Title: *HORUS – a CubeSat-based multi-angle and multi-spectral Earth Observation (EO) system*
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(*) **We apply for Student Prize.**

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Need

In last years, CubeSat standard has drawn a considerable amount of attention as a vehicle to save money and time in space missions. In fact, nano-satellites are currently the core business of several start-up companies related to the space field, as SkyBox, Planet Labs, PlanetiQ and Spire. In particular, they entered in the market developing EO CubeSat constellations and clusters equipped with high-resolution optical nadir-pointing sensors. Unfortunately, measurements only along a restrictive plane with respect to the solar phase are insufficient for accurate analyses and studies. An off-nadir pointing architecture is needed to allow improving low-cost environmental monitoring ensuring a better quantification of atmospheric properties. Nowadays, only the MISR (Multi-angle Imaging SpectroRadiometer) sensor on-board the NASA EOS TERRA satellite is able to provide imagery with these features [1], but it is an old technology that requires huge capitals to be kept alive. The main challenge for the HORUS mission is to create a CubeSat-based multi-angle and multi-spectral system to monitor the Earth.

Mission Objectives

HORUS cluster will be able to offer multiple-perspective and multi-spectral imagery by creating new views well suited for global environmental monitoring with high revisit sampling. The main mission goals are:

1) <u>HORUS optical payload technology evaluation and in-orbit verification</u>.
   The HORUS payload in-orbit proof of concept will guarantee the possibility to adapt multi-spectral and off-nadir optical sensors capabilities to the CubeSat standard.
2) <u>Environmental monitoring and characterization of the atmospheric features</u>.
   The HORUS optical sensor is an imager spectro-radiometer for studying and observing aerosols, optical depth, particle types, surface and albedo BRDF (Bidirectional Reflectance Distribution Function) and Earth climate features.

Concept of Operations

<u>Space Segment</u>: HORUS cluster is composed of four 6U CubeSats in formation flight, equipped with forty cameras able to sample in both nadir and off-nadir views (±26.1, ±45.6, ±60.0 and ±70.5 degrees) in four spectral bands (red, green, blue and near infrared).

<u>Ground Segment</u>: HORUS Ground Segment is based on ground stations (GS) located at high, medium and low latitudes: Kiruna GS, Inuvik Satellite Station, Matera GS, Katsuura Tracking and Communications Station, Malindi GS and Punta Arenas Satellite Station. The GS network has been identified as the most suitable to fulfill the mission requirements related to the orbit and

needed downlink data rate – RX antennas in S or X bands are needed. In fact, the need to download a huge amount of data led to the selection of a GS network able to maximize the visibility time.

Launch Segment: VEGA (Advanced Generation European Carrier Rocket) has been considered as the possible launcher for the orbit insertion of HORUS cast. It allows reaching directly its circular, polar and sun-synchronous orbit.

Key Performance Parameters

1) **Spectral performances**: to fulfil the operational goals of the HORUS optical system, the following bands are needed:
   - **Red** (672 ± 20nm) and **Near-Infrared** (866 ± 20nm) bands provide vegetated surface identification and allow performing marine aerosol studies;
   - Working near the peak of the solar spectrum, the **Green** band (580 ± 15 nm) will be properly used to estimate broadband reflecting properties (albedos);
   - The **Blue** channel at 446 nm (± 21nm) provides nearly a double change in particle size-to-wavelength ratio relative to the near-infrared channel.

2) Radiometric performances: HORUS cameras have to provide high sensitivity for a wide range of scene reflectance (0.02% to 100%) without any change in gain: the peculiar application of HORUS optical system could bring several problems regarding light sensitivity during the sampling.

3) Spatial performances: a sub-kilometre resolution is required because many physical phenomena, such as the lateral diffusion of radiation within aerosol layers, have horizontal scales characteristics of the order of 1 km. The designed optical sensor will obtain a good spatial performance, even if the available resolving power is lower than the MISR's one.

4) Attitude control system stability: to maintain a stable pointing, each nanosatellite needs three reaction wheels for a three-axis stabilization and three magnetorquers for their desaturation. A star tracker (accuracy within one arc second) and an earth sensor (accuracy within six arc minute) have been selected in order to ensure the nano-satellite attitude determination also in the eclipse condition.

