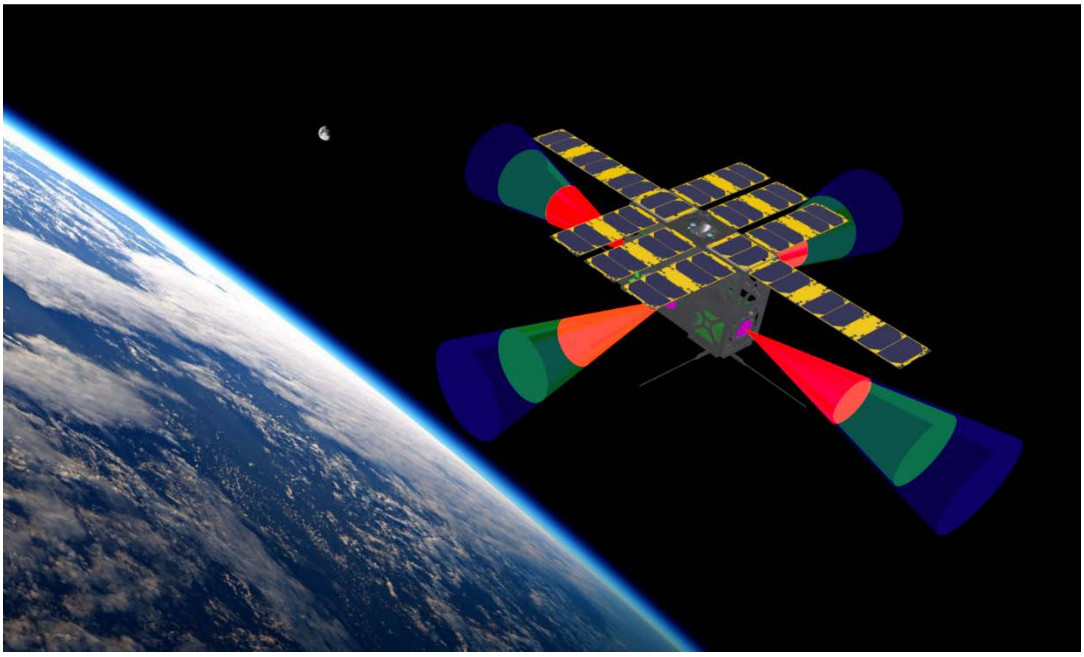
Project: **Coincident Lasersheet Particle Monitor**

COLA

Title: **Executive Summary**



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1 SCOPE

This document is the executive summary (deliverable D9) of the project COLA (Coincident Laser Particle Monitor), ITT Ref. ESA AO/1-10395/20/NL/CRS, ESA contract 4000133569.

The statement of work is given in the ESA-Discovery-TEC-SOW-019123 document titled AO10395-ws00pe.pdf.

2 PROJECT MAIN GOALS

The purpose of the project COLA (Coincident Lasersheet Particle Monitor) is to perform a feasibility study for an in-situ lasersheet particles/debris detection system enabling the detection and identification of small sized space debris/meteoroids currently not detectable from ground and that can nonetheless present important hazards for space misions.

The detection system must be able to determine and reconstruct particle shapes and trajectories for sizes and velocities ranging from 1 mm to 10 mm and 2 km/s to 20 km/s, respectively. The lasersheet detection area must be at least 10 m^2 and trajectory reconstruction must be possible with a resolution of 10°.

This work includes the development of a simulation software for the evaluation of different detection concepts (continuous laser sheet generation and LiDAR) and technical trade-offs. The MASTER database is used to enable the generation of statisticaly representative samples (for the orbit considered). Optical properties (phase function) of debris must be taken into consideration during the simulation and therefore characterization of a series of representative samples in laboratory is necessary.

Finally, a flight model development plan is proposed for the most interesting concept.

3 PARTENERS AND PROJECT ORGANIZATION

As shown in Figure 1, the project was composed of three phases (WP100, WP200 and WP300) in addition the the project management workpackage. Two partners were involved (in addition to ESA): the Finish Geospatial Research Institute (FGI) and the Centre Suisse d’Electronique et de Microthechnique (CSEM), which was the prime contractor.

