Title: “CROSSEYE: a CubeSat constellation for plastic litter detection in open sea by combining electro-optical and synthetic aperture radar acquisitions”

Primary Point of Contact (POC) : R. Minichini[1]
Email: ra.minichini@studenti.unina.it
Co-authors: M. Salvato[1], F. Pelliccia[1], S. Barone[1], S. D. dell’Aquila[1], V. Esposito[1], M. Madonna[1], A. Mazzeo[1], I. Salerno[1], A. Verde[1], M. Grasso[1], A. Gigantino[1], A. Renga[1]
Organization: [1]Università degli Studi di Napoli Federico II, Dipartimento di Ingegneria Industriale, Piazzale Tecchio 80, 80125, Napoli, Italy

Need

Every year, 14 million metric tons of plastic are estimated to enter rivers, lakes, seas [1], becoming one of the main sources of pollution with significant economic and ecological impact on sensitive habitats, welfare, and vulnerable, endangered species. Plastic detection from space is still at an early stage: 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, while Synthetic Aperture Radar (SAR) imagery lacks a robust and reliable approach for plastic detection at sea. CROSSEYE (Combined in pendulum Remote Observation cubeSat System for icEYE) fills this gap with an innovative approach for plastic litter detection by taking advantage of strong points of electro-optical (EO) acquisitions and by merging them with weak points of SAR technology. In particular ICEYE [2], a constellation of 27 X-band SAR microsatellites - the world’s largest SAR-equipped constellation of microsatellites - is chosen as the target for CROSSEYE implementation. CROSSEYE combines its EO acquisitions with the persistent monitoring capabilities and low revisit time [3] of ICEYE, thus enabling the potential development of autonomous plastic litter detection with SAR imaging.

Mission Objectives

Primary objectives

- ✓ Detection of floating plastic debris in open sea (distance of more than 20 km from coast [4])
- ✓ Validation of a measurement principle to demonstrate the potential of combined acquisitions performed by different sensors - EO and SAR - exploiting the strengths of both technologies: the all-weather and all-time inborn properties of radars, and the EO capability to analyze and to discern the spectral signatures of different elements of interest
- ✓ Generation of a wide dataset of multi-spectral and SAR images collected at the same time over the same areas. Plastic detection in multi-spectral images shall be then used to cue SAR-based algorithms to perform the same task [5]

Secondary objectives

- ✓ Water quality monitoring with particular attention to the phenomenon of algal bloom [6] [7]
- ✓ To raise awareness of marine plastic litter among general public, governments and organizations, contributing to stimulate interest and attract investments to search for a solution by also assessing UN SDGs 6, 14 [8] [9]

Concept of Operations

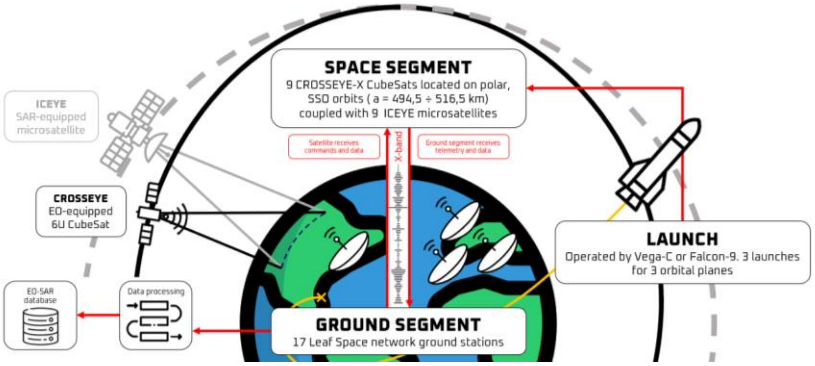

Figure 1 - CROSSEYE mission segments block diagram

CROSSEYE mission space segment consists of a constellation of nine 6U-CubeSats arranged on three orbital planes - all Sun-Synchronous orbits - matching nine corresponding satellites among the ICEYE constellation. Each CROSSEYE-X platform houses a multi-spectral pushbroom scanner specifically designed for plastic debris detection. All the acquired payload data are stored and then forwarded via X-band link to the CROSSEYE ground segment. This segment relies on Leaf Space service, a network of 17 active ground stations placed at middle latitude locations distributed all around the world; The arrangement of Leaf Space stations makes the contact with CROSSEYE particularly convenient in terms of contact time and maximum lag between consecutive accesses. The three needed orbital launches will be operated by Vega-C or, alternatively, by Falcon-9; their selection is due to strict requirements in terms of initial orbit insertion from Orbit Control maneuvers. The three segments and their interaction are represented in Figure 1.