Space Segment Description

HORUS cluster is composed of 6U CubeSats in formation flight located in a circular, polar and sun-synchronous orbit. Each nano-satellite has an angular shift in true anomaly of around 2.3 degrees respect to the previous one to guarantee both the functionality of the formation and the collision avoidance. Two different configurations, shown in Fig. 1, are needed to permit the required multi-angle and multi-spectral capabilities. As shown in Fig. 2-3, configuration A is characterized by twelve cameras, four for each angle (0°, 60° and 70.5°), while configuration B is characterized by eight cameras, four for each angle (45.6° and 26.1°).

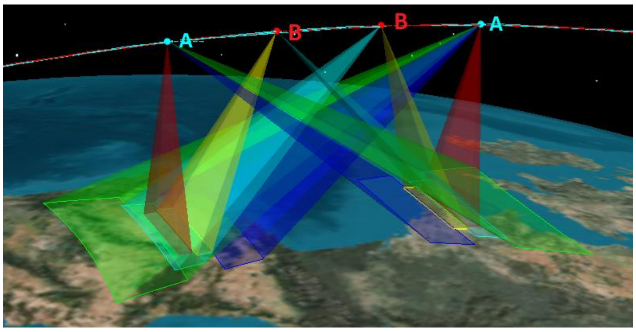

Figure 1. Overview A/B configurations

The optical payload will be hosted in a 3U volume (3-U Payload Module). The four MISR spectral bands are nominally Gaussian [2], centered at 446, 558, 672, and 866nm with equivalent bandwidths of 42, 29, 22, and 40 nm respectively [3]. Apposite filters perform the splitting of the incoming light, one for each channel. In fact, each filter is fixed on the CCD sensor and each camera has four independent line arrays, one per filter. Each camera consists of a CMOS (Complementary Metal-Oxyde Semiconductor) image sensor of 2048 x 1536 pixels with a focal length of 21mm. The estimated volume of each HORUS nano-satellite is around 100x220x340.5 mm with weight within 10 Kg (Conf.A ~ 8.5 Kg and Conf.B ~ 9.5 Kg). All the sub-systems needed for a nominal nano-satellite mission will be located in the other 3U module (3-U Service and Control Module), as shown in Fig. 4.

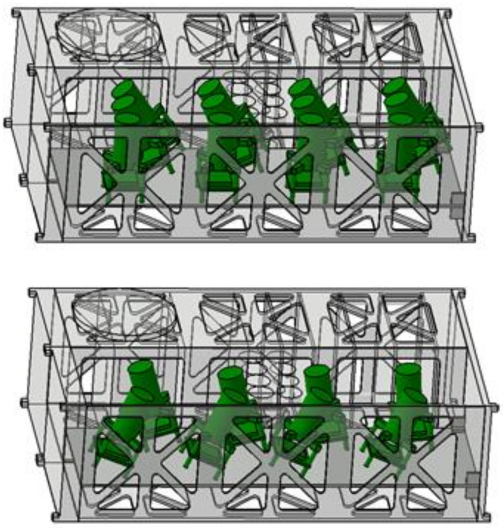

Figure 2-3. Configuration A-B.

The structural design concept is based on two monolithic structures linked together to maximize the stiffness to weight ratio and to provide the most homogeneous thermal conductivity. In order to satisfy the IADC (Inter Agency Space Debris Coordination Commitee) mitigation guidelines, a drag deorbiting sail (ARTICA) has been included in the nano-satellite subsystems.

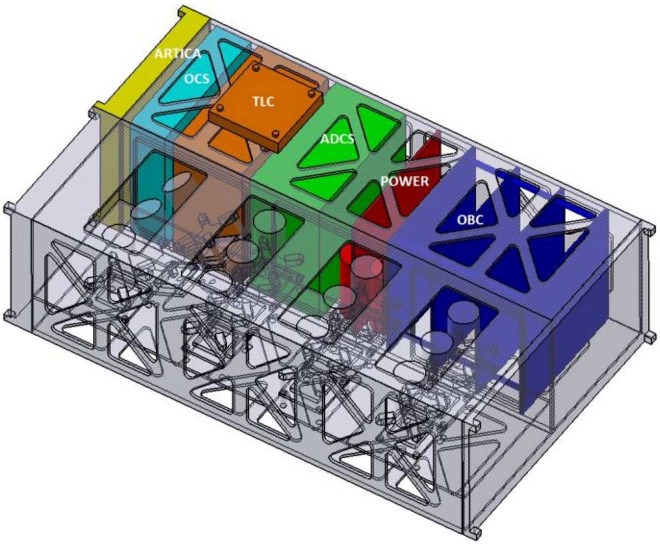

Figure 4. Main HORUS subsystems.