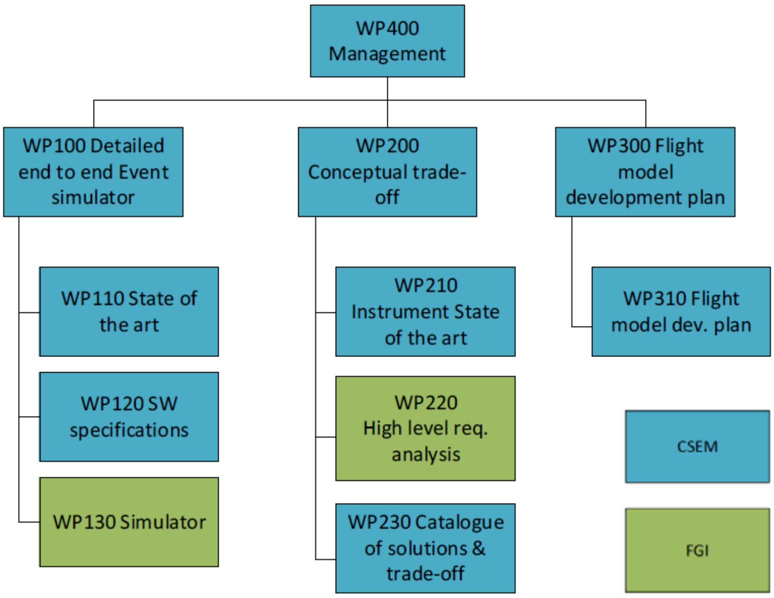


Figure 1: COLA phases and work packages.

The first phase is dedicated to the state of the art (SOA) in microparticles detection and imaging, with emphasis on the applicability to space debris with sizes below 1 cm. This part of the work is based on the project proposal submitted by CSEM and FGI to ESA. The second parts deals with the general description of the Event Simulator (EvS) and technical choices, made in agreement with the ESA.

The state of the art is performed for laser sheet based detection principle with a review of following key technical aspects:

- the generation of laser sheets (CSEM)
- particle distribution, for a given orbit and altitude (FGI)
- the particle physical properties (FGI)
- the propagation of light (FGI)
- the light-particle interaction (FGI)
- laser and detectors (CSEM)
- detection and signal generation (CSEM)

As stated in the statement of work (SoW) provided by ESA, laser sheet generator using moving parts (e.g., scanning mechanism, rotating scanner, etc.) were not considered in this project.

The first part of the second phase was dedicated to a literature review on optical-based detection systems compatible with space-born deployments for the tracking of small debris or meteoroids (< 10 mm) – on earth orbit or during interplanetary missions – and capable of providing information about their shape and composition. The second part of phase 2 provides a critical review of COLA main requirements (as listed in the SoW) and their assessment against established state of the art technologies identified in the literature review.

The las part of the second phase presents and discusses promising laser sheets-based systems concepts, trade-offs, and their evaluation with the Event Simulator (EvS).

The results of the second phase was used as basis for the third phase consisting in establishing a flight model development plan.

4 DEBRIS DETECTION CONCEPTS AND EVENT SIMULATOR

Based on the idea of Englert et al., a new laser sheet based particle detection system was proposed in this work featuring two laser sheets (instead of one) and additional optical detectors for time stamping (enabling debris speed determination), as illustrated in Figure 2.

Several sub-concepts are possible depending on how the laser sheets are generated (and hence its shape). They fall in two main groups depending how the laser sheets are generated: axisymmetric or trapezoidal. These two sub-concepts can be simulated in the EvS. This concept uses two continuous wave (CW) lasers and two types of photpdetectors (for particle crossin position and time stamping). To get a precise measurement of the trajectory and velocity, a trade-off must be found between the distance between the laser sheet, the laser optical power and the detector field of views, which is limited.

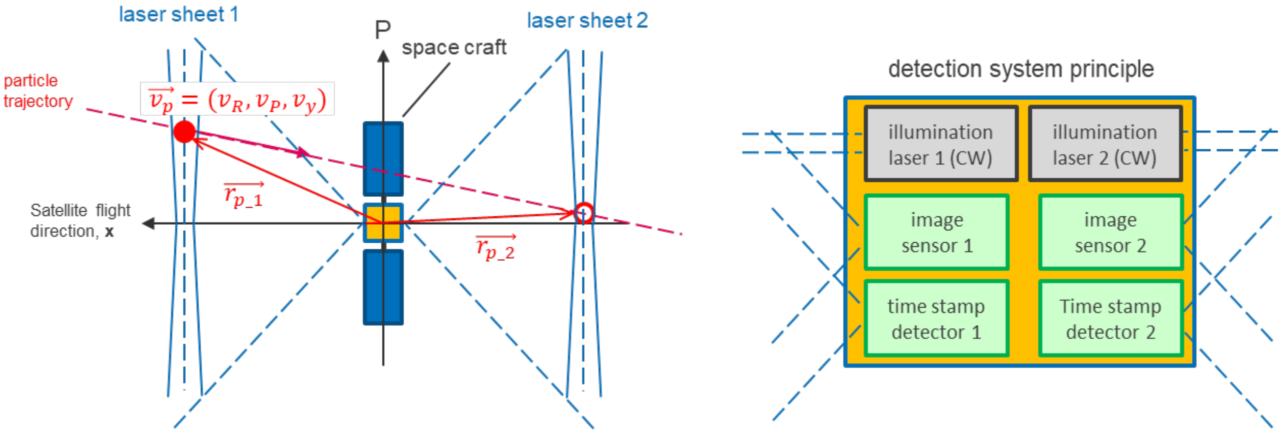


Figure 2: Concept 1, dual of laser sheet detection system.

