MICRO-SATELLITE FOR SPACE DEBRIS OBSERVATION BY OPTICAL SENSORS

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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 characteristics 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 these objects with high kinematics and spacecraft or satellite. Specific sensors based on impact detection are already embedded on low orbits satellites to monitor the very small debris population. Debris with diameter larger than 10 cm can be tracked by ground radar stations. Debris flux provided by mathematical models based on debris measurement enables the calculations of meteoroids flux versus size distribution. To improve these models, additional measurements are necessary for 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 components meeting our needs. Performance criteria are proposed to take into account the spatial and the temporal coverage for different sensors. For the most appropriate concept, an optimization of the sensor characteristics (optics, 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 design.

2. REQUIREMENT AND HYPOTHESIS

Sensor function

The optical sensor is mainly devoted to the detection and the classification of small space debris. The mission of the micro satellite will last about two years.

The debris classification consists in estimating the "albedo*surface" product. A rough information on debris speed is also needed.

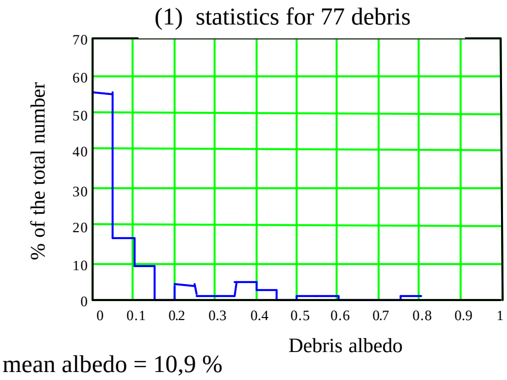
Integration constraints

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

- Volume: 60 cm*60 cm*30 cm
- Electrical power dedicated to the sensor: 35 W on average and 100 W peak
- Sensor weight: <40 kg
- Sensor field of view: 2π sr
- Telemetry TM/TC: 400 kbits/s, CCSDS

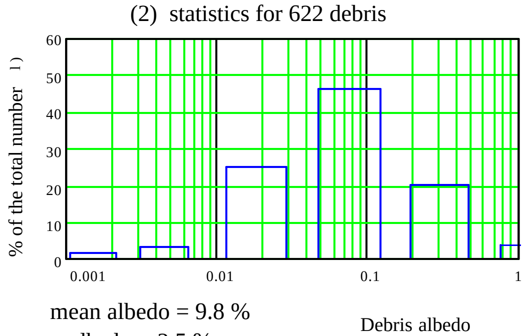
Debris characteristics

The curves in figure 1 and 2 shows debris albedo measurement in visible band for large objects (ref. 1,2).



mean albedo = 10,9 %
σ albedo = 2,3 %

Fig. 1 - Repartition of debris albedo



mean albedo = 9.8 %
σ albedo = 2,5 %

Fig. 2 - Repartition of debris albedo

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

3. PERFORMANCE CRITERIA

The sensor performance assessment is mainly based on calculation of the number of detection per year for a diameter class (d_{min} < diameter < d_{max}). The advantage of this criterion is to take into account the spatio temporal coverage. Calculations are based on theoretical debris distribution provided by existing flux models (fig. 3). 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.

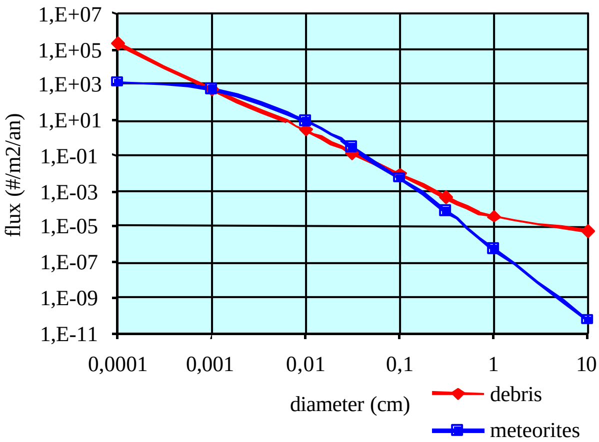

Fig. 3 - Theoretical debris flux / year / m²

3.2 Detectable debris number

The spatial coverage of the sensor is represented below where "fov" represents the sensor field of view and "range" the maximum distance of detection.

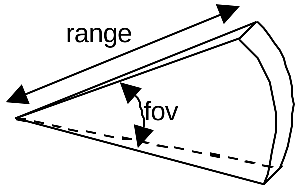

Fig. 4 - Angular beam

For sensors with discontinuous observation (ex: pulsed source) a figure of merit was defined to calculate the number N of detectable debris with diameter classe defined by the interval [Φ, Φ+ΔΦ].