As concerns the Power Unit, each CubeSat is equipped with a 6U body-mounted solar panel installed on the zenith-pointing face, provided with triple junction cells and equipped with a double system of 3U deployable solar panels.

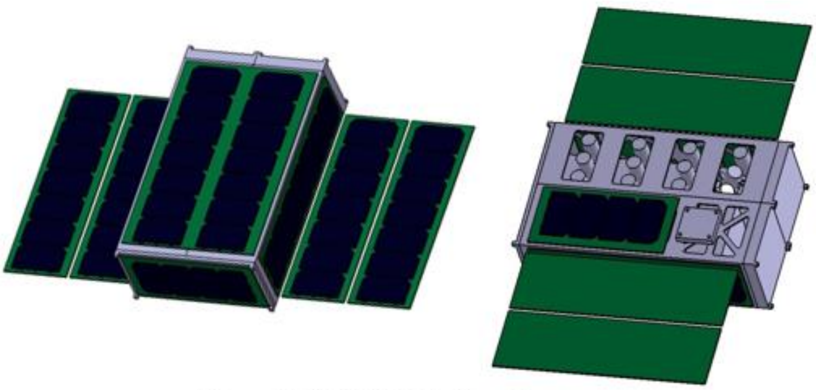

Figure 5. HORUS Solar Panels.

Moreover, two additional 2U body-mounted recovery panels have been designed in order to increase the sun-exposed surface while minimizing the drag effect on satellite orbit, as shown in Fig. 5. The estimated average available power supplied by this configuration is around 30W with a peak of 41W in the best illumination condition. To obtain the data-rate required – within 50 Mbits/s - an X-Band transmitter and low gain patch antenna have been selected. In addition, an omnidirectional S-Band antenna is needed as back-up TT&C subsystem.

The estimated link-budget is shown in Table 1.

Features	Symbol	Data	Result
RF Output Power	P_t	3 dBW	
Antenna Gain at 50° off nadir (HPBW)	G_t	3 dBi	
Free Space Path Loss	L_p	176 dB	
Additional Loss	L_a	5 dB	
Receiver Antenna Figure of Merit	G/T	30 dBK^{-1}	
Boltzmann's Constant	k	-228,6 dBJ/K	
Data Rate	R	77 dBbps	25 Mbits/s
E_b/N_0	**E_b/N_0**	$P_t + G_t - L_P - L_a + G/T - k - R$	**6,6 dB**
E_b/N_0 Required for BER= 10^{-5}	$E_b/N_{0\ min}$	4.4 dB	
Link Margin	-	E_b/N_0 - $E_b/N_{0\ min}$	**2,2 dB**

Table 1. HORUS Link-Budget.

As previously described into the Launch Segment paragraph, VEGA is the launcher considered for the HORUS mission. The ascent trajectory shall be a Hohmann Transfer Ascent (HTA). Assuming impulsive maneuvers, the final speed at the injection point of HORUS orbit is 7.61 Km/s. At the departure, the speed is minus 51 m/s – launching in a retrograde orbit does not allow getting Earth's rotational velocity. Considering additional speed losses (i.e. misalignment, drag and lift and gravity drag), the total delta-V required is about 8.7 Km/s.

Orbit/Constellation Description

The HORUS cluster orbit is a polar, circular and sun-synchronous at an altitude of around 500 Km (inclination of 97.4 degrees). This choice ensures passages over each Area Of Interest (AOI) at the same local solar time on the ground and consequently the same illumination conditions with a revisit time of less than three days. The LMT at DN is 10.30 am for the better compromise between good illumination conditions and low cloud coverage probability. The cluster accesses to the GSs network have been computed by using Systems Tool Kit (STK) [4] and are shown in Table 2.

