HIGH PERFORMANCE OPTICAL PAYLOAD FOR MICROSTELLITE

OECD CONFERENCE CENTER, PARIS, FRANCE / 6–8 FEBRUARY 2018

Roland GEYL[(1)], Jacques RODOLFO[(1)], Jean-Philippe GIRAULT[(2)]

[(1)]Safran Reosc, avenue de la Tour Maury, 91280 Saint Pierre du Perray, France,
[(2)]Safran Electronique & Defence, 18/20 quai du Point du Jour, 92100 Boulogne-Billancourt, France

KEYWORDS: Microsatellite, space camera, earth observation

ABSTRACT:

Safran is presenting two concepts of optical payloads for microsatellites combining high performances and extremely compact volume. The first one offer 10-m Ground Sampling Distance (GSD) over 60x40 km² area from 600 km orbit optimized for twilight conditions. The second one is offering a much finer resolution of 1.8-m over 11x7,5 km² area from the same 600 km orbit.
The two concepts are based on advanced innovative diffraction limited optical systems packaged in a very compact volume lower than 8U = 200x200x200 mm making them the ideal solution for 15-50 kg microsatellites. The maximum number of pixels is served to the end-user space imagery community thanks to 35 mm Full Frame sensors offering, as of today, 6000x4000 pixels. Five to ten spectral bands from 475 to 900 nm can be offered thanks to 2D structured filters.

1. INTRODUCTION

Microsatellites offer many new opportunities thanks to lower cost of the platform, rapid development cycle obtained through standardization of various modules and functions. However, in the domain of earth observation payloads the community seems to still stick with optics design similar to the Questar 3.5 telescope. We present in this paper two concepts of high performance imaging payloads offering snapshot imagery with respectively 10-m and 1.8-m resolution from 600 km orbit over wide field of view thanks to 35mm Full Frame 2D sensor. Butcher's block 2D structured filters inserted before the focal plane allow adaptation of the payload to panchro, 4 bands multispectral or up to around 10 bands hyperspectral earth imagery.

2. SAFRAN CORE CAPABILITIES AND HERITAGE

2.1. Safran Reosc

Safran Reosc is European leader precision space optics and is serving the industry with telescopes, mirror assemblies, lens assemblies, precision filters and optical ground support equipment. In fact, Safran Reosc is pioneering several key technologies for space optics like:

- _Zerodur mirror substrate lightweighting by machining, in the 70's,
- _Computer Controlled Robotic aspheric Polishing, in the 80's,
- _The use of Three Mirror Anastigmats with ISRO's IRS 1-C satellite, launched in 1995,
- _Silicon Carbide optics precision optics, e.g. Formosat-2 optics delivered to Airbus in 2000.
- _Freeform precision optics with IASI-NG and MicroCarb telescope and spectrometer optics presently under fabrication.

While Safran Reosc has built its reputation on larger and larger space and astronomy optics the company hold key capabilities in 'small' but high performance lens assemblies and catadioptric optics. These skills are now adapted to microsatellites optical payloads.

Figure 1. Safran Reosc space optics heritage

2.2. Safran Electronics & Defense

Safran Electronics & Defense is European Leader in optronics for defense, i.e. combining precision optics with advanced Vis and IR sensors, specialized electronics, critical image processing software and integrating these within orientation and stabilization gimbals to offer ultimate pointing and tracking capabilities on-board any vehicle.

Safran Electronics & Defense operate in Valence a unique electronics design, development and

production of advanced electronics and already serve the space community with various power supply, video processing, memory module, etc. on-board satellites.
Safran also delivers unique Hemispherical Resonant Gyroscope (HRG) units that are critical contributors to the launch success on-board the vehicle.

Figure 2: Safran Electronics & Defense optronics heritage

3. Smallsat optical payloads and applications

3.1. Review of smallsat space camera

Planet is the pioneer in earth observation from space with microsatellites and has sent several constellations of 28 3U cubesats of 10x10x30 cm volume fitted with a Questar 3.5 type of optics: 90-mm aperture, 1400 mm focal length, 1.4° FoV and offer 3,70-m GSD from the relatively short lived 475 km orbit.

Media Lario has built a demonstrator of its Streego payload based on a 200 mm aperture TMA telescope. This instrument is based on metal mirrors mounted within a metal structure with a much larger volume of 600x550x330 mm (plus a 200 mm long front entrance baffle). It is designed to deliver 2.75-m GSD imagery over 11.3x8.5 km² from 600 km orbit.

The young Spanish entity **Satlantis** is developing a serie of iSIM sensors based on twin Cassegrain-type telescopes collecting images in two spectral bands. The Instrument volume is again relatively large with 590 x 490 x 318 mm.