CROSSEYE mission consists of six phases, hereinafter described:

- ✓ **LEOP (Launch and Early OPerations) -** launch, detumbling, deployment of solar panels, Sun pointing (duration: few orbits)
- ✓ **COMMISSIONING** - initial orbit determination and tracking, first contact, sequential activation and checkout of spacecraft subsystems, calibration of payloads, sensors, and control systems (duration: 1 week)
- ✓ **FINAL ORBIT INSERTION -** propulsion subsystem activation for nominal orbit insertion and phasing, ADCS to point the thrust (duration: 1 month)
- ✓ **OPERATIONS** - payload acquisitions (duty cycle = 5% of the orbit period) in Nadir pointing thanks to ADCS, downlink for payload data (alternatively store and forward), communication link with the ground station also for telemetry and commands, station keeping when required (duration: 20 months)
- ✓ **EOL (End Of Life) DISPOSAL -** depletion of propellant and battery discharge (decay within 5 years in compliance with CubeSat Federal Communications Commission guidelines)
- ✓ **SAFE MODE** - Sun pointing, communications on for H/K data, payload equipment off

Key Performance Parameters

- ✓ CROSSEYE-X platform shall acquire images through a multi-spectral pushbroom scanner designed to have a resolution of 20 m (this is the minimum ground resolution that allows to detect plastic patches in open sea [10])
- ✓ CROSSEYE-X platform shall coordinate its electro-optical acquisitions so that they are simultaneous [5] with respect to the corresponding ICEYE radar acquisitions. The ideal operating condition in terms of EO-radar relative geometry is the one in which the overlap between the swath widths of the two instruments occurs
- ✓ CROSSEYE-X payload shall acquire images in six bands from VNIR to SWIR wavelengths to recognize all the spectral signatures of plastic objects and to allow the computation of FDI, NDVI, FAI indexes [7] [10] [11]. This will represent the plastic ground truth part of the database, which will become instrumental for the training of an accurate detection SAR-based algorithm

Space Segment Description

CROSSEYE mission involves different CubeSats operating at different working conditions (i.e., altitudes, orbital planes, illumination conditions). Instead of designing a dedicated platform for each one of the aforementioned conditions, a *worst-case scenario philosophy* has been adopted throughout the platform design process. Each subsystem included in the platform is sized for the most demanding scenario among all nine CubeSats in the constellation, resulting in a unified, scalable platform, the core of the CROSSEYE mission: CROSSEYE-X.

Since plastic detection from space poses significant mission constraints both in terms of ground resolution (≤ 20 m) and needed spectral bands (VNIR-SWIR), different electro-optical technologies are necessary to realize a payload that has the capability to capture all the spectral signatures of interest: a custom double-detector single-focal plane pushbroom scanner is conceived for CROSSEYE-X. Other than the payload, each platform consists of an attitude determination and control subsystem (ADCS), an on-board data-handling subsystem (OBDH), an on-board computer (OBC), a communication subsystem (TT&C), an electric power subsystem (EPS), a passive thermal control subsystem (TCS), and a chemical propulsion subsystem. A GNSS receiver is mounted to obtain accurate position and velocity measurements. ADCS ensures highly accurate Nadir pointing (1% of the FOV of the equipped payload) during observations. In terms of attitude control, a three-axis stabilized strategy is adopted using reaction wheels and magnetorquers. For EPS, triple junction GaAs solar cells are selected for the solar arrays, coupled with Lithium-Polymer batteries. TCS consists of a thermal coating formed by a mixture of aluminium and white paint. The TT&C subsystem is composed by an X-band antenna and a diplexer interfacing with an X-band transceiver. As for the Propulsion subsystem, thrusters use an ammonium dinitramide-based *green* monopropellant. The block diagram summarizing all the interfaces between subsystems is represented in Figure 2 (red connections represent TCS control, light blue lines display EPS control over subsystems' required power; all subsystems communicate with the OBC). The mass and power budgets of CROSSEYE-X Phase 0/A design are detailed in Table 1. This proves the platform (Figure 3) to be compliant with CubeSat design specifications [12] and feasible in terms of hardware availability on the market, with the only exception of the custom payload.

