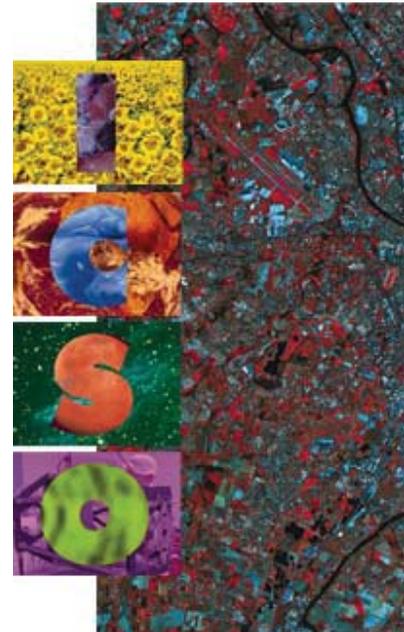


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Micro-satellite for space debris observation by optical sensors

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**MICRO-SATELLITE
FOR SPACE DEBRIS OBSERVATION
BY OPTICAL SENSORS**

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THOMSON-CSF Optronique

RESUME – Cette étude théorique réalisée sur contrat CNES porte sur la faisabilité d'un capteur optronique embarqué sur microsatellite dédié à la détection et à la classification de petits débris spatiaux. Différents concepts basés sur des capteurs passif et actif ont été analysés et comparés. Une optimisation des paramètres de l'équipement est réalisée pour le concept le mieux approprié. Les performances théoriques indiquant le nombre de détections par classe de diamètre de débris ont été calculées. Des ordres de grandeur des caractéristiques physiques (poids, volume, consommation...) ont été estimés pour illustrer l'architecture du capteur retenu.

ABSTRACT - The purpose of this theoretical study carried out under CNES contract is to analyze the feasibility of small space debris detection and classification with an optical sensor on-board micro-satellite. Technical solutions based on active and passive sensors are analyzed and compared. For the most appropriated concept an optimization was made and theoretical performances in terms of number of detection versus class of diameter were calculated. Finally we give some preliminary physical sensor features to illustrate the concept (weight, volume, consumption,...).

1 INTRODUCTION

The growing activity of man in space generates artificial debris with a larger population than for meteoroids. This artificial population increases the risk of collision between hyper velocity objects and spacecraft or satellites. Specific sensors based on impact detection are already embedded on low orbits satellites to monitor the very small debris population. The debris with diameter larger than 10 cm can be tracked by ground radar station. Flux models based on debris measurement enables the calculations of meteoroids flux versus size distribution. To improve these models, additional measurements are necessary in the debris population range with a diameter between 100 μm and 10 cm.

This paper deals with space based optical sensors on-board micro-satellite. Technical solutions based on active and passive sensors are analyzed and compared. A survey of key components was performed to propose the best available component meeting our needs. Performance criteria are proposed to take into account the sensors spatio temporal coverage. For the most appropriated concept an optimization of the sensor characteristics (optical, resolution, temporal parameters...) was made and theoretical performances in terms of detection number versus class of diameter were calculated. Finally we give some preliminary elements on the sensor architecture.

2 REQUIREMENT

2.1 Sensor function

The optical sensor is mainly devoted to detection and classification of small space debris and the mission duration is about two years. The classification of the object is made in estimating the albedo surface product. A rough information on debris speed is also needed.

2.2 Integration constraints

The optical sensor on-board micro-satellite will present the following characteristics :

- Volume: 60 cm*60 cm*30 cm
- Sensor power consumption: 35 W average and 100 W peak
- Sensor mass: <40 kg
- Sensor field of view: 2π sr
- Telemetry TM/TC: 400 kbits/s, CCSDS

2.3 Debris characteristics

Debris albedos in visible band were measured for large objects (ref. 1,2).

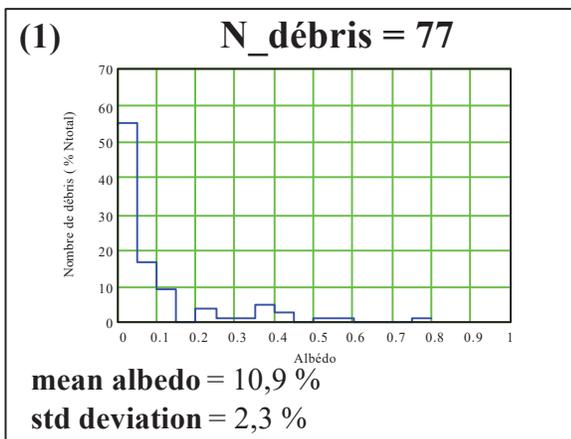


Fig 1.