Other actors like Hera Systems, Astrodigital, Malin Space, etc. are developing their optical payloads. JPL on its side is developing its Intellicam camera for imaging asteroids.

Airbus Defence and Space has developed the high performance Astroterra constellation's New Astrosat Optical Modular Instruments (NAOMI) offering 1.5 to 2.5-m GSD from long life 700 km orbit. These are based on a Silicon Carbide Korsch type telescope with 200 mm aperture offering up to 30 km trace length in push-broom mode.
Safran Reosc is proud to have been selected by Airbus for the supply of the Astroterra constellation optics. First two models SPOT-6 and SPOT-7 have been launched in 2011 and deliver excellent imagery.

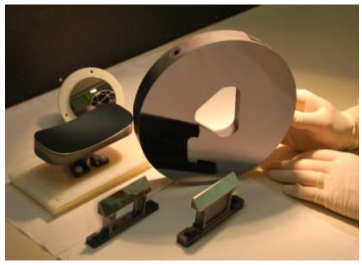

Figure 3: Safran Reosc SiC optics polished for Astroterra

Harris in the US is offering its family of Space View instruments of 23, 35 or 42-cm aperture targeting sub-meter resolution thanks to these large apertures.

These larger instruments are built on a more conventional Cassegrain + field corrector or Korsch configuration. Due to their size, one can consider that they are probably more dedicated to the higher end of the market with minisatellites rather than microsatellites.

3.2. Importance of the orbit and piggyback effect

The resolution and field of view are directly linked to the altitude of the orbit where the satellite has been sent. The lower the orbit, the higher the resolution and the smaller the FoV and, as a direct consequence, the longer the revisit time. Lower orbit therefore impose to build more expensive and complex constellations of many satellites in order to offer global imagery service to the community.

In addition, the lower the orbit, the shorter the lifetime on orbit. Down to 400 km orbit altitude the lifetime become less than 2 years. Therefore, in order to offer the imagery service over 10 years long periods it is necessary to send to space a total of 5 constellations, thus multiplying the total cost for the end-user by nearly the same factor.

We see an additional difficulty in the piggyback effect. Due to high launch costs and lack of specific microsatellite cost effective launch offer these microsatellites remain generally secondary passengers of larger satellite. The drawback resulting from this situation is that there is no choice possible for the orbit and the satellite is placed at the main instrument orbit. Most of the large satellites are placed on orbit of 600 km and above (or at ISS level). The lesson is then that new payloads shall be designed for at least 600 km orbit in order to be able to offer their service for 10 years and not be penalized by piggyback effect.

3.3. Lessons from Planet development

Planet has reported their development of the Planet Scope instrument in 3 successive generations: PS0, PS1 and PS2.

- _PS0 is a 2 element Maksutov Cassegrain optical system with an 11 Mpx CCD detector. Optical elements are mounted relative to the structure of the spacecraft.
- _PS1: features the same optical system as PS0, aligned and mounted in an isolated carbon fiber/titanium telescope. Telescope matched with an 11 Mpx CCD detector.
- _PS2: features a five element optical system that provides a wider field of view and superior image quality. This optical system is paired with a 29 Mpx CCD detector.

The lessons we learn from this roadmap are multiple:

- _First, it confirms that optics onboard small satellites are not much simpler than optics on-board big satellites. Mounting problems, thermal effects, decoupling from the platform global structure, etc. all these problems are still there, with similar or even higher criticity and have all to be addressed with the same rigor.
- _Secondly, money can be saved if one immediately pushes the design toward the ultimate performance that can be offered. Any simpler and low-cost option taken at the beginning appears to have to be paid later with some redesign or improvement effort to be undertaken.
- _The end user of space imagery is mainly looking forward to the maximum pixel count for the desired resolution. This reduces the number of necessary satellites, reduces the post-processing efforts, etc…

Therefore, we have designed our concept of microsatellite payloads presented below with the key considerations of maximum number of pixels with large format detector, highest quality and smallest volume optics.

3.4. The application

An offer of space imaging payload must be designed to be able to address the maximum of potential applications.
These can be classified along the two main parameters of spatial resolution (GSD) and spectral resolution as shown on the figure below.
We have identified the green area of main applications of imagery from microsatellites with two limits in term of GSD with respectively 10-m and 1.8-m ground resolution.
In term of spectral resolution, panchro imagery and 4 to 10 spectral bands appears to us as capable to answer to the maximum potential needs of the community. Our filter solution is perfectly answering to such demand.

