Preliminary design of a CubeSat in loose formation with ICEYE-X16 for plastic litter detection

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Abstract. Every year, more than 14 million metric tons of plastic are estimated to enter rivers, lakes, and seas [1], becoming one of the main sources of pollution with significant economic and ecological impact on sensitive habitats, welfare, and vulnerable, endangered species. In this context, keeping track of plastic litter hot-spots and their evolution in time - both in open sea and coastal areas - becomes of fundamental importance. Plastic detection from space is at an early stage and, although some interesting capabilities have been demonstrated by multi-spectral imagery, hyperspectral sensing, and GNSS reflectometry, such technologies do not yet allow for the operational detection and monitoring of plastic from space on a global scale, with sufficient temporal and spatial coverage. The characteristics of Synthetic Aperture Radar (SAR) imagery would represent a keystone to realize almost continuous global monitoring of plastic litter at sea, but robust and reliable approaches for SAR-based plastic detection at sea are not available. The main problem is the lack of a large and assessed dataset to train and test new procedures and methods (e.g., deep learning) on large scales. Starting from this point, CROSSEYE (Combined in pendulum Remote Observation cubeSat System for icEYE) mission is presented with the objective to generate a wide dataset of multi-spectral and SAR images collected at the same time over the same areas. Plastic detection in multi-spectral images is mature enough to be used as a ground truth to cue SAR-based algorithms that autonomously perform the same task. CROSSEYE exploits a pre-existing SAR satellite belonging to ICEYE constellation - ICEYE-X16 - and completes it with an additional multi-spectral camera equipped on a 6U CubeSat. The results coming from the preliminary design of CROSSEYE demonstrate the feasibility of a mission capable of detecting plastic debris from space by using state-of-the-art technologies.

Introduction

The primary objective of this mission is to validate an innovative measurement principle of combining acquisitions from different sensors, specifically electro-optical (EO) and radar systems. By leveraging the respective strengths of these technologies, namely the all-weather and all-time capabilities of radars and the spectral analysis capabilities of EO sensors, the aim is to detect plastic pollution floating in open sea (20 km or more from the coast) [2]. To achieve this, the mission will gather a comprehensive dataset of multi-spectral and synthetic aperture radar (SAR) images collected simultaneously (within four hours) over the same areas. The detection of plastic in the multi-spectral images will serve as a cue for SAR-based algorithms to perform the same task [3]. Furthermore, CROSSEYE will demonstrate how the aforementioned measurement principle can be enabled by means of a simple low-cost platform, both exploiting and enhancing the capabilities of other missions already in orbit. The mission will raise awareness of marine plastic litter among the general public, governments, and related organizations, stimulating interest in the topic and attracting investments towards finding solutions. These objectives are aligned with the United Nations Sustainable Development Goals (SDGs) 6 [4] and 14 [5] addressing clean water, sanitation, conservation and sustainable use of marine resources.

Payload

Electro-optical pushbroom scanners have a long history of successful implementation in space applications, often relying on readily available Commercial Off-The-Shelf (COTS) components. However, the requirements of the CROSSEYE mission pose a challenge in finding off-the-shelf sensors that can meet the mission criteria while being compatible with a 6U CubeSat standard platform in terms of mass and sizes. For plastic debris detection, a 20 m ground resolution is needed [6] as well as a wide spectral range from VNIR to SWIR bands. In particular, [6] and [7] report how the computation of certain indexes might aid the detection of floating debris: the Floating Debris Index (FDI), the Normalized Difference Vegetation Index (NDVI), and the Floating Algae Index (FAI). To calculate these indexes, the payload will need to detect several bands inspired from the Sentinel-2 Multi-Spectral Instrument (MSI) - B2, B3, B4, B6, B8, B11 [8]. Consequently, a custom multispectral pushbroom scanner (Table 1) is specifically designed to meet the needs of the mission. To accommodate the different wavelength ranges, two separate detectors are necessary as the technology employed for Visible and NIR wavelengths (VNIR) differs from that required for SWIR (Short-Wave InfraRed) wavelengths. To address CubeSat size limitations, the camera utilizes a single focal plane, where the two mentioned detectors share the same optic scheme rather than having separate pushbroom designs. Special band-pass filters are necessary for the detectors to effectively sense the specific bands listed before.

Table 1 - Pushbroom scanner main specifications

		VNIR	SWIR
Telescope parameters	Focal length [mm]	400	400
	Aperture [mm]	96.0	96.0
	F/#	4.17	4.17
	FOV across track [deg]	1.76	2.20
	Swath width [km]	16.0	20.0
	Ground sampling distance [m]	15.6	9.80
	MTF @ 32.5 lin/mm	0.66	0.66
Focal plane parameters	Number of pixel (H x V)	1024 x 25	2048 x 1
	Pixel size [µm]	12 x 12	7.5 x 7.5
	Number of bands	5	1
	Pixel depth [bits per pixel]	8	8
Mission parameters	Altitude [km]	520	
	Ground resolution [m]	20.0	
	Target frequency [lin/mm]	32.5	
Sizing parameters	Mass [kg]	4.09	
	Volume [mm^3]	1.59e+06 (< 2U)	
	Data rate [Mbps]	473	
	Power consumption (Standby-On) [W]	1.00-35.0 W	

Orbit design - pendulum formation

CROSSEYE mission concept is developed around the notion of pendulum configuration, a particular type of loose formation flying, also known as parallel orbits formation. CROSSEYE CubeSat flies at a safe distance from ICEYE-X16, without affecting, limiting, or altering its functionalities. The goal is to have CROSSEYE S/C as deputy and to have the chief role covered by ICEYE-X16 S/C, an X-band SAR satellite launched in January 2022. The orbital parameters of the chief satellite are reported in Table 2.