Table 1 - CROSSEYE-X subsystems, mass and power budget

	Component	Hardware	Quantity	Mass (g)	Volume (mm^3)	Peak Power (W)
ADCS	ADCS sensors	Cubespace CubeADCS 3-Axis	1	555	88.1 x 94.5 x 61.5	2.30
PROP	Propulsion	ArgoMoon MiPS	1	2065	1.3 U	20.0-1.00
TT&C	Antenna	X-Band Payload Telemetry Antenna	1	60.0	72.6 x 72.6 x 11.0	3.00
	Diplexer	WiRan X-band Diplexer	1	115	96.0 x 96.0 x 14.5	15.0
	Transceiver	IQ spacecom XLink-X	1	220	90.0 x 65.0 x 25.3	1.45
OBC	CPU	Proton200k-L	1	140	94.0 x 91.1 x 13.0	1.50
EPS	Solar panels	EnduroSat 3U deployable solar array	2	270	-	-
	Battery + PCDU	EnduroSat EPS I PLUS	1	283	90.0 x 96.0 x 30.0	1.00
PAY	Multi-spectral pushbroom scanner	CUSTOM component	1	4089	2.2 U	35.0/1.00 On/Stand-by
TCS	White paint	AZW/LA-II	1	-		Passive
STR		6U CubeSat structure	1	~1200	6.7 U	-
TOTAL MASS (kg)				**11.1**		
TOTAL AVERAGE POWER CONSUMPTION (W)				**7.50**		

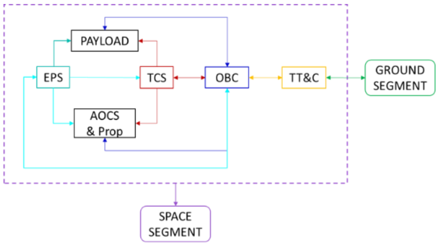

Figure 2 - CROSSEYE-X system architecture

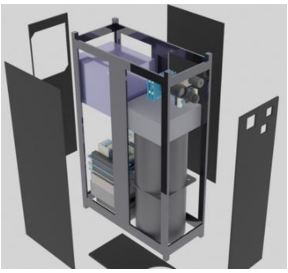

Figure 3 - CROSSEYE-X exploded view, Blender

Orbit/Constellation/Description

Among the 27 currently operative ICEYE satellites, the ones examined are narrowed down by investigating the Local Time of Ascending Node (LTAN): the most appropriate ones with respect to illumination conditions for passive multi-spectral acquisitions performed by CROSSEYE-X are then chosen for the constellation design. The orbital parameters of the compatible ICEYE satellites, at a given date and time (29/11/2023, 00:00 UTC), are listed in Table 2 [13]: inclination (i), right ascension of the ascending node (Ω), eccentricity (e), Mean anomaly (M), semi-major axis (a). Starting from the primary objectives of CROSSEYE mission, each CROSSEYE-X satellite is coupled with a compatible ICEYE satellite from Table 2, and coordinates its electro-optical acquisitions with the ones performed by the SAR of the latter. To do this, all the spacecraft in the CROSSEYE constellation are arranged in pendulum loose formation [14] [15] with one of the listed satellites of the ICEYE constellation. This type of formation guarantees that all CROSSEYE-X CubeSats fly at safe distance from ICEYE satellites without affecting, limiting, or altering their functionalities and without the need for an intersatellite link between coupled platforms. For each CROSSEYE-X, the orbital parameters that enable the pendulum formation with the corresponding ICEYE (referenced to the same date and time of Table 2) are calculated:

- ✓ a is defined so to have the same orbital period among platforms
- ✓ i, M, Ω are calculated so to have a complete overlap between the swath widths of the instruments onboard the two satellites. This is achieved by separating their respective orbits in terms of Right Ascension of the Ascending Node ($\Delta\Omega$) and mean anomaly (ΔM). These quantities are determined from geometrical considerations (Figure 4), where R_B is the Slant Range at boresight, α is the angle between CROSSEYE-X and ICEYE nadiral direction of observation, θ is the aperture angle of ICEYE SAR
- ✓ e is slightly modified in order to have a safety spatial separation where the two orbits intersect (at their poles)

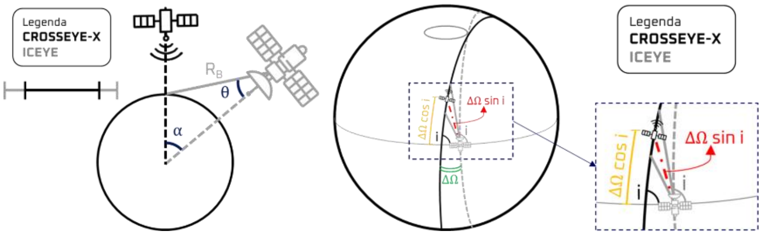

Figure 4 - Derivation of ICEYE and CROSSEYE-X pendulum formation parameters

The resulting constellation (Table 3, Figure 5) consists of three orbital planes of Sun-Synchronous orbits, LTAN of 10:00 PM, 1:15 AM, 9:30 PM and a from 493.5 km to 516.5 km, for a total of nine CROSSEYE-X platforms.

Table 2 - ICEYE constellation orbital elements, Space-Track.org and STK Student

Satellite	**i** (deg)	**Ω** (deg)	**e**	**M** (deg)	**a** (km)	LTAN
ICEYE-X14	97.4404	237.1289	0.0009237	137.5233	497.5	10:00 PM
ICEYE-X16	97.4387	237.1008	0.0008227	140.4296	494.5	10:00 PM
ICEYE-X17	97.5436	287.5070	0.0008028	31.2636	494.5	1:15 AM
ICEYE-X18	97.5396	286.3550	0.0016521	34.2496	516.0	1:15 AM
ICEYE-X19	97.5415	286.5129	0.0018223	40.2412	514.5	1:15 AM
ICEYE-X20	97.5424	287.4013	0.0009826	20.6571	499.0	1:15 AM
ICEYE-X24	97.5426	287.2467	0.0006704	30.9484	493.5	1:15 AM
ICEYE-X21	97.4792	229.5738	0.0012587	349.3874	516.5	9:30 PM
ICEYE-X27	97.4797	229.5714	0.0012910	348.0208	515.5	9:30 PM

Table 3 - CROSSEYE constellation orbital elements

Satellite	**i** (deg)	**Ω** (deg)	**e**	**M** (deg)	**a** (km)	LTAN
CROSSEYE-X14	97.3970	236.0270	0.0010754	137.6660	497.5	10:00 PM
CROSSEYE-X16	97.3856	235.9989	0.0010759	140.5723	494.5	10:00 PM
CROSSEYE-X17	97.3856	286.4051	0.0010756	31.4063	494.5	1:15 AM
CROSSEYE-X18	97.4673	285.2531	0.0010723	34.3942	516.0	1:15 AM
CROSSEYE-X19	97.4615	285.4110	0.0010725	40.3858	514.5	1:15 AM
CROSSEYE-X20	97.4027	286.2994	0.0010749	20.8017	499.0	1:15 AM
CROSSEYE-X24	97.3819	286.1448	0.0010758	31.0930	493.5	1:15 AM
CROSSEYE-X21	97.4692	228.4719	0.0010723	349.5308	516.5	9:30 PM
CROSSEYE-X27	97.4653	228.4695	0.0010725	348.1642	515.5	9:30 PM