For active sensors we obtain Eq. 1.

$$N = fov \int_{\Phi}^{\Phi+\Delta\Phi} \int_{r_{\min}}^{Range(f)} dFlux(f))Pro_{illum}(r)rdrdf \quad \text{Eq. 1}$$

The term dFlux is derived from the theoretical debris flux described in fig.3. $Pro_{illum}(r)$ is the probability to illuminate debris when crossing the field of view of the sensor with r for the range. Pro_{illum} is depending of the laser repetition rate and the pulse length.

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

$$N = k.\frac{fov}{2} \int_{\Phi}^{\Phi+\Delta\Phi} dFlux(f)[range(f)^2 - r_{\min}^2]df \quad \text{Eq. 2}$$

where k is an eclipse ratio and r_{min} the minimum range.

4. COMPARISON OF ACTIVE AND PASSIVE CONCEPTS

4.1 Active concept

The principle of detection with active sensors consists in illuminating the debris with an artificial source and measuring 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 performance is limited by the available power. The best spatial instantaneous coverage is reached 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. The sensor features are defined in table 1.

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 [Φ, 1.6*Φ].

Performances are calculated with laser or sun illumination and with both.

transmitter		reception	
Wavelength	1.06 µm	Pupil diameter	55 mm
Divergence	2.5 deg. * 1.5 mrad	Transmission T/R	50 %
Peak power	2.10^5 W	detectors	32 APD
Energy/ pulse	200 µJ	Detector length	75 µm
Cadence	10 kHz	Gain	75
Transmitter efficiency	10 %	Electronic noise in	1 pA/√Hz
Pulse length	1 ns	Band pass	300 MHz
Mean power	20 W	Nep	670 pW

Table 1 - Active sensor characteristics

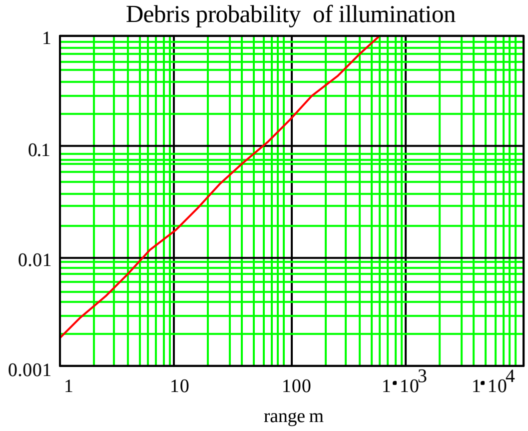

Fig. 5 - probability of illumination

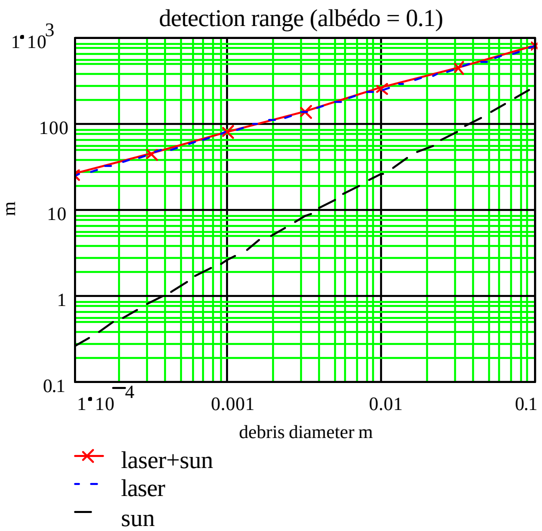

Fig. 6 - maximum detection range

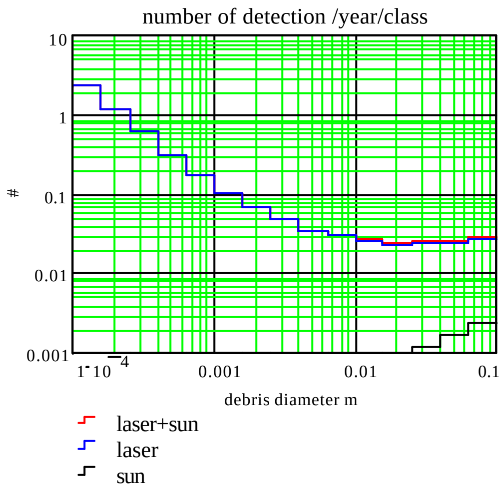

Fig. 7 - number of detection per class and per year

Following this criteria we conclude that the active concept is better suited for small space debris at short range because of the low available mean power on micro-satellite. Furthermore the returned signal is penalized at long range because the returned energy is inversely proportional to the range to the fourth power.

