and different concepts, TMA (Three Mirror Anastigmat), catadioptric and Korsch concepts have been studied and compared.

The compactness impacts the opto-mechanical sensitivity and the optical performances. Also, the need to implement active optics can arise. The different telescope concepts must be analyzed with care in order to choose the right configuration.

Different optical concepts are candidates for our system. For long focal length telescopes, the Korsch concept is the most common. The Pleiades telescopes are Korsch telescopes. We intend to compare the compactness and the opto-mechanical constraints of Korsch, TMA and catadioptric designs.

II. F/8 DESIGNS

A. F/8 Three Mirror Anastigmat

The TMA concept is well known for being very well suited to compact and wide field of view telescopes. As it is a catoptric system, the powered mirrors give the possibility to fold the optical beam and to compact the configuration several times compared to the focal length. This concept is also usually appreciated for its opto-mechanical tolerances and its un-obscured aperture.

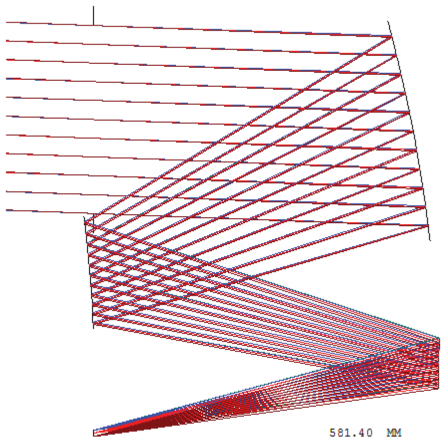

Figure 1. TMA design

Although the axial dimension is four times smaller than the focal length, the telescope volume is very big. In the off-axis direction, the dimension is more than twice that of the primary mirror. Moreover the secondary and tertiary mirrors are big. The focal plane position can be adapted by introducing a flat folding mirror.

The main characteristics of this TMA design are given in the following table.

TABLE II. OPTICAL CHARACTERISTICS OF THE TMA F/8 DESIGN

Optical characteristic	***Value***
Telescope Focal length	12 m
Primary / Secondary / Tertiary mirror f-number	3.4 / 4.4 / 23
Axial Primary / Secondary / Tertiary mirror magnification	4.5 / 5 / 1.5

The TMA design is diffraction limited all over the field of view.

B. F/8 Catadioptric telescope

The catadioptric concept is very interesting for its compactness. Even if a central obscuration is introduced, the secondary mirror and all the dioptric elements are centered in order to keep the optical beam in the axial direction.

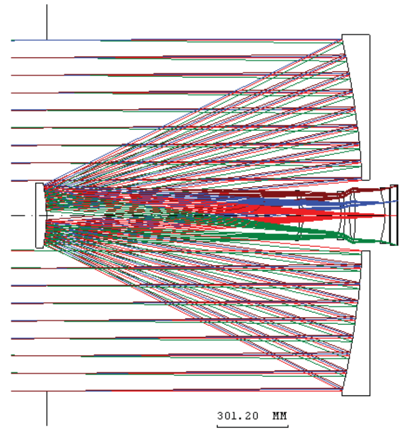

Figure 2. Catadioptric F/8 design

The field of view is radial. This design is extremely compact. The axial dimension is close to nine times smaller than the focal length. The radial dimension is that of the primary mirror aperture.

The main characteristics are given in the following table.

TABLE III. OPTICAL CHARACTERISTICS OF THE CATADIOPTRIC F/8 DESIGN

Optical characteristic	***Value***
Telescope Focal length	12 m
Primary / Secondary mirror f-number	1.6 / 2.4
Axial Primary / Secondary mirror magnification	23 / 26

If the main driver for the satellite design is the compactness of the telescope, this is a good candidate. Nevertheless, this is not the best optical design. Key optical performances have to be optimized : diffraction, chromatism, distorsion. Moreover a deep straylight analysis must be done. This concept is well known for the need of baffles on the primary and secondary mirrors and for the need of diaphragms in the dioptric subsystem. The obscuration will increase. The MTF performances will decrease.

C. F/8.5 Korsch telescope

The Korsch concept is well known for high resolution imaging systems. Pleiades satellite is operating with a Korsch telescope. These telescopes are classically designed for F-number close to F/20. Is it an interesting concept for F/8 telescope ?