The second detection concept (different from the one of Engelbert *et al.*) is based on a flash imaging LiDAR (direct time-of-flight (ToF) measurement). As shown in Figure 3, several laser sheets are generated with a pulsed laser (each “pulse” being a laser sheet). The light scattered back by the debris is collected by a single LiDAR which provides all the information necessary to determine the trajectory and the velocity of the object.

In this concept, trade-offs must be made on one hand on the laser source (pulse duration vs. output power), and on the other hand, between the field of view of the detector and the trajectory measurement precision.

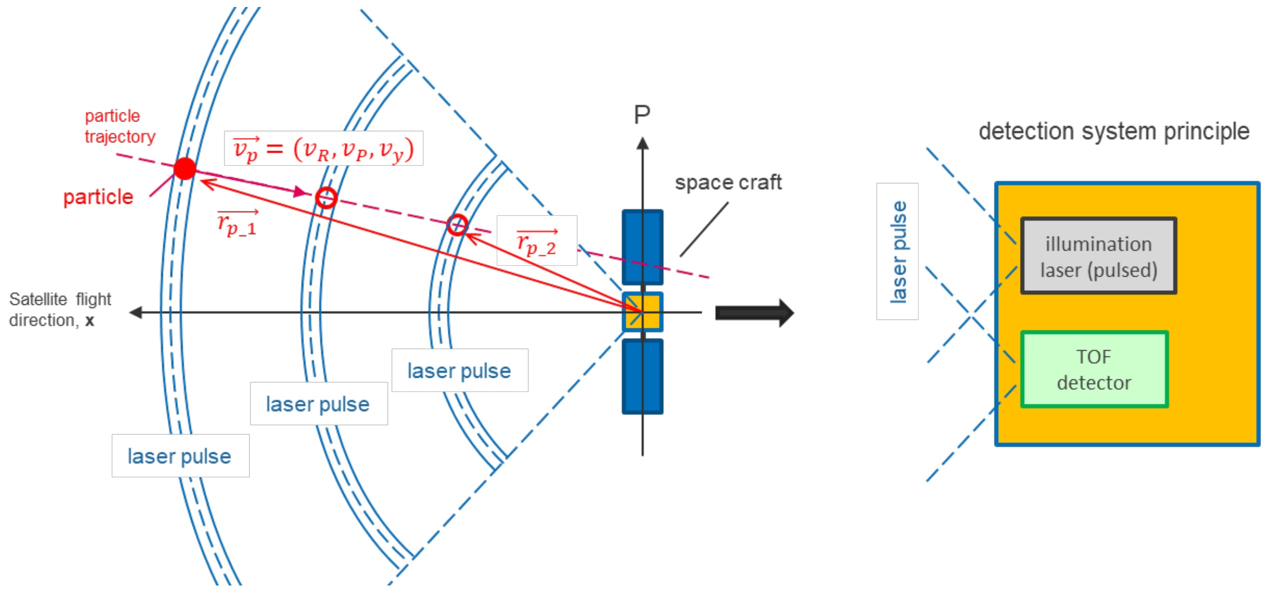
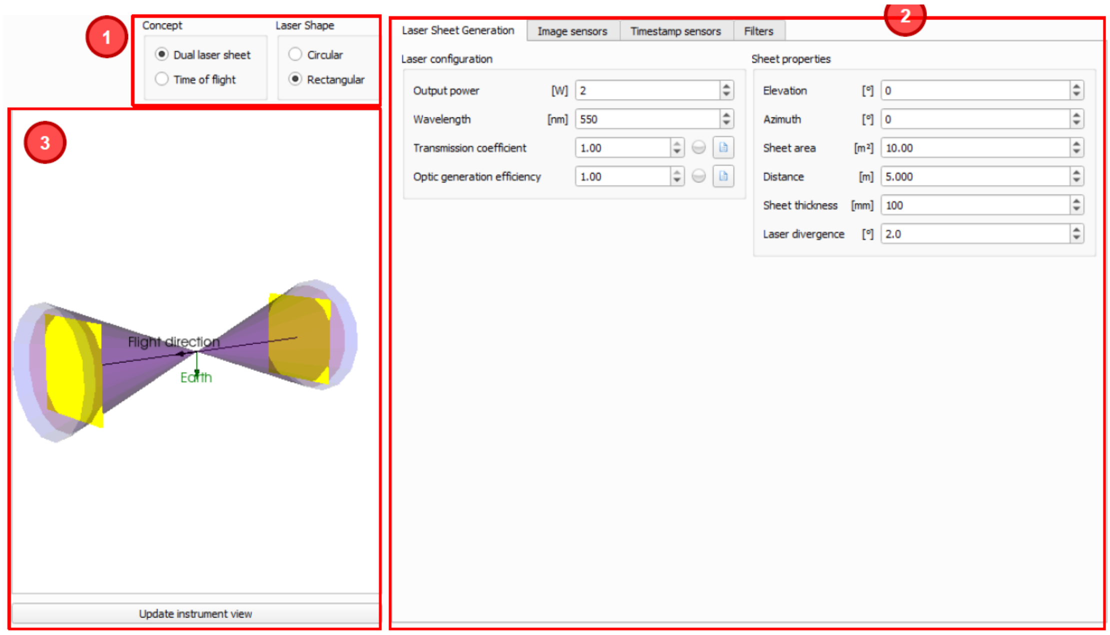