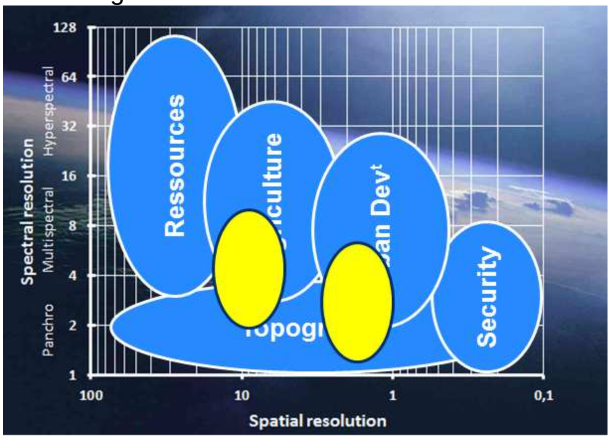

Figure 4: Applications vs GSD and spectral resolution

4. THE SEEING 10-M EO PAYLOAD

4.1. Concept and main characteristics

The concept of our **S**mall sat**E**llite instrument for **E**arth imag**ING** with 10-m resolution (SEEING 10-m) is presented on the figure below. This system is designed to take snapshots of a 60x40 km² area, with 10-m resolution in panchro mode or with several spectral bands under low light conditions.

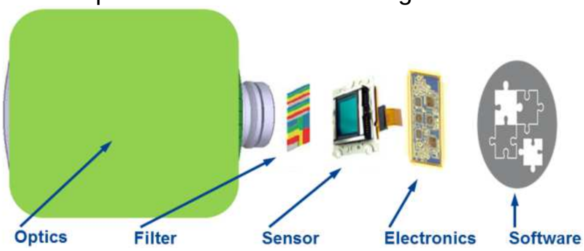

Figure 5: The SEEING 10-m concept

The optics: Its detailed design is kept confidential for the time being. It is a 130 mm aperture, 6.3°x4.3° FoV and 330 mm focal length system with diffraction limited performance over 475 to 900 nm spectral domain. The system shows very low distortion of less than 1.5 µm, i.e. below 0,001%. The design MTF is better than 55% for the 91 lp/mm corresponding to 5.5 µm pixel size and 10-m GSD from 600 km orbit. The high F/# of F/2.5, despite the effect of some obscuration, offer capability of imagery in low light conditions like twilights and close to the poles. The key design drivers are: wide FoV, High NA for high detectivity and moderate resolution.
The design is pushed to high enough performance level in order to be still able to offer sufficient MTF level with 50 Mpx sensors that may appear soon on the market. This will enable 7-m GSD imagery over the same 60x40 km² from 600 km orbit.

The volume of the optics alone is very compact and remains within a volume lower than 160x160x150 mm3. The whole payload can then easily fit within an 8U or 12U cubesat.
With performances directly comparable or even better than the one of the SPOT-1 satellite developed more than 30 years ago our SEEING 10-m payload can be qualified as '***SPOT-1 in a shoebox***'

The filter: A 2D structured filter is placed in front of the detector. The required number of spectral bands is distributed through the Along Track dimension of the FoV. Each spectral band is therefore captured over a 60 km x 40/N km area, with N the number of spectral bands. Acquiring and combining images taken every 40/N km along the orbit of the satellite will therefore allow to reconstruct the imagery of an entire 60 km wide trace on the earth with the desired N spectral bands.
The N parameter can be tuned for each specific mission from 1 to 10.

The 2D sensor: A strategic choice has been made to select the ambitious 2D sensor format of Full Frame 35 mm format, i.e. 24x36 mm². This will allow using sensors from several vendors, to benefit from evolution of the sensor technologies driven by the strong technology push provided by the photographic market without redesigning our optomechanics.
We still have the choice today between CCD sensors and CMOS technologies with 5.5 µm pixel size offering the 10-m GSD with the designed optics. While the space heritage and performance level of CMOS sensors are rapidly increasing for the benefit of the community, we conduct discussions with several sensor vendors. The end-user remains welcome to participate to the choice of the sensor if he finds some interest in such customization of the payload.

The electronics: will be adapted to the detector. This activity is one of the core skills of Safran Electronics & Defense. There are also some reputed specialists like 3DPlus serving the market with innovative approaches. Modular electronic concept is being developed to drive the 2D sensor and acquire the data.

The software: Safran Electronics & Defense extensive catalog of image processing modules can be implemented for on-board image pre-processing and data volume reduction before transmission to the ground. We offer full flexibility to rapidly develop this section of the payload per the targeted mission of the instrument.