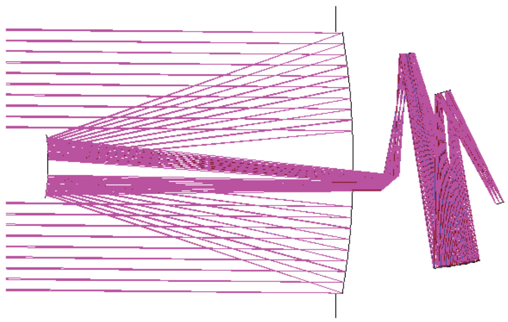

Figure 3. Korsch F/8.5 design

The compactness of this configuration is between that of the TMA and that of the catadioptric concept. The axial dimension is about five times smaller than the focal length. The back cavity is kept behind the primary mirror.

The main characteristics are given in the following table.

TABLE IV. OPTICAL CHARACTERISTICS OF THE KORSCH F/8.5 DESIGN

Optical characteristic	***Value***
Telescope Focal length	13 m
Primary / Secondary / Tertiary mirror f-number	1.5 / 1.9 / 3.9
Axial Primary / Secondary / Tertiary mirror magnification	30 / 31 / 2.2

This design is diffraction limited all over the field of view. This is a good candidate.

III. F/5.4 DESIGNS

A. F/5.4 TMA telescope

The TMA concept is very adapted for short focal length. It is interesting to compare the previous F/8 solution with a F/5.4 solution.

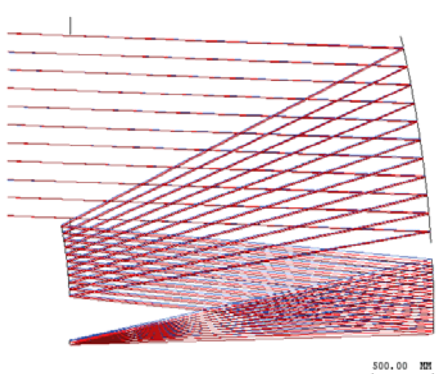

Figure 4. TMA F/5.4 design

The main characteristics are given in the following table.

TABLE V. OPTICAL CHARACTERISTICS OF THE TMA F/5.4 DESIGN

Optical characteristic	***Value***
Telescope Focal length	8.1 m
Primary / Secondary / Tertiary mirror f-number	3.2 / 3.2 / 5.4
Axial Primary / Secondary / Tertiary mirror magnification	2.5 / 2.5 / 1.0

The axial dimension is three times smaller than the focal length. The telescope volume is still very big. The secondary and tertiary mirrors are very big. The focal plane position should be adapted with the introduction of a flat folding mirror.

Compared to the TMA F/8 design, the compactness has been relaxed : both designs need the same volume though the focal length is 8.1m compared to 12 m.

B. F/5.4 Catadioptric telescope

For short focal length and two-dimensional field of view, the catadioptric solution can be an interesting solution. The powered back optics can easily focus the incident beam and adapt the telescope F-number. In our search for extreme compacity, this solution is worth studying.

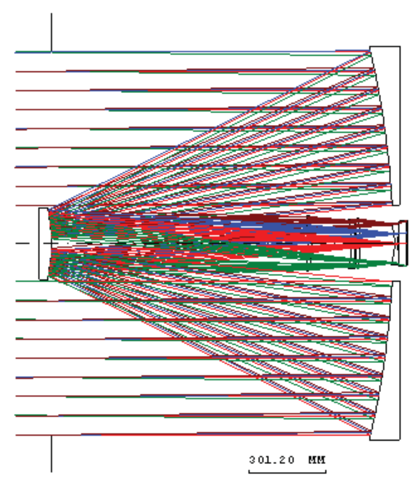

Figure 5. Catadioptric F/5.4 design

The main characteristics are given in the following table.

TABLE VI. OPTICAL CHARACTERISTICS OF THE CATADIOPTRIC F/5.4 DESIGN

Optical characteristic	***Value***
Telescope Focal length	8.1 m
Primary / Secondary mirror f-number	1.1 / 1.3
Axial Primary / Secondary mirror magnification	20 / 21

The axial dimension is more than five times smaller than the focal length. The telescope volume is very compact. This design is very close to the catadioptric F/8 design.