Figure 3: Concept 2, Time of Flight (ToF) detection concept.

All the conceptes can be decomposed in six modules, used as basis for the definition and the development of the EvS:

1. A light source used to generate one or several sheets (e.g., CW or pulsed laser)
2. An optical system to “transport” the light from the light source to the laser sheet generation optics (e.g., collimating optics, optical fiber, etc.)
3. A laser sheet generation optics (without moving parts, e.g., Powel lens, DOE, etc.)
4. A particle (also called debris) to interact with the laser sheet
5. A collection optics (e.g., detector lens, interference filter, etc.)
6. A photodetector (e.g., CEMOS, APD, TOF detector, etc.)

A state of the art for each of these modules was also performed. An example of the EvS graphical user interface (programmed in Python) is shown in Figure 4 and an example simulation result in Figure 5.



Concept
● Dual laser sheet
○ Time of flight

Laser Shape
○ Circular
● Rectangular

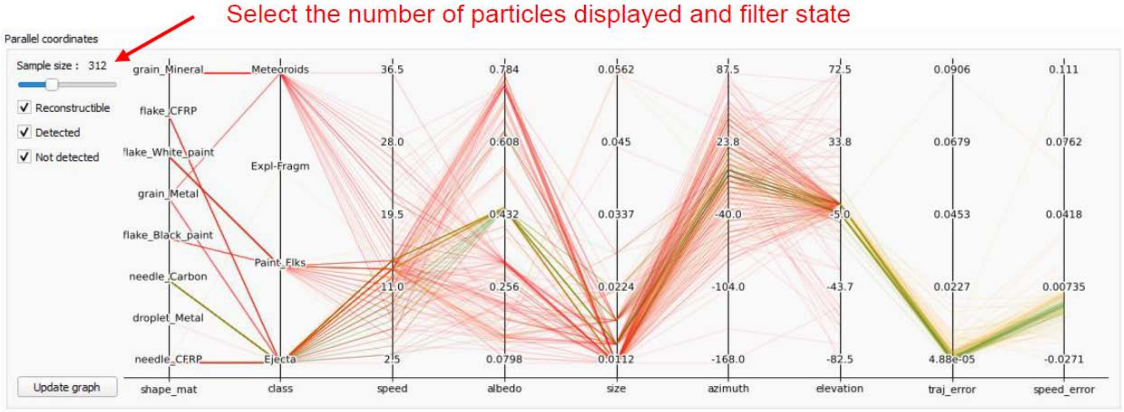
Laser Sheet Generation | Image sensors | Timestamp sensors | Filters

Laser configuration
Output power [W] 2
Wavelength [nm] 550
Transmission coefficient 1.00
Optic generation efficiency 1.00

Sheet properties
Elevation [°] 0
Azimuth [°] 0
Sheet area [m²] 10.00
Distance [m] 5.000
Sheet thickness [mm] 100
Laser divergence [°] 2.0

Figure 4: Graphical user interface of the Event Simulator (with 1: concept, 2: parameters and 3: concept visualization).

Select the number of particles displayed and filter state



Parallel coordinates
Sample size : 312
☑ Reconstructible
☑ Detected
☑ Not detected

Figure 5: Event Simulator output example (parallel coordinates visualization).