4.2. Filter technology

Since two decades Safran Reosc is offering stripe filters for push broom optical instruments made of several tiny stripes of high efficiency bandpass coating deposited close to each other on a substrate placed in front of the detector. Typical transmission curves are shown on figure 6.

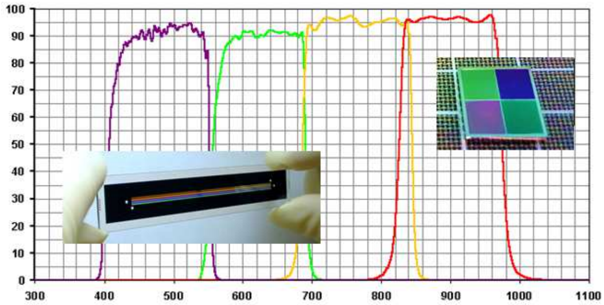

Figure 6: Reosc 2D structured high efficiency filters

More recently, the technology of depositing spectral filters directly on the detector has emerged several years ago. This consists in depositing simple Fabry Perot based spectral filters onto the detector surface and 2D structuring them properly. Safran Reosc has conducted similar developments on the subject from visible up to thermal IR spectral domain.
However, we want to point out that the Fabry Perot filter design has some limitation in term of throughput as shown on the figure 7

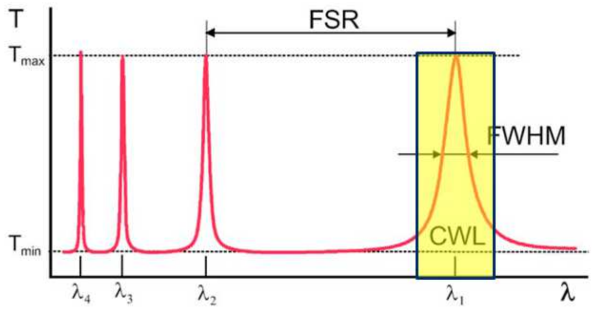

Figure 7: Limited integrated transmission of Fabry Perot filter

When considering a spectral band of about twice the FWHM bandwidth of the Fabry Perot filter one can realize that the total integrated light throughput is much lower than the peak central transmission. It is in fact nearly only one half of this. This is a major disadvantage and has a severe impact of the system optical throughput.
For this reason, Safran Reosc is selecting today its technology of 2D structuration in a so-called butcher-block configuration of high efficiency spectral filters deposited on a separate substrate in order to preserve the highest throughput and maximal SNR of the proposed instrument.

4.3. Mass & Power

Thanks to its extremely compact design the mass of the optics itself is kept below 8 Kg.
Including the sensor and its electronics, the thermal protections and interface mounting flexures, the total mass of the instrument is

evaluated to less than 10 kg.

Our preliminary evaluation of the electrical power needed to operate the sensor, its electronics, the various heaters, etc.. is established at around 30 W.

4.4. Thermal engineering

Thermal effects management onboard microsatellites or cubesats are known as a key issue because, due to the smaller size of the satellite, the instrument and its optics become more exposed the thermal variations. This subject has been taken into account in our design in several ways:

_First, we propose to place the satellite on a sun-synchronous orbit that will allow the progressive installation of a stable thermal configuration within the satellite: Sun on one side, deep space on the other and the earth surface in front.

_Second, all state of the art passive MLI thermal insulation dispositions will be implemented to reduce the thermal load coming from the sun side and the thermal sink on the opposite side.

_Adequate management of the heat generated at detector and its electronic level will also contribute to reduce the thermal perturbation on the opto-mechanics. This will be done in the usual way of thermal straps used to passively evacuate heat generated by the detector and heaters to be used in the case of temperature coming below the safe operation range.

_Finally the optomechanical engineering itself is optimized along various directions to reduce the thermal effect on the performance of the system: lens design is tuned to approach self athermalization, the housing material and its thermal conductivity is optimized to also contribute in the same direction, the interface mounting bipods are optimized to decouple the optics from the external mechanical perturbations and thermal perturbations.

Today, we are evaluating the operational temperature range to stay within 15-25°C where the system will deliver high quality imagery thanks to passive athermalization of the system and low sensitivity to gradients.

5. THE SEEING 1.8-M EO PAYLOAD

The second EO payload is designed to offer highest resolution within smallest payload volume, while staying in the same range of less than 8U microsatellite volume.

The architecture of the SEEING 1.8-m is in fact strictly identical to the one of the SEEING 10-m presented above in figure 5 with an optics, a filter, the sensor, the electronics and the selected software package.

