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Innovative focal plane segmentation for high-resolution planetary-observation

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ABSTRACT

As of today, Earth and planetary high-resolution observations rely on linear focal plane arrays used in TDI mode to acquire images delivered by the telescope. To both reach high angular resolution and keep a large field-of-view, homothetic imaging systems as used in Pleiades satellites or Mars Reconnaissance Orbiter [1] would lead to prohibitive linear focal plane dimensions. Reducing this parameter would therefore allow for a significant decrease in the size of space optical systems.
The solution described in this paper intends to optically reduce this dimension by segmenting the linear FOV into smaller sub-fields that are stacked on a CMOS TDI sensor. It is therefore possible to drastically reduce the linear size of the array, at the expense however of a small increase in terms of complexity of the optical system.

Keywords: Optical design, High-resolution, Earth-observation, Focal Plane, Freeform.

1. INTRODUCTION

To solve this "resolution vs. field-of-view" issue, the proposed solution intends to subdivide the linear field-of-view of a usual Korsh telescope with what we call a *slicing unit*. This unit comes right after the Korsh's focal plane, segments the linear 1D image and re-images it on a 2D array detector, allowing for both wide-field and high-resolution imagery in a smaller volume. The image quality and packaging constraints as well as the inherent tilts and decenters of the system force us to implement freeform mirrors into the design. A preliminary feasibility study has been conducted by Wilfried Jahn during his PhD thesis [2], showing that reaching the diffraction limit is possible for a few modules of the unit, while at the same time allowing for a 17x reduction of the focal plane size. The work described hereon extends the results to the whole field-of-view while considering space limitations.

1.1 Current technology

The French state of the art of high-resolution Earth observation technologies can be found in the Spot and Pléiades satellites [3], which deliver sub-meter ground images while boarding focal plane arrays a few decimeters wide. This is achieved by using folding mirrors *inside* the focal plane - while this size is acceptable, next generations of high-resolution imagers cannot rely on this specific technology to continue increasing their resolution.

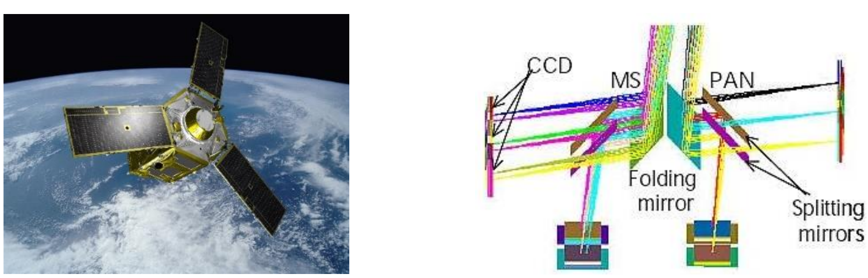

Figure 1. The Pléiades satellite and its focal plane array. The use of multiple folding mirrors to reduce the size of the image greatly complexifies the focal plane and its integration.

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1.2 Proposed solution

The solution brought by LAM is based on its expertise on Integral Field Units, with image slicers, for spectro-imaging in Astrophysics [4]. Now studied in a mission-like scenario with Thales Alenia Space, it intends to optically reduce this dimension by segmenting the linear FOV into smaller sub-fields that are stacked on a CMOS TDI sensor; the array is this way more compact. This is done at a small expense in terms of the optical system's complexity and of surface shapes, as the use of freeform optics become mandatory.