An important part of the EvS is the creation of a database providing improved optical information (phase function) to completed data from the MASTER database. For this purpose an original test set-up was created (Figure 6) to measure different types of samples representing typical ejecta from carbon fiber-reinforced plastic (CFRP) targets (Figure 7).

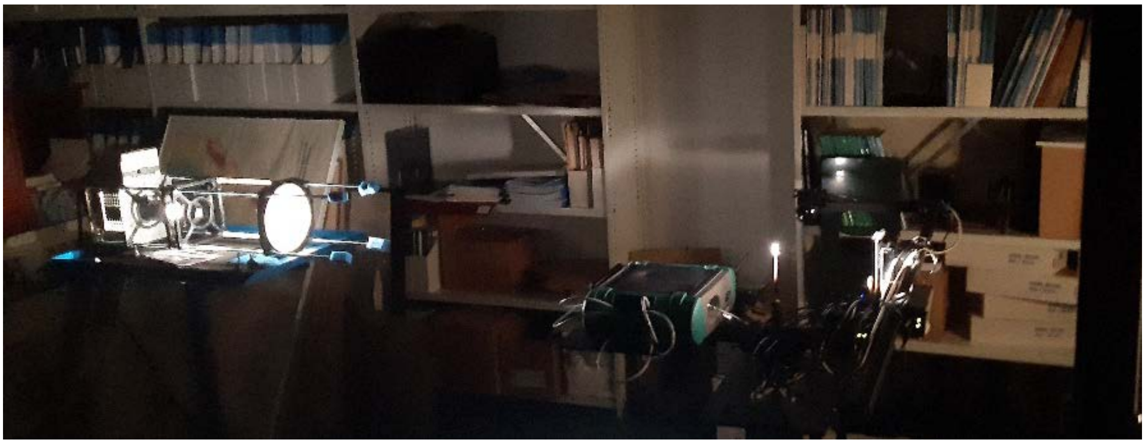
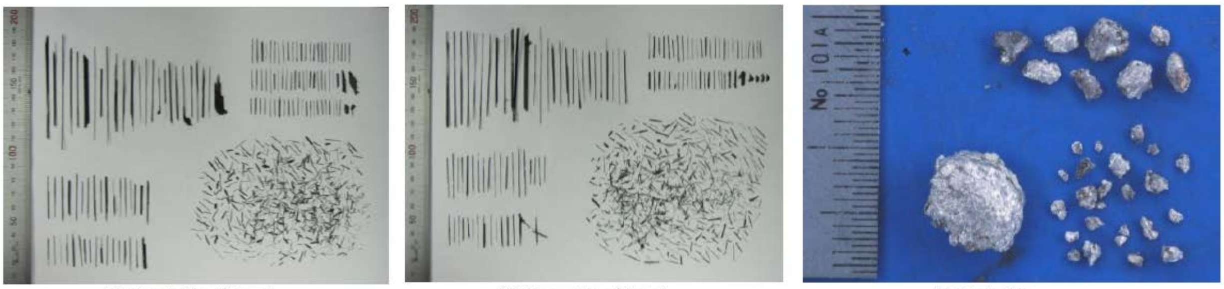


Figure 6: Debris characterization test set-up.



(a) Front side of target (b) Rear side of target (c) Projectile

Fig. 7. Ejecta fragments collected from test chamber (2.82 km/s).

Figure 7: Typical ejecta from caron fiber-reinforced plastic targets.

The particle database contains twelve particle models with eleve sizes and six orientations and can easily be extended with new categories. An example of measurements and phase function fitting (as a function of the phase angle) for a CFRP stick is shown in Figure 8. This phase function is used in the block 3 of the EvS (Figure 9) to set optical properties of the particle (debris) simulated as a function of its type, trajectory and orientation randomly generated (Monte Carlo). The particle list is first generated from the MASTER database according to the mission parameters (LEO, MEO, orbit parameters, etc.). This list can be updated and modified by the users.

The measurements were performed at different wavelengths (500 nm, 700 nm and 1100 nm) to evaluate the possibility to use debris' phase function variations (as a function of wavelength) in the debris' nature identification (material).