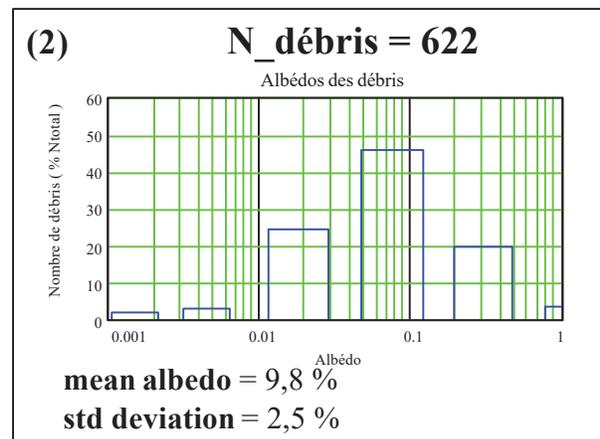


Fig 2.

In thermal band, debris signature is depending on the material emissivity and the surface temperature. The temperature is varying periodically during solar illumination and eclipse cycle.

3 PERFORMANCES CRITERIA

The sensor performances assessment is mainly based on calculations of the detectable debris number per year for a diameter class ($d_{\min} < \text{diameter} < d_{\max}$). The advantage of this criterion is to take into account the spatio temporal coverage. Calculations are based on theoretical debris distribution given by existing flux models. Therefore, calculation results are subject to circumspection.

3.1 Flux versus debris size distribution

The fig.3 shows the theoretical debris flux per year per squared meter versus the debris diameter. For performance calculations the debris repartition is supposed homogenous in space. Of course the goal of the sensor is to complete this curve assumption with experimental measurements.

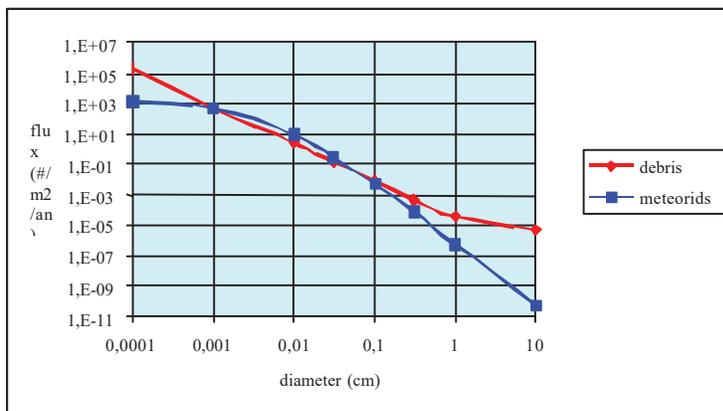


Fig 3.

3.2 Detectable debris number

The angular coverage of the sensor is represented below. Fov represents the sensor field of view and the range represents the maximum distance of detection.

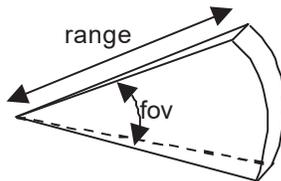


Fig 4.

For discontinuous observation sensors (ex: pulsed source) a figure of merit was defined to represent the number of detectable debris for diameter classes defined by $[\Phi, \Phi + \Delta\Phi]$.

For active sensors we obtain Eq. 1.

$$N_{\text{detection}} = \int_{\Phi}^{\Phi + \Delta\Phi} |d\text{FLUX}(\phi)| \cdot \int_{d_{\text{min}}}^{\text{Range}(\phi)} \text{Pro}_{\text{illum}}(F_{\text{laser}}, \tau_{\text{pulse}}, r) \cdot r \, dr \, d\phi \quad (\text{Eq. 1})$$

The term dFlux is derived from the theoretical debris flux (fig.3), $\text{Pro}_{\text{illum}}$ is the debris probability to be illuminated when crossing the field of view of the sensor at a range r , F_{laser} is the laser repetition rate, τ_{pulse} is the temporal length of the pulse.

For passive sensors with a quasi-continuous temporal observation the number of detectable debris is given by Eq. 2 after simplification of Eq. 1.

$$N_{\text{detection}} = \frac{k_{\text{eclipse}}}{2} \int_{\Phi}^{\Phi + \Delta\Phi} d\text{Flux}(\phi) \cdot \text{fov} \cdot \left(\text{Range}_{\text{max}}(\phi)^2 - \text{Range}_{\text{min}}^2 \right) d\phi \quad (\text{Eq. 2})$$

where k_{eclipse} is the eclipse ratio.