IV. F/20 Korsch Telescope

The Korsch concept is well known for being very compact and presenting optical key advantages for high F-number telescopes: little occultation, easy baffling, intermediate image, real exit pupil.

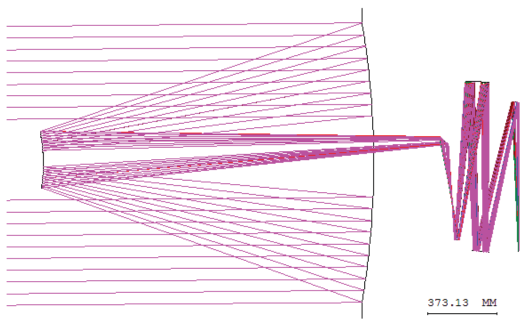

Figure 6. Korsch F/20 design

The axial dimension is more than eleven times smaller than the focal length. The back cavity needs several folding mirrors to keep the optical path behind the primary mirror.

The main characteristics are given in the following table.

TABLE VII. Optical characteristics of the Korsch F/20 design

Optical characteristic	*Value*
Telescope Focal length	30 m
Primary / Secondary / Tertiary mirror f-number	1.5 / 1.8 / 5.8
Axial Primary / Secondary / Tertiary mirror magnification	165 / 170 / 6.5

This Korsch design is diffraction limited all over the field of view. As expected, it is very compact. Both front and back cavities have been designed in order to optimize the telescope compactness.
The exit pupil is easily accessible, making the use of a folding pupil mirror possible.

V. Design Trade-off

A. Optical performances analyses

The optical MTF requirement is 0.25 at the frequency of interest. The angular frequency is the same for all the designs. Its value of 1.17 10^6 rad^{-1} corresponds to an instantaneous field of view of 30cm at 700km altitude.

For each design, we have to determine the corresponding opto-mechanical tolerances budget. Starting with a reference tolerancing budget, we calculate the scaled factor that guarantees this optical MTF performance.

The mechanical reference tolerancing budget for each mirror is

- 5 microns focus,
- 50 microns decentering,
- 50 microns tilt.

This factor is named α (alpha). The smaller α is, the smaller the tolerance budget is and the more stable the mechanical structure must be. Comparing the α of each design is an easy way to compare the sensitivity of the designs.

The main optical performances are given in the following table.

TABLE VIII. Optical performances synthesis

Optical performance	*TMA F/8*	*Catad. F/8*	*Korsch F/8.5*	*TMA F/5.4*	*Catad. F/5.4*	*Korsch F/20*
Optical Theoretical MTF (*)	0.39	0.31	0.33	0.38	0.33	0.34
α tolerancing factor	0.15	0.19	0.27	0.14	0.16	0.27
X distorsion	0.07%	7%	1.2%	0.04%	3.2%	0.9%
Y distorsion	0.03%	7%	1.0%	0.08%	3.2%	0.3%

(*) The optical theoretical MTF is the optical MTF performance before tolerancing. It is given for the angular frequency 1.17 10^6 rad^{-1}.

The TMA and catadioptric designs have to cope with a demanding α tolerancing factor because of their unusual compactness. The tolerances of the Korsch solutions are easier even if still challenging. A sensitivity study is detailed in chapter C.

The optical distortion is very low for TMA designs. This is a classic advantage of TMA designs. It is acceptable for the Korsch designs. It must be optimized for catadioptric designs. This exercise has not been done in the frame of this study.

B. Design trade-off

The detailed comparison of the different designs is given in the following table.

TABLE IX. Design trade-off

	TMA F/8	*Catad. F/8*	*Korsch F/8.5*	*TMA F/5.4*	*Catad. F/5.4*	*Korsch F/20*
Compactness	☹	☺	☺	☹	☺	☺
α tolerancing factor	😐	😐	😐	😐	😐	😐
Distorsion	☺	😐	☺	☺	😐	☺
Telescope mass	😐	😐	☺	😐	😐	☺

The choice of the Korsch solutions seems natural. Nevertheless, if the compacity goal should be extremely important, the catadioptric configuration could be chosen.

For all the designs the α tolerancing factor will be hard to cope with.

C. Compactness impact

Considering the F/20 Korsch design, we intend to compare different configurations in order to quantify the impact of compactness on the opto-mechanical tolerances requirements.