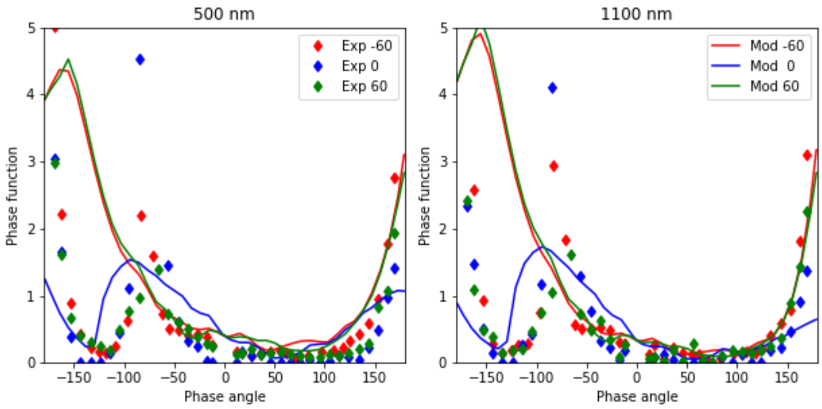


Figure 8: Phase function measurement (dots) and model (continuous lines) for a CRP needle at 500 nm (left) and 1100 nm (right).

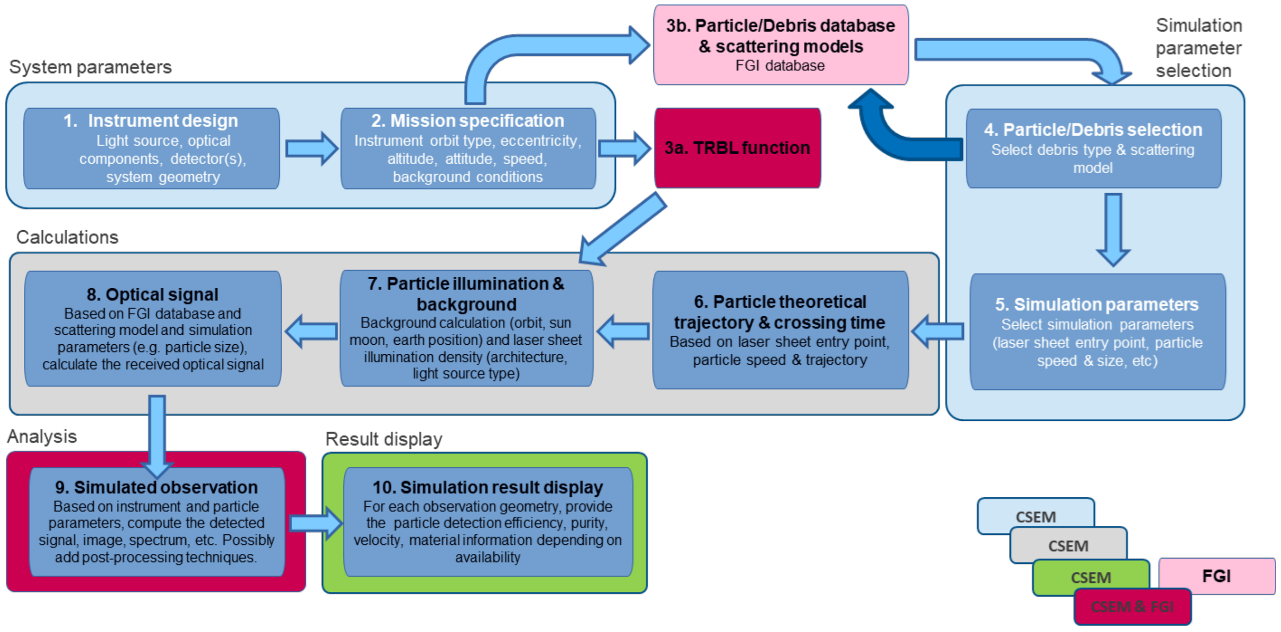


Figure 9: Event Simulator block diagram.

5 COLA PROJECT RESULTS

The high level requirement analysis for each of the concepts showed that CW based systems rating is similar. CW concepts present the advantage of using standard image sensor available in space grade quality and with a higher number of pixles (resolution) than the LiDAR sensor. Despite this advantage, none of the concepts evaluated in the COLA project present a resolution sufficient to enable particle shape determination for a size below 6 mm (for a detection area of 10 m^2). As reminder, the requirement was 1 to 10 mm.

Simulations performed with the EvS brought a lot of important information and knowledge about the potential performances of the CW and LiDAR concepts and confirmed that – to the exeption of the debris's shape determination – LiDAR systems present potentially better detection performances due to its "volumic" detection space issued from the high laser repetition pulse rate (Figure 3). Moreover, this concept is less impacted by particle trajectories. Indeed In CW concepts, many particle are detected on only one laser sheet – due to the trajectory angle formed with respect to the laser sheet (LS) surface – and therefore, no trajectory and speed evaluation can be performed with a single point.

In terms of noise level, the read noise of the CCD is the most limiting noise source for the LS concept. In the case of the LiDAR, dark noise is intrinsically lower allowing more a higher number of detection and hence reconstruction.

