COMPACT MULTISPECTRAL AND HYPERSPECTRAL IMAGERS BASED ON A WIDE FIELD OF VIEW TMA.

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INTRODUCTION

Three mirror anastigmat (TMA) telescope designs [1] had been implemented in different projects ranging from the narrow Field-Of-View large instruments as Quickbird (2° FOV) [2] to smaller telescopes as JSS 12° FOV developed for RapidEye mission [3].

This telescope configuration had been also selected for the PROBA-V payload, the successor of Vegetation, a multispectral imager flown on Spot-4 and subsequently on Spot-5 French satellites for Earth Observation and defence. PROBA-V, small PROBA-type satellite, will continue acquisition of vegetation data after the lifetime of Spot-5 expires in 2012.

The PROBA-V TMA optical design achieves a 34° FOV across track and makes use of highly aspherical mirrors. Such a telescope had become feasible due to the recently developed Single Point Diamond Turning fabrication technology. The telescope mirrors and structure are fabricated in aluminium and form an athermal optical system.

This paper presents the development of the compact wide FOV TMA, its implementation in PROBA-V multispectral imager and reviews optics fabrication technology that made this development possible. Furthermore, this TMA is being used in combination with a linear variable filter in a breadboard of a compact hyperspectral imager. Moreover, current technology allows miniaturization of TMA, so it is possible to use a TMA-based hyperspectral imager on a cubesat platform.

DESCRIPTION OF PROBA-V INSTRUMENT

The PROBA-V main mission requirement is to provide data continuity with the Spot V vegetation payload (VGT). Due to the platform constraints this requires a design based on a much smaller instrument concept. The main differences between PROBA-V and VGT are shown in the following table:

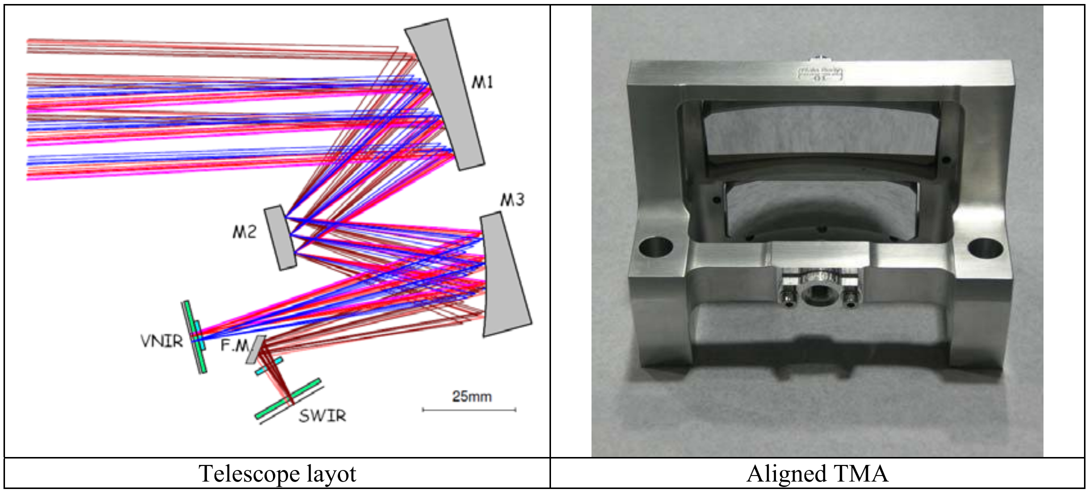
Table 1 – Comparison of the PROBA-V and Spot VGT instrument budgets

Parameter	**Spot VGT**	**Available for PROBA-V**
Power consumption	200W	~30W
Volume	700x1000x1000 mm3	200x800x500 mm3
Mass	152 Kg	~25Kg

The instrument, which is a push-broom multispectral imager composed of the three separate spectral imagers, is orbiting the earth in a sun-synchronous orbit at 820km altitude. Each of these spectral imagers is based on a large FOV TMA of 34.6°. By combining the three TMA's, it is possible to obtain an overall FOV of 102.6° corresponding to a swath width of over 2250km.