4.2 Passive concept

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

4.2.1 Infrared sensors

"Hot debris" can be detected with high sensitive thermal camera including a 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

During solar illumination debris can be detected by implementing a focal plan array camera CCD, CMOS or APS. Images are processed to detect aligned pixels corresponding to debris displacement during the integration time of the camera (fig. 8). Detection thresholding can be performed after signal integration in the Hough domain to get high detection sensitivity for speedy debris or long traces.

Range measurement can be 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 estimation and the debris signal.

The speed vector can be estimated after range and angular position differentiation or by using the debris trace length in the focal plan.

Fig. 8 – debris trace in the focal plane

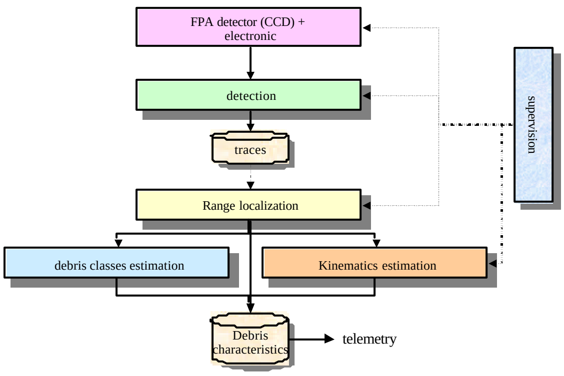

Fig. 9 – synoptic of the sensor

The instrument includes:

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

Performances in detection were evaluated for passive sensors with the following features in table 2.

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

Table 2 – passive sensor characteristics

Figure 10 shows the number of detections 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 debris that can be detected and localized per class and per year in the same conditions.

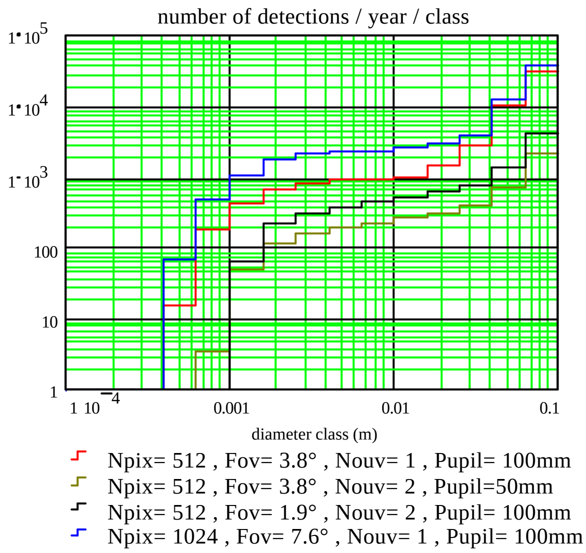

Fig. 10 - number of detections per class and per year

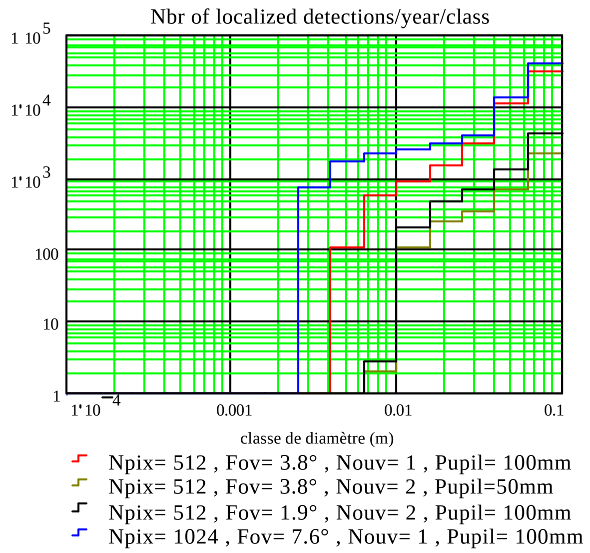

Fig. 11 - number of detections that can be detected and localized per class and per year

Integration of the signal corresponding to the debris trace in a single frame 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:

- weight : 3 kg
- electrical consumption : 35 watts
- optics volume : Φ = 110 mm * 200 mm
- 2 electronic cards (FPGA, DSP…)

5. CONCLUSION

These incentive results show 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.

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

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

These performances are reached with a large optic aperture, a very sensitive and low noise backthinned CCD, a processing in charge of detection, localization and classification.

This analysis will be carried on in a next step during the detailed design of the instrument.

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