Another important result of the simulations is that an instrument based on the above discussed concepts cannot ensure a sufficient number of event detection per year (to be valuable) and resolution sufficient to enable particle nature determination (sensor resolution). Based on MASTER and the evaluation of particle flux (number of particles/m^2/year) for the different orbits the flux appears to be rather low, even in orbits at around 900 km (which contains the highest number of debris). The total flux of particles with a size over 1 mm is < 0.01/m²/year. Since the detection area envisoned are 10 m^2 (must requirement) or 100 m^2 (wish), less than one detection event per year can be expected. For particles over 1 cm, the flux is even lower!

Orbits with higher flux could exist but could not be identified using the MASTER database. Though, it is estimated that the flux for 0.1 mm particles is around 250/m²/year (providing a significant of possible event detection) dropping fast as the size of particle increases. In other orbits, the meteoroid background is most dominating, in this case maximum flux is 2/m²/year for > 0.1 mm particles, and about 1E-3/m²/year for 1 mm particles and over (Figure 10).

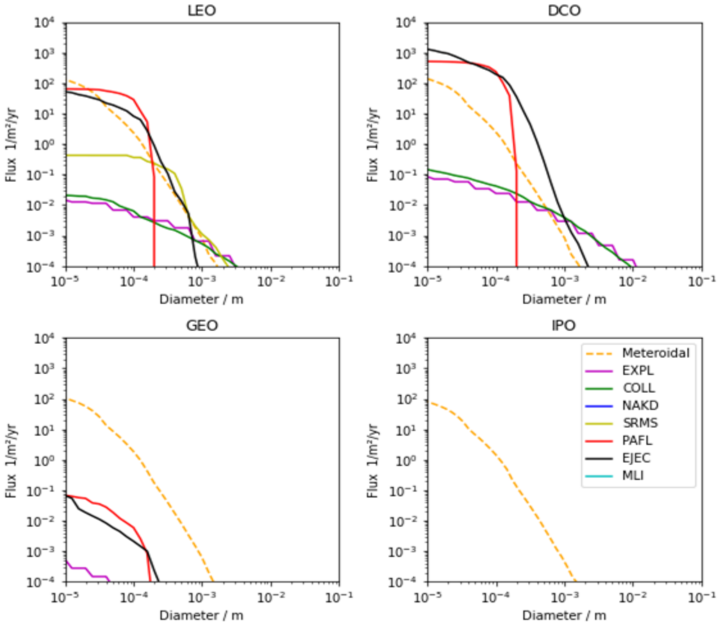


Figure 10: Cumulative size distribution from Master database at different orbits.

For such a few potential event detections, the interest for in-situ missions with detection areas up to 100 m^2 can be questionable. Though, since the particle flux of small particles

< 1 mm is only a rough estimation, such a mission could be interesting to refine small particle data flux on the orbits considered.

It is important to mention that after a first loop with the EvS, several improvements have been identified that can bring new insights. First, the surface generation of particles can be redesigned to avoid the artificial effect that more particles are detected for smaller surfaces. Generating the particles on a sphere could be a solution. Then, the sensor models can be improved by considering more parameters and more complex concepts, even though the actual ones provide already a realistic discussion and evaluation basis.

Finally, more elaborated concepts could be developed and implemented with potentially better detection performances provided some trade of on payload requirements (volume, mass, electrical power, etc.) or price (number of sattelites). Several ideas have been proposed and discussed, among them:

- Increase platform size to increase electrical power available (more pover full lasers),
- Develop and simulate more complex light collection optics (compound eye) to improve the FoV,
- Multiplication of detection systems (on a single or several platforms),
- The development of dedicated sensor (higher number of pixels, sensitivity, etc.)

On of the concept is shown as illustration in the first page of this document (multiple LiDAR systems on a single platform). Another is presented in **Figure 11**. In this concept, two satellites are coordinating their measurements. In this configuration, the distance *d* between them can be increased and, for a given and limited FoV, the detection area can be increased. This concept can be extended to a satellite swarm that a could be a very interesting approach of any of the basic concepts developed in the COLA project.