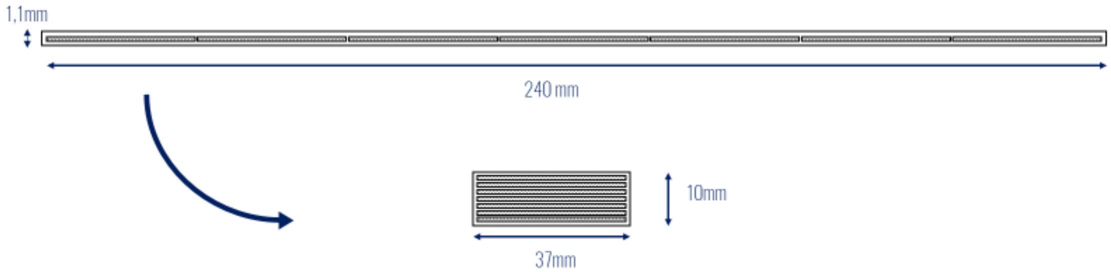

Figure 2. Segmentation solution described in this paper. The values (not scaled) are extrapolated from a hypothetic high-resolution Earth-observation mission.

2. DESIGN SPECIFICATIONS

2.1 Focal plane array

TDI versions of CMOS detectors are currently developed at various places in the world [5] [6] [7]. The detector we choose for our study is a multi-spectral CMOS TDI sensor that we virtually divided in 7 segments (called *modules*), each one being sub-divided in 5 spectral bands, allowing for multi-spectral and panchromatic imaging. The modules, corresponding to sub-fields, are isolated from each other by a 50-pixels blank band.

Figure 3. Schematics of the detector used in our design.

2.2 Mission specifications

Our case study is a mission configuration that can be either a hypothetic high-resolution Earth-observation mission or a future high-resolution planetary mission in the solar system. The high-level specifications for this hypothetical mission are presented in Table 1.

Table 1. General specs of the hypothetical mission.

IMAGE SPEC	VALUE
Number of sub-images (modules)	7
Overlap between modules	> 50 pix
Nominal MTF at Nyquist	> 0.15 @ 632.8 nm

The specs of the ground-images are derived from the Pléiades satellites, and slightly updated to simulate some of the needs of next generations of high-resolution spatial telescopes.

The point is not to demonstrate that we can do much better - because we can - but to prove that it is possible to segment the FOV into smaller sub-fields and still reach the diffraction limit across the whole image. This implies the following characteristics for the telescope:

Table 2. Telescope characteristics of the hypothetical mission.

TELESCOPE SPEC	VALUE
F number	N = 12.5
FOV	Y = 1.5°
Optical structure	All-reflective Korsh + Slicing module

- The focal length has been chosen as a reference: the performances can therefore easily be compared to those of other telescopes in terms of image quality, global size and complexity.
- The F/number has been chosen relative to the alignment process, in terms of radiometry, FTM and tolerances sensitivity.

3. RESULTS

3.1 Optical layout and mirrors' characteristics

In this first study the whole optical system is divided in two parts : {Korsh telescope + slicing unit}. This is due to an AIT (*Assembly, Integration & Tests*) trade-off : this way, the two parts can be integrated and aligned independently. A second version is currently under study, with the slicing unit and Korsh telescope integrated, allowing optimization of a simpler global system with better performances - but at the expense of a new philosophy for the AIT phase.

As the slicing unit is becoming a part of the whole system, its characteristics impact the one's of the Korsh telescope. Following Jahn's parametric study and in order to facilitate the design, the unit's magnification has been chosen to be 1.

Korsh telescope:

The Korsh is first optimized independently to the diffraction limit across the whole field. Bearing in mind the alignment process, the distances and radii of curvature are constrained to reduce overall sensitivities. The bulk of the system is known to be high, but as the Korsh is not part of the study, the sensitivity overrules the size.

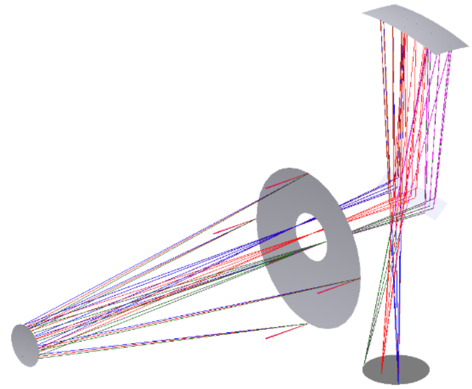

Figure 4. The Korsh telescope is first optimized, then frozen.