Location	Antenna band type	Passages a-day	Average access time (sec)
High latitudes	S/X bands	11	550/570
Medium latitudes	S/X bands	4	600
Low latitudes	S/X bands	7	530

Table 2. Results of the analysis about cluster accesses to the HORUS GSs network

Implementation Plan

Since 1999, NASA's EOS TERRA satellite provides global and seasonal measurements of the Earth [1]. By now, its technology is quite old and obsolete compared to the current State-of-the-art in the space development field. International agencies and organizations, research centers and private companies interested in monitoring the main natural events could be the main users of future data gathered by the HORUS optical payload and can also be considered possible players for the mission implementation and sponsoring. The HORUS mission idea is a university student project developed in the framework of the Sapienza Space System and Space Surveillance Laboratory (S5Lab). Sapienza Engineering university laboratories offer several facilities allowing students to design, analyse, develop assembly and test a nanosatellite without additional costs for these mission phases. S5Lab collaborates with ASI and has a direct access to the Malindi GS – Kenya and Matera GS (Italy) for the data management. The launch is the most critical and expensive aspect of the mission in terms of cost: the HORUS cluster consists of four 6U CubeSats and on the basis of previous nano-satellite launches, the total estimates cost will be within 900k € (20k € per kg). The total estimated cost of the HORUS mission is around 2M €, including the launch. The Project GANTT, shown in Fig. 6, summarizes the mission main tasks and phases and in red are underlined the four top-level project milestones.

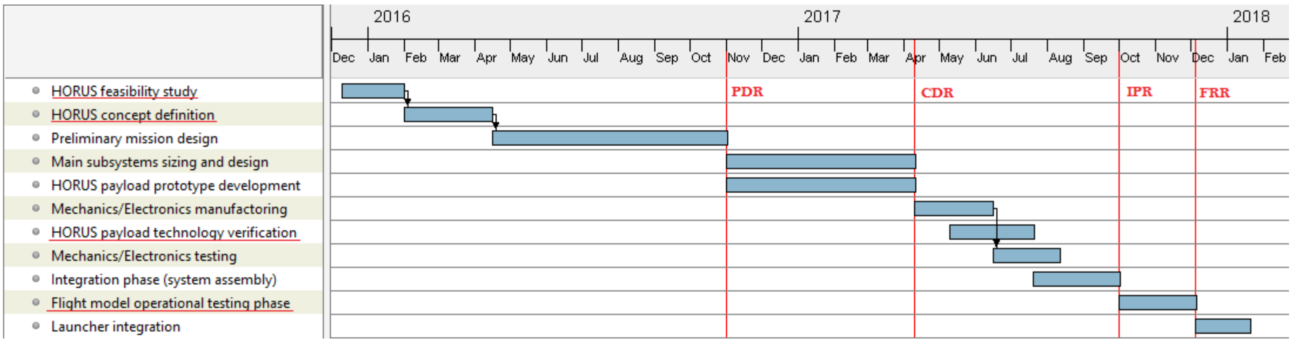

Figure 6. HORUS GANTT.

The top 5 Project Risks are listed in Table 3.

RISK	PROBABILITY	PREVENTION
Non-nominal performances of HORUS optical payload	**Low**	Robust and reliable algorithm simulation tools will be used to predict and simulate the HORUS optical payload operational performances.
Problems in in-orbit optical system calibration	**Low**	Reliable calibration methods already tested in other EO CubeSats missions will be used for the HORUS cluster,
Problems in OCS operational performances	**Low**	The design of the HORUS OBC will be based on technology already tested and with a flight heritage.
Delays in components procurement	**Low**	After the feasibility analysis and the concept definition, this phase will immediately start to ensure enough time for the components procurement.
Insufficient funding for the mission development	**Medium**	Alternative funding sources and opportunities will be sought and identified.

Table 3. Risk Register Table.

References

[1] http://www-misr.jpl.nasa.gov/Mission/

[2] https://eosweb.larc.nasa.gov/sites/default/files/project/misr/guide/misr_ov.pdf

[3] http://www-isr.jpl.nasa.gov/publicationFiles/Chrien2002-TGRS.pdf

[4] https://www.agi.com/