Each of the TMAs is equipped with a VNIR sensor with 5200 pixels of 13μm. This enables to acquire images with a ground sampling distance of 100m at nadir, and just over 300m at the edge of the FOV. This is an improvement with respect to the 1 km GSD of the VGT sensor.
The VNIR is equipped with a multispectral window which enables to acquire images at the above stated resolution with the following wavelength bands:
- Blue band: 463nm – 46nm FWHM
- Red band: 655nm – 77nm FWHM
- NIR band: 843nm – 127nm FWHM

In addition, a SWIR sensor with a spectral window is added to the focal plane of each of the TMA's to acquire image data at a wavelength 1600nm with FWHM of 75nm. The pixel size of the SWIR detector is 25μm, nearly twice the pixel size of the VNIR detector. Therefore the ground sampling distance in the SWIR channel is twice as large: nearly 200m at nadir, and over 600m at the edge of the FOV.



Telescope layot | Aligned TMA

Fig. 1. PROBA-V TMA telescope layout.

PROBA-V is currently in the Critical Design Review of the Phase C/D. The prime contractor of the mission is QinetiQ Space, OIP is responsible for the instrument and AMOS is responsible for the manufacturing and alignment of the telescope.

The entire telescope is an athermal design made of the same aluminium material. The mirrors quality is achieved by SPDT and the alignment rely on the very precise matching of the mirrors with the mounting structure.

A breadboard of the TMA has been already built to prove the manufacturability of the mirrors and the alignment concept (see Fig. 1). The alignment of the telescope at AMOS was reached in few days and the optical quality achieved was better than the original estimates based on the tolerance analysis as shown in Fig. 2.
One of the key elements for the performance of the instrument is the mirror roughness which has to be limited as much as possible to reduce in field straylight and MTF degradation. The values obtained for the breadboard mirrors are within 3÷4 nm rms to be compared with a requirement of 6 nm rms.

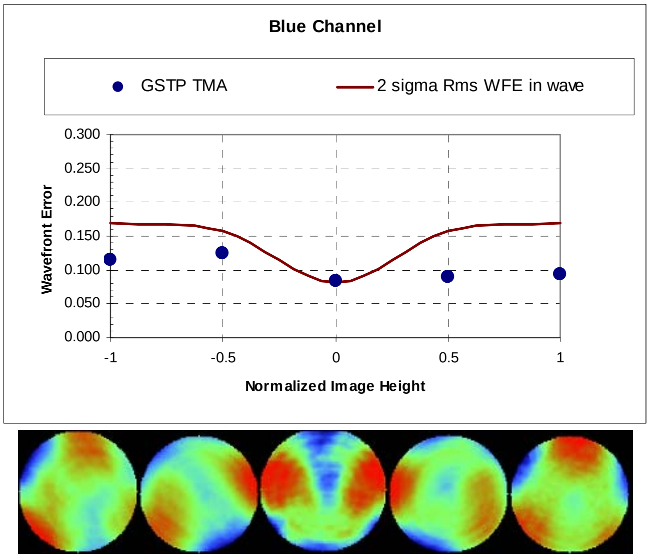


Fig. 2. Interferometric maps and WFE of TMA telescope compared with prediction based on tolerance analysis.

IMPROVEMENT OF MIRROR ROUGHNESS

One of the main limitations of the aluminium mirrors obtained by SPDT is the surface roughness. Due to the material structure it is very difficult to obtain a roughness lower than 5 nm rms without nickel plating.
The use of nickel plating complicates the manufacturing because an additional process is needed and also because after SPDT the mirror usually requires a post polishing. Moreover, for some instruments working in cryogenic environments or with high thermal loads the use of nickel can be an issue due to bimetallic effects.
An ESA GSTP study with TNO is currently in progress to understand the limits of the SPDT of aluminium alloys without nickel plating.

The study is focused on alloys obtained by rapid solidification processing. Rapid solidification processing (RSP) is a melt-spinning technique for producing alloys with very high cooling speeds up to 10^6 K per second, providing ultra fine and homogeneous microstructures. After rapid solidification the ribbon is chopped to very fine particles of size ranging from 3 x 2 x 0.1 mm^3 to 0.1 x 0.1 x 0.1 mm^3. These are collected in a vessel after which it is compacted to form the billit (consolidation). This billit can be processed further, e.g. extrusion or forging. Extrusion and forging lead to specific sizes and it results in the final very fine RSA structure.