Slicing unit:

Once this is done, the slicing unit is constructed step by step:

- General positioning of the two sets of mirrors, all centered and spherical, while paying attention to the bulk of the system: the unit shall fit in the Korsh's footprint.
- First round of optimization using only conics, to set up the system and have an approximate location of the sub-images (modules) on the detector plane.
- Freeze of the whole system and modification of the unit's surfaces type to Zernike Polynomials. Gradual incrementation of the number of Zernike, one module at a time to greatly reduce the number of variables (which improves the convergence of the optimization) : when a module is optimized, it is frozen and the next one is considered.

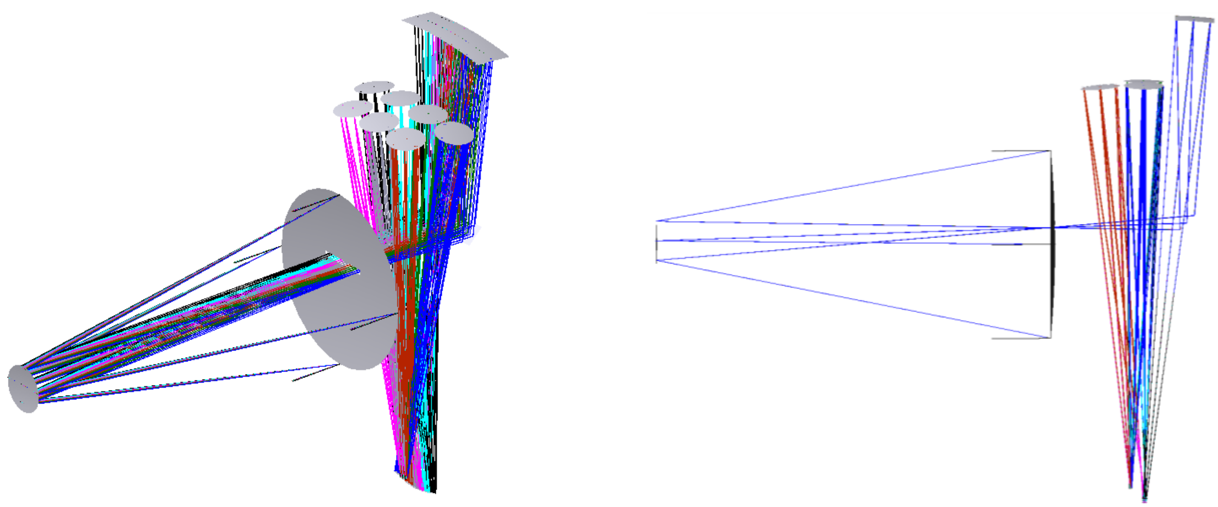

Figure 5. The whole system in its final configuration. The slicing unit is entirely fitting in the Korsh's footprint

Special attention is given to the second mirror set: they shall not overlap, otherwise parts of the beams would be obstructed while having a small overall lateral size.

3.2 Optical performances

The seven linear sub-FOVs are now stacked on the different modules defined on the image sensor, allowing for a drastic reduction in the linear size of the array.

For the slicing unit, Fringe Zernike up to the 5th order on the first mirrors set and 4th order on the second mirrors set have been used. This is due to the proximity of the first set to the Korsh's image: this set geometrically contributes less to the overall aberrations correction.