4 COMPARISON OF ACTIVE AND PASSIVE CONCEPTS

4.1 Active concept

The principle of detection with active sensors is based on debris illumination with a source and measurement of the back scattered light with a receiver. Various optical sources are available (incandescent light, flash, laser diode, pulsed laser) to realize the illumination. To respect the energy budget and to reach the best performances in terms of spatio temporal coverage we have selected laser diode and pumped laser.

The best temporal coverage is reached with Laser diode (Continuous Wave) but the range performances are limited by the available averaged power. The best spatial instantaneous coverage is obtained with pulsed pumped laser but unfortunately with a low temporal coverage.

Performances are illustrated for a pulsed micro laser Nd:Yag operating at 1.064 μm . We have calculated the probability of illumination (fig. 5), the maximum range (fig. 6) and the number of detection per class and per year (fig. 7) for debris with 10 % albedo and 8 km/s relative transverse speed. A diameter class is defined by the following interval $[\Phi, 1.6 \cdot \Phi]$.

The sensor feature is defined by the following parameters.

transmitter		reception	
Wavelength	1.06 μm	Pupil diameter	30 mm
Divergence	5 deg. * 2.7 mrad	Transmission T/R	50 %
Peak power	$4 \cdot 10^4$ W	detectors	32 APD
Energy/ pulse	400 μJ	Detector length	75 μm
Cadence	1 kHz	Gain	75
Transmitter efficiency	2 %	Electronic noise in	1 pA/ $\sqrt{\text{Hz}}$
Pulse length	10 ns	Band pass	30 MHz
Mean electric power	20 W	Nep	210 pW
Mean optical power	0.4 W	Detection threshold	5

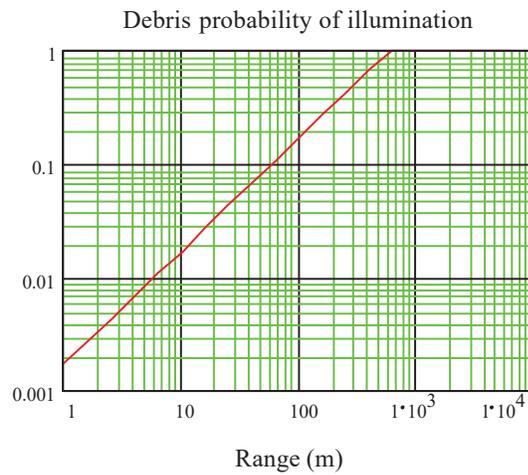


Fig. 5

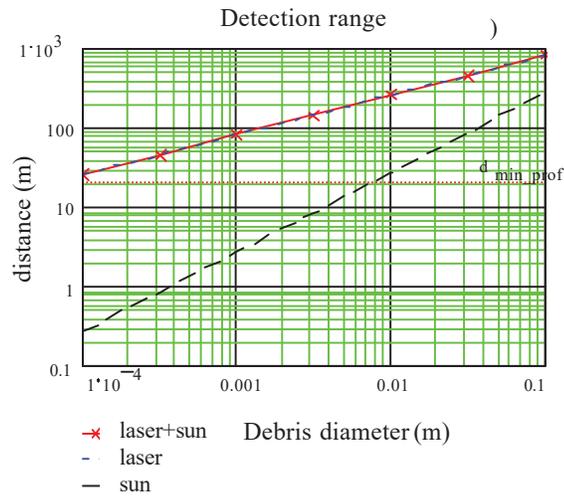


Fig. 6

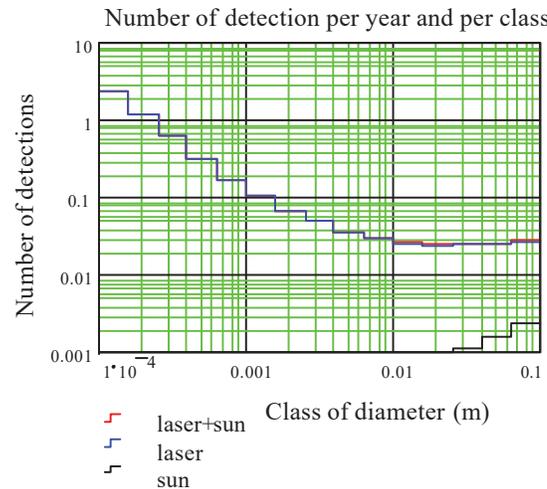


Fig. 7

Following this criteria we conclude that the active concept is better suited for small space debris at short range. The return signal is penalized at long range because the return energy is inversely proportional to the range to the fourth power.