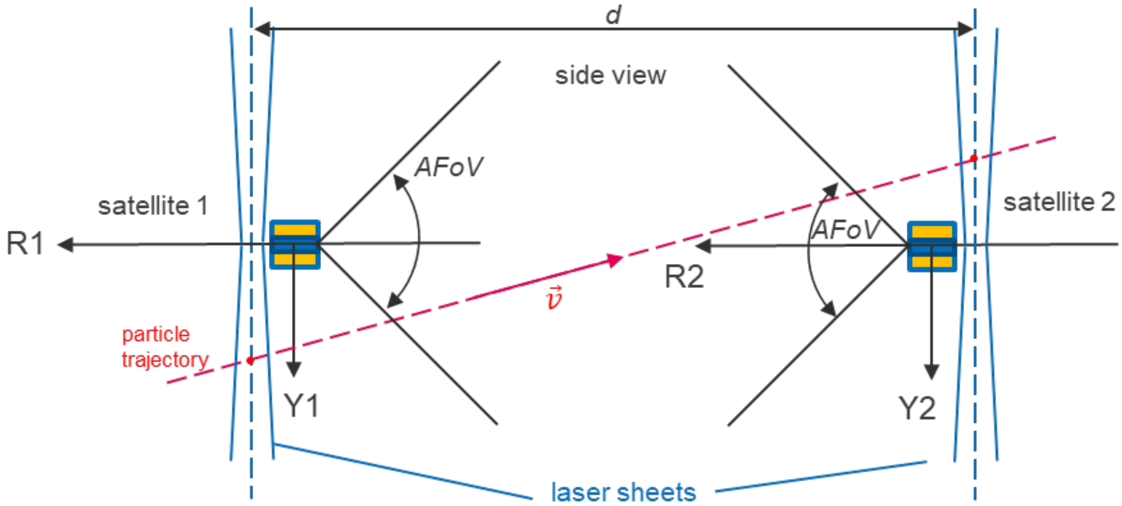


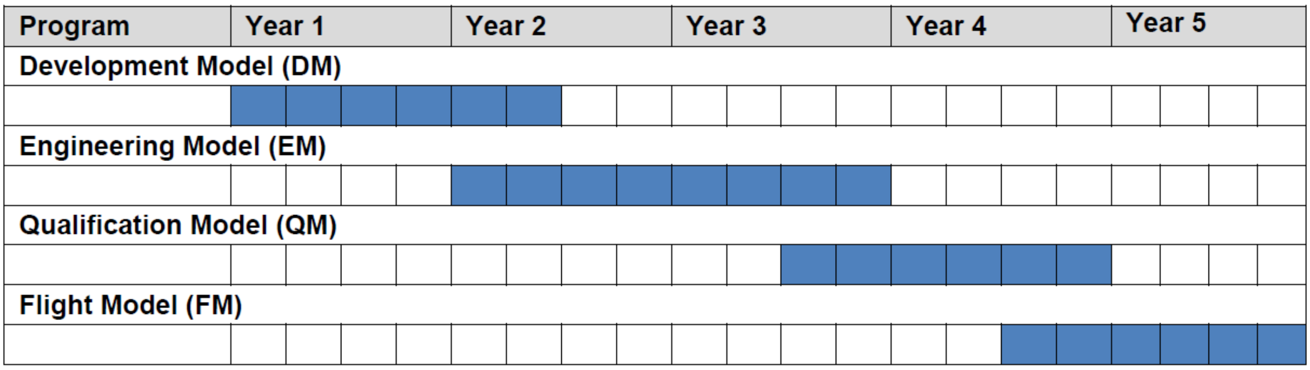
Figure 11: Dual micro-satellite concept.

The flash LiDAR technology has a higher potential than the laser sheet approach for particle detection, trajectory, and speed reconstruction thanks to very fast 3D images acquisition.

Moreover, the advantage of using a multi-wavelength laser illumination paves the way to the development of advanced algorithms for the determination of the particle’s nature.

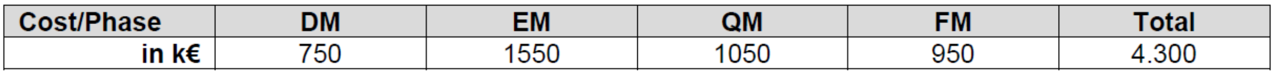
If the priority is given to particle shape and hence nature identification, then the laser sheet concept (or a mixed technology, LiDAR – LS) could be considered.

Finaly a flight model development plan (FMDP) for an instrument was developed (valid for any concept). The platform selected is a 6U to 12U CubeSat (to ensure enough electrical power), the total development time for a flight model is estimated to 4 years (Figure 12). The development costs for each phase is given in . This development plan do not take into consideration the development of specific space grade image sensors.



Program	Year 1				Year 2				Year 3				Year 4				Year 5			
Development Model (DM)																				
	■	■	■	■	■	■														
Engineering Model (EM)																				
					■	■	■	■	■	■	■	■								
Qualification Model (QM)																				
											■	■	■	■	■	■				
Flight Model (FM)																				
															■	■	■	■	■	■

Figure 12: Flight Model development plan.



Cost/Phase in k€	DM	EM	QM	FM	Total
	750	1550	1050	950	4.300

Figure 13: Flight Model development costs (per phase).