The image quality for the seven linear sub-FOV are listed below:

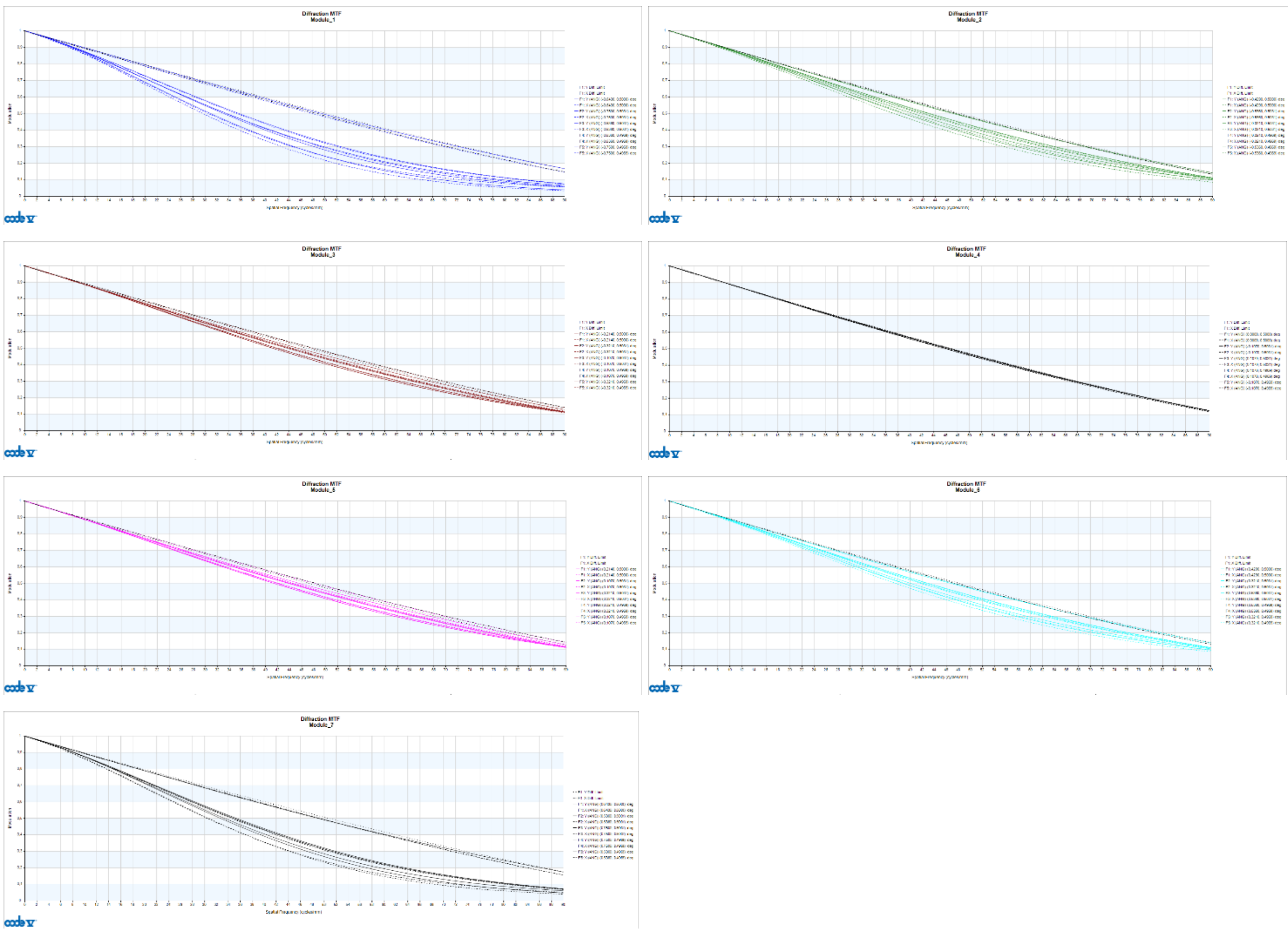

Figure 6. MTF charts of the 7 linear sub-FOV up to the Nyquist frequency.