Table 2 - ICEYE X-16 orbital parameters

Altitude [km]	Inclination [deg]	LTAN	Eccentricity	AOP [deg]
525	97.485	10:00 PM	0.0011925	67.3522

According to the chosen configuration, CROSSEYE S/C orbit is defined in relation to the orbital parameters of ICEYE-X16 S/C: the formation is achieved by separating the orbits of the two spacecrafts in terms of Right Ascension of the Ascending Node (RAAN) Ω and true anomaly ν. $\Delta\Omega$ and $\Delta\nu$ are determined from geometrical considerations (Fig. 1), where R_B is the Slant Range at boresight, a is the angle between CROSSEYE S/C and ICEYE-X16 S/C nadiral direction of observation, q is the aperture angle of ICEYE-X16 SAR. Given the risk of collision, especially when flying where the orbits cross - at poles -, CROSSEYE S/C and ICEYE-X16 S/C are separated in eccentricity, too [9]. The pendulum formation parameters are listed in Table 3; the CROSSEYE S/C orbital parameters are derived (Table 4). The orbit is defined as SSO, and the Argument of Perigee (AOP) is chosen to make the orbit of CROSSEYE S/C frozen [10].

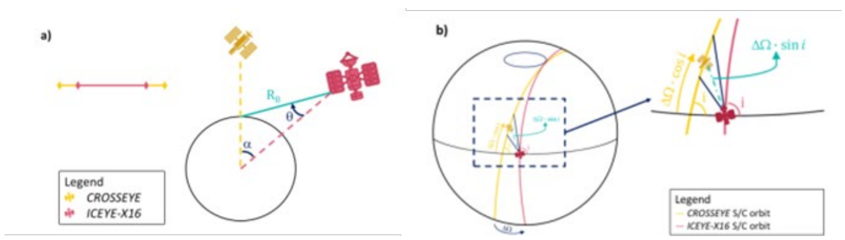

Fig. 1 - a) CROSSEYE and ICEYE-X16 relative observation geometry; b) Pendulum configuration: geometry

Table 3 - Pendulum formation parameters

$\Delta\Omega$ [deg]	$\Delta\nu$ [deg]	Δe
1.7263	-0.22488	-1.2149 e-04

Table 4 - CROSSEYE S/C orbital parameters

Altitude [km]	Inclination [deg]	LTAN	Eccentricity	AOP [deg]
525	97.485	10:00 PM	0.0010710	90

Space Segment

Other than the payload, CROSSEYE S/C consists of an attitude determination and control subsystem (ADCS), an on-board data-handling subsystem, an on-board software, a communication subsystem, an electric power subsystem (EPS), a passive thermal control subsystem (TCS), a chemical propulsion subsystem. A GNSS receiver is mounted on the platform to obtain accurate position and velocity measurements. ADCS guarantees Nadir pointing during observations with a minimum accuracy of 1% of the FOV of the equipped EO payload. As attitude control, a three-axis stabilized strategy is adopted by pairing reaction wheels with magnetorquers. Concerning the EPS, triple junction GaAs solar cells are selected for the solar arrays and Lithium-Polymer are chosen for the batteries. TCS consists of a thermal coating formed by a mixture of aluminium and white paint. Considering the significant data rate of the payload, TT&C subsystem is composed of an X-band antenna and a diplexer interfacing with an X-band transceiver. As for to the propulsion subsystem, thrusters use an ammonium dinitramide-based *green* monopropellant, in line with the sustainable nature of the mission. Except for the payload, all the components of the subsystems are COTS and easily integrable with each other, resulting in a standard 6U CubeSat architecture compliant with the CubeSat Design Specifications [11]. CROSSEYE space segment communicates with its ground segment. This relies on 11 of the 17 active Leaf Space network ground stations placed at middle latitudes all around the world.

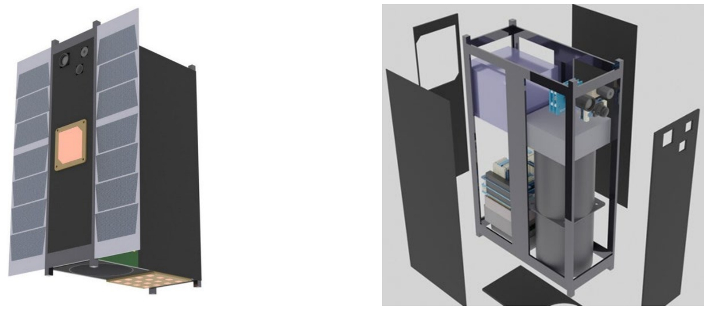

Fig. 2 - CROSSEYE platform CAD model and exploded view

Conclusions and further development

An incremental strategy can be implemented for CROSSEYE mission: by limiting the initial expenditure to a single CubeSat mission, this can be replaced or augmented with future missions of the same type to widen the quantity and quality of collected data. The design here proposed is easily adaptable to other SAR-equipped platforms that, mutatis mutandis, will have the capability to build a database that is tailored to fit the customer's demands (i.e., wildfire, coastal erosion, plastics). In general, the capabilities of CubeSat-related technologies are expected to improve in coming years: the combination of miniaturization challenges, and the potential for future technological advancements create an exciting prospect for the CROSSEYE mission. Else than technicalities, the mission will set the stage for significant contribution to plastic litter detection from space, promoting sustainability and furthering the understanding of Earth's ecosystem.

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