4.2 Passive concept

4.2.1 infrared sensors

Out of solar eclipse debris are illuminated by the sun. Passive concepts are based on detection of solar radiance reflecting by the debris (visible and near infrared spectrum) or thermal radiation (infrared spectrum).

"Hot debris" can be detected with high sensitive thermal camera including Focal Plane Array detector. On one hand this solution is penalized by the reliability of the cooling machine. On the other hand the thermal signature of the debris can vary in a wide range. For these mains reasons thermal sensors were not selected.

4.2.2 visible sensors

Solar illuminated debris can be detected with focal plan array CCD or APS camera. Images are processed to detect aligned pixels corresponding to debris displacement during the integration time of the camera (fig. 8). Detection will be performed after signal integration in the Hough domain to get high detection sensitivity for speedy debris or long traces.

Range measurement is performed by stereoscopic observations with at least two consecutive detections. The measurement of the satellite displacement between two frames and the angular position of the debris allows range estimation.

The class of "albedo-surface" product is calculated from the debris range and the debris signal.

The speed vector is estimated after range and angular position differentiation or by exploitation of the debris trace length in the focal plan.



Fig. 8

The synoptic of the sensor is given fig 9.

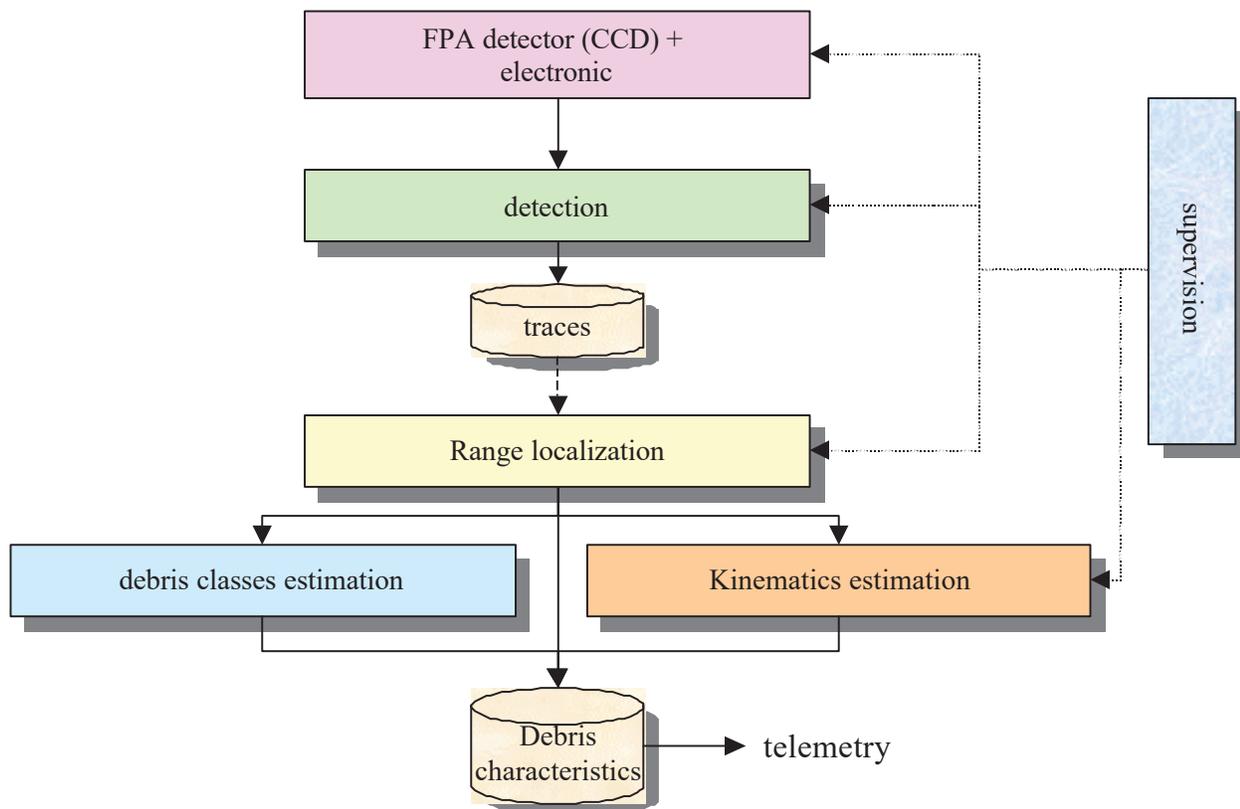


Fig. 9

The instrument includes:

- optical head including the optics, the focal plan array detector (CCD or APS) and related electronics,
- signal processing for image correction, bright star rejection, calculation of image differences, Hough transform, detection,
- high level information processing for debris localization, albedo-surface product classification and kinematics estimation.

Detection performances were evaluated for passive sensors with the following features.

Optics	Pupil diameter	100 mm
	Aperture	F/1 or F/2
	Transmission	70 %
Detector (backthinned CCD)	Number of pixels	512*512 or 1024*1024
	Pixel size	13 μm *13 μm
	Fill factor	100 %
	Wave length (QE=10%)	[300 ; 1000] nm
	Readout noise	10 e
	Integration time	50 ms (512*512) 100 ms (1024*1024)
processing	Detection	Integration in Hough domain
	SNR threshold	3

Figure 10 shows the number of detectable debris per class and per year for 10 % albedo debris, three fields of view, two pupil diameters and 8 km/s transverse relative speed.

Figure 11 shows the number of detectable and localizable debris per class and per year in the same conditions.

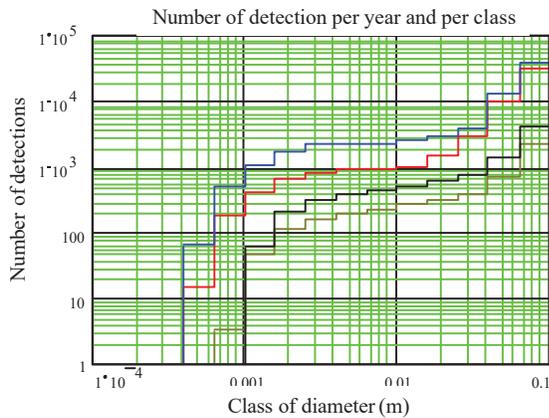


Fig. 10

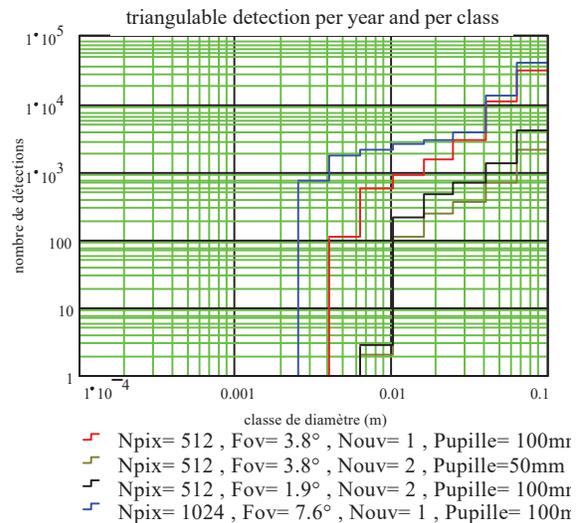


Fig. 11

Integration of the signal corresponding to debris traces enables small debris detection at short range. At long range in passive mode the signal is less penalized than in active mode because the received flux is inversely proportional to the range to the square power.

The range localization domain is lower than the detectable domain.

A preliminary design analysis leads to the following physical features:

- mass : 3 kg
- electrical consumption : 35 watts
- optics volume : $\Phi = 110 \text{ mm} * 200 \text{ mm}$
- 2 electronic cards

5 CONCLUSION

These incentive results have shown the interest of a passive visible sensor on-board micro-satellite for small space debris detection and classification. The performances of active sensors could be interesting if the available power for the instrument is increased.

The passive sensors allows good detection performances about some hundreds detections per year for debris with diameter less than one millimeter and some thousands for debris with diameter between 10 and 100 mm. The total number of detection is about 70000 per year with the flux hypothesis defined.

Furthermore this sensor allows the debris classification and the kinematics estimation by stereoscopic localization.

The passive sensor is based on optics with a large aperture, a very sensitive and low noise backthinned CCD, a processing in charge of detection, localization and classification.

The next stage after this theoretical study is the detailed design of the instrument.

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