As expected, the image quality deteriorates on the sub-FOV at the edge of the field. Residual aberrations remain: mainly coma and astigmatism, which will be corrected more precisely in future designs. Looking at the spot-diagrams gives another insight about the image quality, as shown in figure 7 :

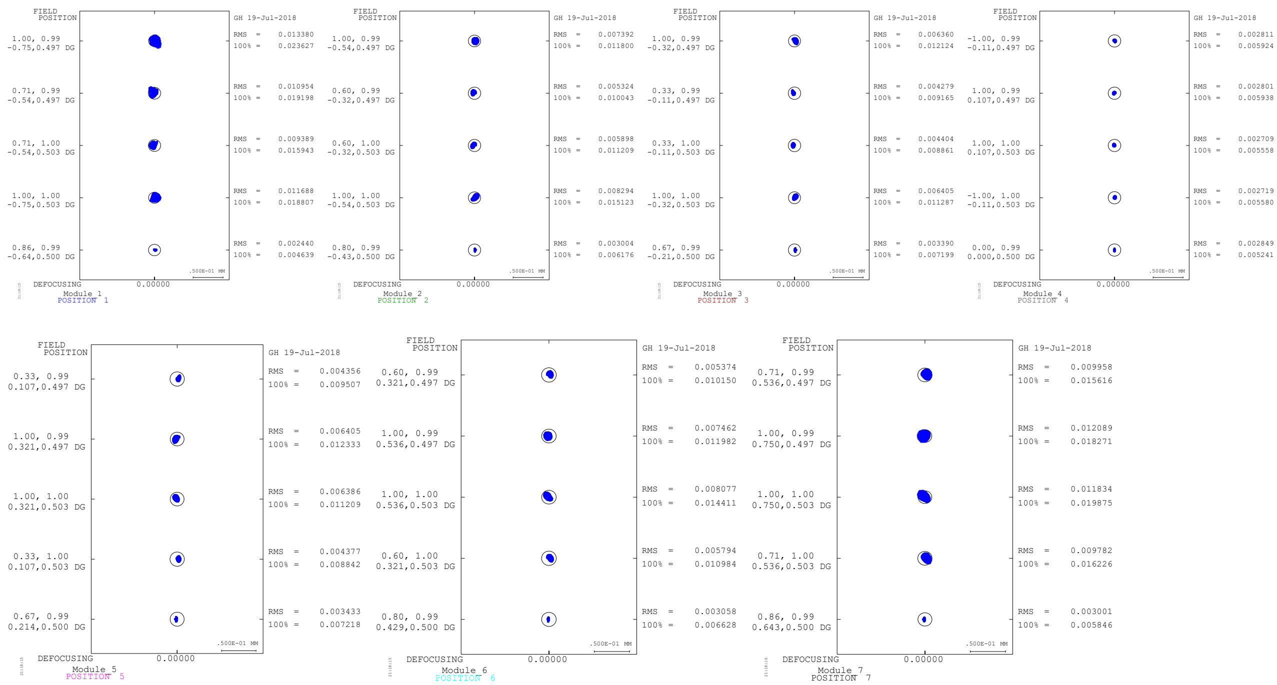

Figure 7. Spot-Diagrams of the 7 linear sub-FOVs on top of the Airy Disks.

The consistency in image quality that we reached across the seven sub-FOVs is a critical parameter in high-resolution observations : the ground images shall deliver the same standards of information whether it's at the center or at the edge of the field.

4. CONCLUSION

Recent progresses in optical manufacturing and testing allow for the design of gradually more complex systems: the gains in image quality and size reduction, which are critical for space applications, are unprecedented. We take plain advantage of this new optimization space with freeform surfaces, defined as Fringe Zernike surfaces. Using the herein described method, we segment the linear FOV of a usual Korsh telescope into smaller images stacked on a CMOS TDI sensor.

As of now, the image quality almost reaches the diffraction limit across the whole field. All in all, results obtained with CodeV show very promising perspectives, with possible improvements in the following fields :

- Use of new freeform optimization methods [8] to greatly reduce the number of Zernike terms in the surfaces descriptions
- Exploration of other optimization methods
- Exploration of new configurations: different spatial positionings of the mirrors sets

Compared to the example of the Pléiades mission, our focal plane is drastically simpler and smaller : this opens new and exciting perspectives for the future of high-resolution Earth and planetary missions.

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