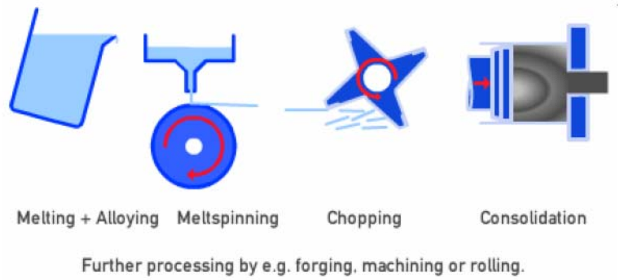
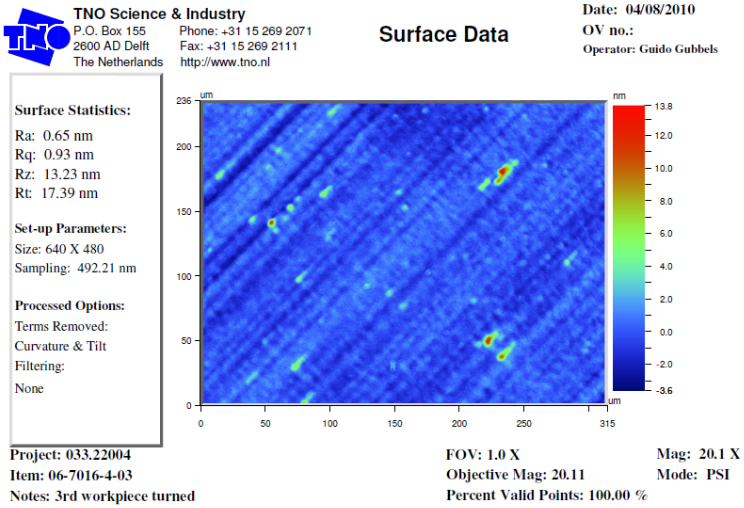


Fig. 3. Schematic representation of Rapid Solidification Processing (RSP) of an alloy.

Currently only one supplier is worldwide available that manufactures rapidly solidified aluminium: RSP Technology B.V. in Delfzijl, The Netherlands (part of the Hittech Group).

Preliminary results on flat mirrors RSA-6061 showed that optimising the thermal treatment of the material and the turning process a surface roughness lower than 1 nm rms can be achieved. The same quality needs to be confirmed on aspherical mirrors but the results achieved are already very important because they demonstrate that the aluminium material is not anymore the main limitation.



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Surface Data

Date: 04/08/2010
OV no.:
Operator: Guido Gubbels

Surface Statistics:
Ra: 0.65 nm
Rq: 0.93 nm
Rz: 13.23 nm
Rt: 17.39 nm

Set-up Parameters:
Size: 640 X 480
Sampling: 492.21 nm

Processed Options:
Terms Removed:
Curvature & Tilt
Filtering:
None

Project: 033.22004
Item: 06-7016-4-03
Notes: 3rd workpiece turned

FOV: 1.0 X
Objective Mag: 20.11
Percent Valid Points: 100.00 %

Mag: 20.1 X
Mode: PSI

Fig. 4. Microroughness measurement of SPDT flat mirror (0.9 nm rms).

FURTHER DEVELOPMENTS – HYPERSPECTRAL IMAGING

The hyperspectral imagery data is a source of a wealth of information [4], which had prompted for use of hyperspectral sensors onboard of satellites. The examples include CHRIS and Hyperion instruments currently operating in orbit and Prisma, EnMap and HyspIRI instrument planned for launch in the near future.

Typically, the hyperspectral imagers are relatively large and expensive instruments with a narrow Field Of View (1^{o} – 2^{o}) and ground resolution ranging from a few meters to several tens meters. With such a narrow FOV the instruments are not able to provide global coverage on a daily basis.

The advantages of the TMA described above such as large FOV and telecentricity in the image space can be exploited further to develop a low cost and compact hyperspectral imager. The hyperspectral imaging is achieved with the strip detector arrays covered by bandpass wavelength filters replaced by a 2D large detector with a linear variable bandpass filter. This idea is illustrated in Fig. 5.

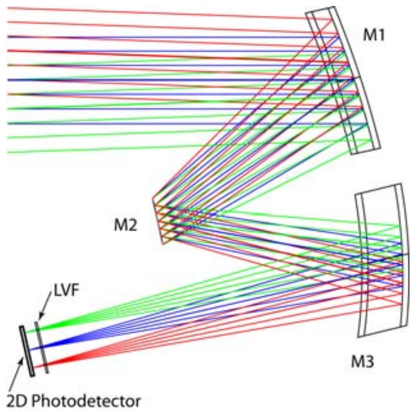
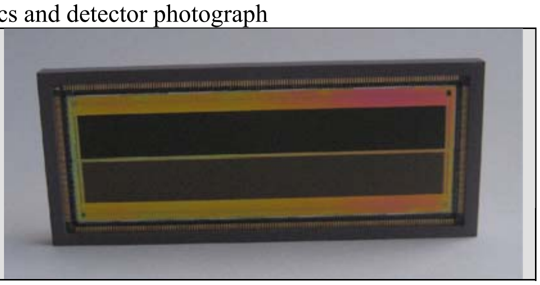


Fig. 5. TMA-based hyperspectral imager. The 2D photodetector array and a Linear Variable Filter in the focal plane enable hyperspectral pushbroom imaging.