Implementation Plan

University of Naples Federico II has a long-term heritage in the field of analysis and design of space missions and payloads, with particular reference to missions in LEO for Earth Observation. By taking advantage of the collaboration with industrial partners and from Department of Industrial Engineering laboratories headed by different research groups, CROSSEYE mission will be developed, from phases 0/A to F (Figure 6). CROSSEYE mission cost (Table 5) can be estimated by using the Earth Orbiting Total Nonrecurring Cost [16] for 2023 fiscal year. The team of CROSSEYE mission is composed of ten permanent members organized in eleven work packages (WP). Each WP can count on a Responsible and,

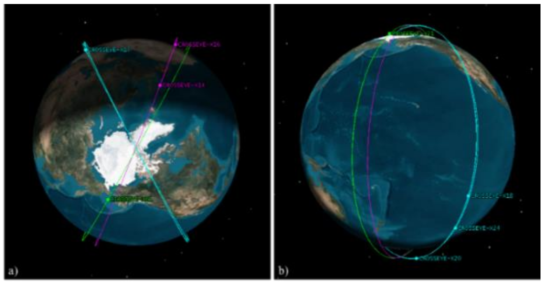

Figure 5 - CROSSEYE constellation: a) XY plane, b) YZ plane in the Earth Inertial Reference Frame, STK Student

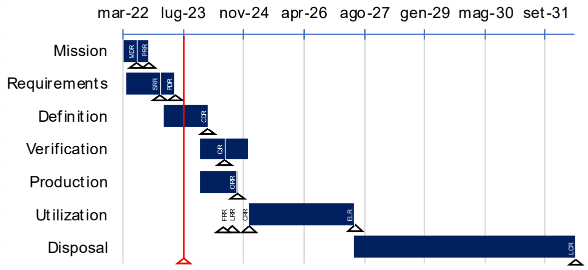

Figure 6 - CROSSEYE mission program

on request, on other contributions coming from professors or mentors from industrial partners. All actions are traced through document production. The mission exhibits five major risks, assessed in Table 4 and Figure 7.

CROSSEYE mission has already benefitted from a constant contact with European Space Agency educational programs - such as CubeSat Concurrent Engineering Workshop 2023 - that has provided the team with procedural, technical and organizational tools specific for CubeSat missions.

Table 5 - CROSSEYE mission estimated cost

Satellite	Cost, FY 2023 ($K)
Spacecraft + Payload	13767
Integration, Assembly and Test	1836
Program Level	3025
Flight Support	806
Aerospace Ground Equipment	872
Total cost per satellite	**19870**
Total cost CROSSEYE	**178833**

CROSSEYE constellation brings a fresh and outstanding idea on how a constellation of small, modular satellites could be used to expand the functionalities of much larger missions like ICEYE. CROSSEYE's principle of measurement is the key to the innovation it brings: the idea of moving *together with* already existing satellite constellations to generate a common database of high intrinsic scientific value has countless applications, both civil and strategic. In the future, CROSSEYE could mirror the ICEYE mission launch schedule, adopting an incremental approach with a new CROSSEYE-X for every new, compatible, ICEYE platform. Alternatively, CROSSEYE primary objectives can be switched, *mutatis mutandis*, to build a database that is tailored to the customer's needs (i.e., wildfires, coastal erosion, plastics), ensuring a determinant interchangeability in possible developments of the mission with different - yet modular - constellations of low-cost satellites.

Table 4 - CROSSEYE mission major risks, likelihood and impact

Risk	Description	L	I
PAY	Custom payload not feasible or integrable	2	5
FOR	Pendulum formation with ICEYE not reached	3	4
DATA	EO/SAR database building technique not implementable	3	4
FAIL	Not mature subsystems parts cause unexpected failures	1	5
MAN	Lack of handover, schedule delay, loss of information	2	3

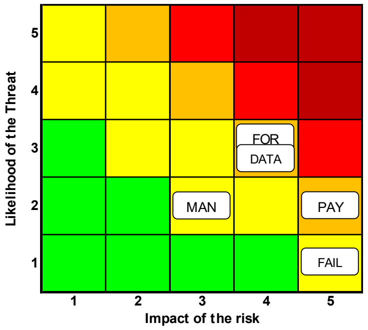

Figure 7 - CROSSEYE mission major risks chart

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