The key difference is only the optics itself which is now evolving to a longer focal length of 1.8-m, a larger aperture of 190 mm. The Full Frame 35 mm sensor is now covering a reduced FoV to 1.1°x0,7° representing 11x7,5 km² from 600 km orbit with a 1.8-m GSD.

Again, the SEEING 1.8-m optical design is kept confidential at this time. This optical concept is completely different from the one of the SEEING 10-m. It involves some freeform surfaces in order to be squeezed within the ultimate very compact packaging of 200x200x200 mm3

Our SEEING 1.8-m appears therefore to exhibit the key advantage of 10 times smaller volume than other instruments presently developed for similar performances. Weight is of course going in the same direction.

The optics shows a design MTF value of 35% and a residual distortion lower than 0,05%.

Filter, sensor, electronics and software considerations are exactly the same for this new payload proposed. All these modular technology bricks are shared between the two instruments in order to standardize their construction.

In term of thermal management, the high compactness of the optical system will make it naturally less sensitive to thermal perturbations and will develop much lower internal gradients. Today, our design involves ceramic mirrors and structure in order to further ensure perfect stability of the optics and its performances thanks to the high thermal diffusivity of the selected ceramic material.

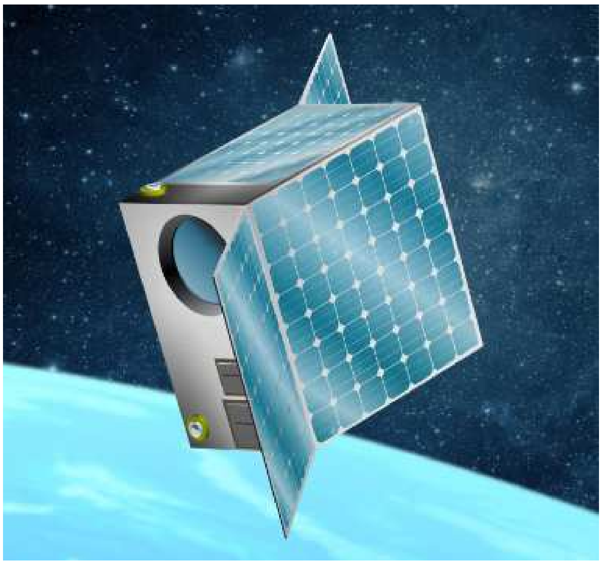

Figure 8: SEEING 10-m (or SEEING 1.8-m) implemented within a 18U Cubesat

The images in figure 8 above show a possible implementation of SEEING 10-m within an 18U cubesat. The artist rendering of the cubesat shows the solar panels oriented towards the sun and acting as sunshade for the optics.

The SEEING 1.8-m implementation within a same 18U cubesat would be in fact very similar.

6. CONCLUSION

Safran, combining the skills of Safran Reosc in high performance space optics and Safran Electronics & Defence in space electronics, software and defense optronics, is developing efforts to offer two ultra-compact optical imagery payloads to the space community fitted with 2D sensors for snapshot panchro or multispectral imagery.

A first instrument is dedicated to 10-m moderate resolution but over 60 km x 40 km wide area with high NA optics for highest detectivity in twilight conditions.

The second one is dedicated to high resolution down to 1.8-m.

Both optics concepts are packaged in the extremely low volume lower than 8U = 200x200x200 mm, 10 times smaller than similar instruments, and have a mass of around 10 kg, less than one half over the competition.

These key characteristics make them ideally suited to be placed on-board very small microsatellites for the most cost-effective, but high quality missions.
A summary table of the key performances of the instruments is shown below:

	SEEING 10-m	**SEEING 1.8-m**
GSD	10-m	1,8-m
FoV from 600 km orbit	60 x 40	11 x 7,5 km²
Pixel count	6000x4000	6000x4000
Sensor	FF 35 mm	FF 35 mm
Focal length	330 mm	1800
Aperture	130 mm	190
Spectral channels	Up to 10	Up to 10
Design MTF @ Nyquist	55%	35%
In orbit MTF (estimated)	> 18%	> 12%
SNR Panchro (estimated)	> 256	> 128
Mass	10 kg	10 kg
Optics volume (mm^3)	160x160x140	200x200x200

The design effort presented above relative to these two types of payloads is undertaken on internal SAFRAN funding. Efforts will continue with a demonstrator optical system to be produced in 2018 and sensor and electronics detailed design and development conducted in parallel.

The two optical concepts studies presented here are technology demonstrators. These concepts can be adapted, to some extent, to different specifications like larger angular FoV or longer focal length without changing their design essence. The technology details linked to optical manufacturing, testing and assembly, detector choice with electronics and software will remain valid for the possible customization that might be desired by the commercial, security or scientific mission.