The breadboard of this instrument is currently being developed by AMOS and makes use of the PROBA-V telescope, large detector array developed by Cypress for MEDUSA [5] and LVF fabricated by Selex-Galileo.

The detector is a 1200x10000 pixels CMOS image sensor with a pixels size of 5.5x 5.5 μm^{2}. The main characteristics of the sensor are reported in Table 2.

Table 2 - Detector Characteristics and detector photograph

Parameter	Specifications	
Pixel Architecture	6 transistor pixel	
Pixel Size	5.5 μm x 5.5 μm	
Format	10000 x 1200 (each detector)	
FWC	> 30000 e-	
Dark Current	600 e-/s @ 20 °C	
Operational Temperature	-70 °C ÷ 70 °C	

The linear variable filter (LVF) is a fused silica plate coated with an interference filter with increasing thickness in along-track direction. The peak of the transmission curve varies with the thickness of the deposition. This implies that all detector pixels in a row across-track receive information in the same spectral channel. The detector pixels in the along track rows receive information in different spectral channels, and the closer pixels to each other, the less difference between the corresponding spectral channels. Thus, in principle, the total number of spectral channels is equal to the number of pixels in an along track detector row covered by LVF. The filter used in the breadboard described in this article has operating spectral range 450 nm – 900 nm, FWHM spectral resolution of less than 15 nm and gradient of the peak transmission wavelength of 60 nm/mm.

The instrument spectral resolution, operating spectral range and spatial resolution are comparable with the characteristics of other instruments [6], while the coverage is larger, physical dimensions and potential cost of the instrument are smaller as compared to respective parameters of those hyperspectral sensors.

The main limitation of this instrument is SNR which is in the range 10 – 20 (for the 3 ms integration time) as predicted by radiometric analysis. This is significantly lower than the SNR of high-performance instruments. The SNR could be increased further with the LVF filter of higher transmission. Irrespective to the possible improvements of LVF, the instrument can be considered to serve applications requiring fast detection of anomalies, for which SNR of about 20 is enough. For such applications the coverage and size advantages of the instrument would be paramount.

FURTHER DEVELOPMENTS – MINIATURIZATION

The recent developments in small satellites like Cubesats with the typical dimensions of the order of tens centimetres indicate a need for payloads that could fit in such a small volume. An extremely compact hyperspectral/multispectral imager can be a potential candidate for Cubesat missions, and the optical technology validated in the manufacturing of PROBA-V instrument can be used to produce such an imager.

The design of the telescope stems from a miniaturisation of the ProbaV TMA to accommodate the payload inside a Cubesat unit. The dimensions of the miniaturized TMA (excluding the external baffle) fit into the envelope of 45x25x45 mm^3. The parameters of the mirrors are given in Tab. 3 and distances between the different optical elements are given in Tab. 4.

Table 3 – Parameters of the telescope mirrors

	Curv. radius (mm)	Conic cst	4th order asph coeff (mm^{-3})	6th order asph coeff (mm^{-5})	8th order asph coeff (mm^{-7})	Aperture (mm^2)	Y offset (mm)
M1	94.697 CC	-4.431	1.14E-7	-4.073E-10	3.566E-13	36.0 x 9.0	4.635
M2	34.688 CX	0				4.5 x 4.5	0
M3	50.524 CC	0.431	4.105E-7	1.512E-11	1.702E-13	43.2 x 9.0	-12.15

Table 4 – Distance between the optical elements of the miniaturized telescope.

	Distance [mm]
M1 – M2	15.556
M2 – M3	19.976
M3 – Focal plane	39.784

The mirrors and the telescope structure are supposed to be made of the same material (aluminium), implementing the concept of quasiathermal design as in PROBA-V.

However, the three TMAs on PROBA-V with the total FOV of 104° can not be scaled down to fit in the Cubesat. Therefore, an effort has been done to increase the field of view of the telescope from 34° to 50° obtaining larger swath coverage. This requires launching of two satellites to cover the same swath as PROBA-V, but still it is a very cost-effective solution taking into account the costs of a Cubesat.