The driver for our different designs is the aperture number of the primary mirror. Compactness of the telescope is directly coupled with low aperture number.

The following F/2, F/1.5 and F/1 primary mirror Korsch configurations have been designed.

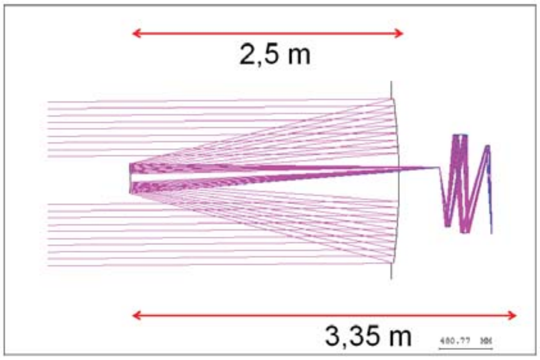

Figure 7. Korsch design with F/2 primary mirror

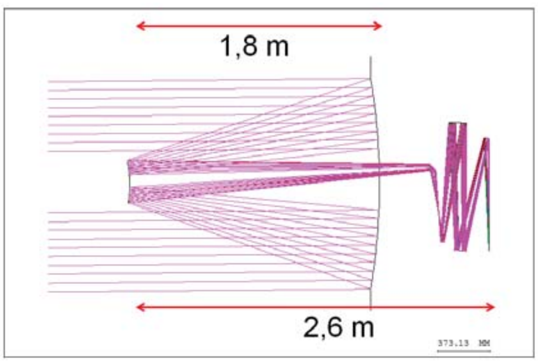

Figure 8. Korsch design with F/1.5 primary mirror

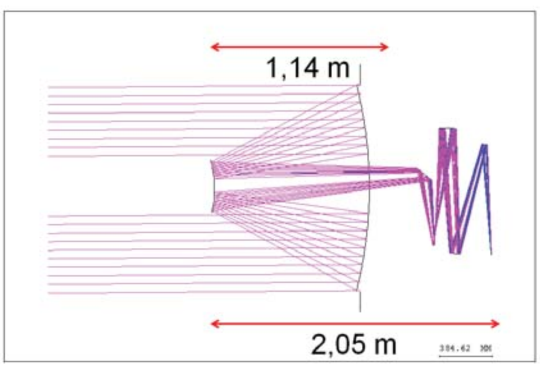

Figure 9. Korsch design with F/1 primary mirror

For these configurations, the back cavity is very similar. The main change comes from the front cavity axial dimension.

The comparison of the main optical characteristics and performances is summarized in the following table.

TABLE X. OPTICAL CHARACTERISTICS AND PERFORMANCES

	F/2 primary mirror	***F/1.5 primary mirror***	***F/1 primary mirror***
M1 f-number	2.0	1.5	1.0
M2 f-number	2.5	1.8	1.2
M3 f-number	6.8	5.8	4.6
Axial M2 magnification	96	170	381
Axial M3 magnification	5	6.5	12
α tolerancing factor	0.45	0.27	0.10
X distorsion	1.2%	0.9%	0.7%
Y distorsion	0.4%	0.3%	0.26%

This sensitivity study points out how important the front M1-M2 cavity is for the compromise between compactness and opto-mechanical tolerances. The α tolerancing factor is approximately proportional to the square ratio of the distance between primary and secondary mirror or to the square ratio of the primary mirror F-number.

The opto-mechanical tolerances budget is really small for these extremely compact configurations. The compactness is mainly achieved thanks to the compactness of the M1-M2 collecting cavity. This is obtained with the decrease of the primary mirror F-number.

The gain in telescope size must be balanced with the increase in both tolerance requirements and manufacturing complexity. Considering all these parameters, the choice of the F/20 Korsch with F/1.5 primary mirror is done.

VI. CONCLUSION

In the frame of CXCI high resolution activities, a comparative study has been done to choose the best concept for a compact optical telescope. The Korsch concept is fully satisfactory considering its optical performances and its compactness. It is diffraction limited and more than ten times shorter than the focal length.

The opto-mechanical tolerances are very challenging. We need to implement active optics in order to guarantee mechanical mirror stability within 1 micron focus, 10 microns decentering and 10 microns tilt for each mirror.

CNES CXCI program is going on with technical studies and developments. The next generation telescope will be extremely compact and it will be active.

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