The wavefront error map of the nominal design for the 0° field of view (nadir looking) is shown in Figure 5. RMS values as a function of the across track FOV are also plotted in Figure 5. The WFE is 20 nm rms on axis ($\lambda/30$ rms) and increases rapidly for the fields of view larger than 22° to a maximum value of 89 nm rms ($\lambda/7$ rms). As a general conclusion, it can be stated that the optical performances of the telescope are quite good and in line with already existing hyperspectral imagers.

The robustness of the proposed design had been assessed performing the analysis of sensitivity to alignment and manufacturing tolerances. For this analysis the similar alignment and manufacturing tolerances values of the PROBA-V telescope had been considered. Some tolerances have been tightened with respect to PROBA-V specifications (in blue in Table5). These values are considered feasible, based on the past experience of AMOS, the company that is in charge of the manufacturing and alignment of the PROBA-V telescope. Also radiuses of curvature and conic constant tolerances are estimated from AMOS background (in grey in the same table). The complete list of values is presented in Table 5.

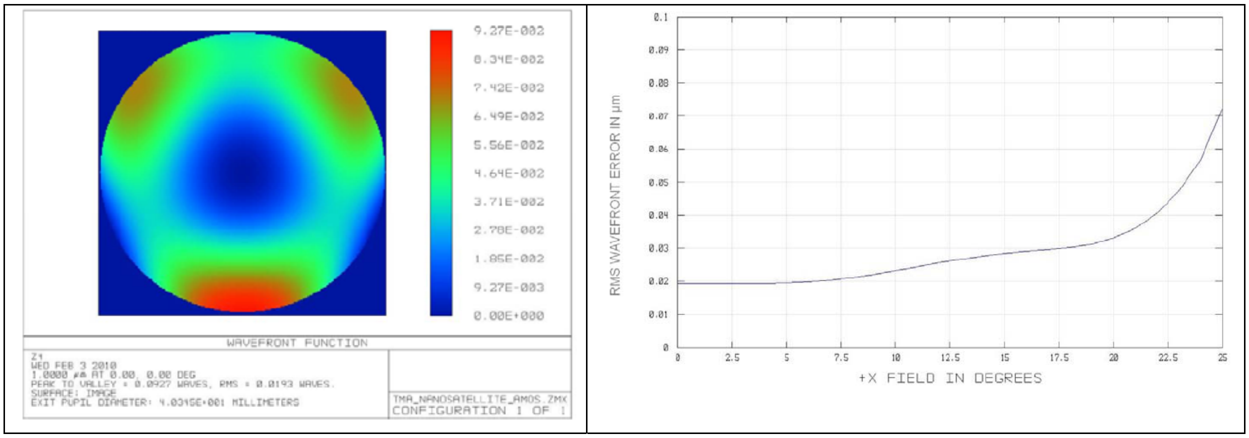


Fig. 5. WFE of the telescope nominal design for zero FOV

Table 5. Tolerances on alignment of the mini TMA mirrors

		M1	M2	M3
Alignment and Stability	Decentering X (µm)	**15**	**25**	**25**
	Decentering Y (µm)	**15**	**25**	**25**
	Decentering Z (µm)	**60**	**25**	**50**
	Tilt X (arcsec)	**45**	**90**	**60**
	Tilt Y (arcsec)	**30**	**60**	**45**
	Tilt Z (arcsec)	**120**	-	**160**
Manufacturing	Curvature radius (µm)	5	5	5
	Conic constant (E-3)	0.5	0.5	0.5
	SFE (nm)	**25**	**15**	**25**

Table 6. Wavefront errors resulting from the telescope design and tolerance

	WFE (nm RMS)		
	0 deg	17 deg	25 deg
Nominal design	19	29	61
Budget	48	62	98
Specifications (Proba V)	150	150	150
Margins	142	136	114

Wavefront errors resulting from the nominal design and WFE degradation coming from the tolerance analysis are presented in Table 6 for three FOV positions (axial, maximum and intermediate FOV). Wavefront errors are well below the 150 nm RMS considered as requirement for the similar PROBA-V telescope. The degradation of the optical quality corresponding to the maximum FOV can be associated to the previously noted degradation of the system performances at FOV larger than 22°.

CONCLUSIONS

This article described the TMA telescope developed for PROBA-V and possible new generations of spectral imagers. These instruments all are based on a wide FOV TMA which can be fabricated using Single Point Diamond Turning of aluminium alloys. Based on the recent improvement of SPDT technology it is now possible to build very compact multy/hyperspectral imagers with medium spatial resolution (about 100 m) at relatively low cost.

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