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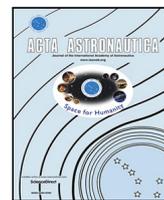
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## Review article

# Highly-miniaturized spacecraft “PlanarSat”: Evaluating prospects and challenges through a survey of femto & atto satellite missions

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## ABSTRACT

As satellite technology advances, there has been a notable trend towards miniaturization, leading to the development of increasingly smaller satellites such as femtosatellites and attosatellites. A new emerging form of such satellites is often called ChipSat, with unique designs that utilize both surfaces of a single plane to maximize functionality within limited dimensions. Initially, the term ChipSat referred to system-on-a-chip satellites but it has since expanded to include centimeter and millimeter scale spacecraft. To provide a clearer terminology, this paper introduces the term “PlanarSat” for such a planar spacecraft. Despite the challenges in deployment and the constraints, such as cost, size, access to space, and capabilities, of miniaturized subsystems, these satellites represent a significant shift in space technology, aiming for cost-effective solutions and innovative mission capabilities. This study reviews thirty sub-100-gram satellites, analyzing their design, deployment, and potential for future advancements in a comparative manner. In this study, satellite independence was defined based on system-wise independence, highlighting operational autonomy irrespective of physical connections. The survey’s findings highlight technological advancements and potential applications for these very small spacecraft, which are pushing the boundaries of what is feasible with smaller satellites and how these satellites were or planned to be delivered to orbit. The analysis results provide a basic cost comparison, providing information on hardware and launch costs, taking the instantaneous data rate as a reference point, underscoring the need for a new systems engineering approach to the design of such satellites.

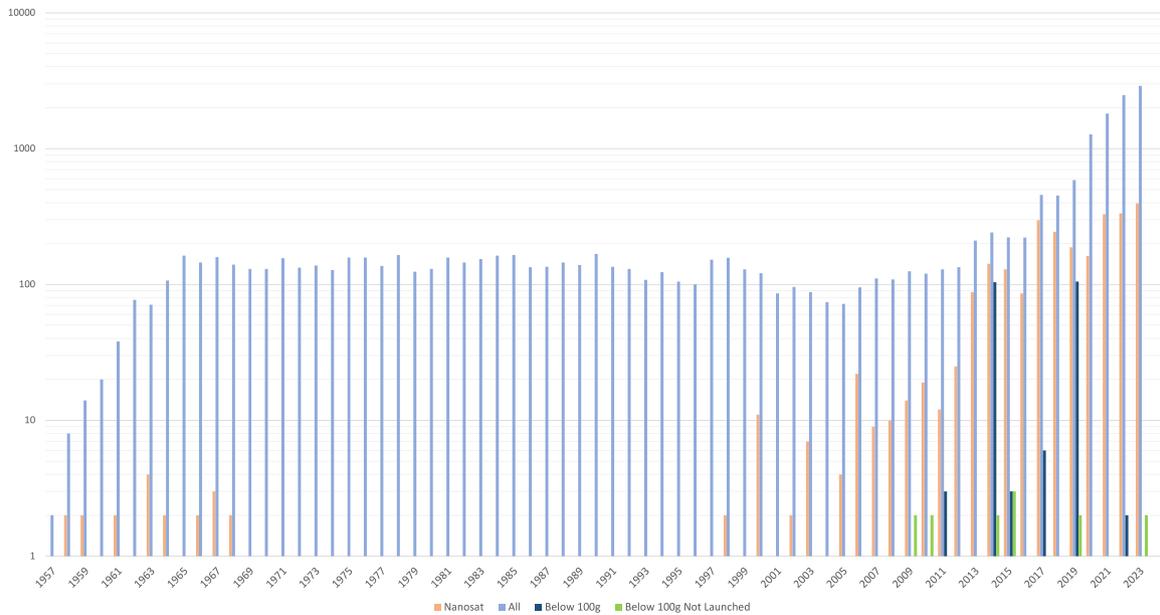
## 1. Introduction

Since the launch of Sputnik, the number of satellites launched has increased significantly. By the end of 2023, the total number of satellites launched reached 20 257, as calculated from the individual numbers shown in Fig. 1 [1]. Initially, these satellites, without any detailed classification, had various sizes and masses. A mass-based classification was introduced to organize satellite classes such as small satellites, microsatellites, nanosatellites, picosatellites, femtosatellites, and attosatellites as satellite technology and usage expanded, as shown in Table 1. These classifications have proven useful for standardization and subsequent planning of satellite launches and missions, influencing parameters such as launch costs, system development, and deployment strategies.

While there has been significant progress in miniaturization, evidenced by the increasing use of smaller satellites, larger satellites remain critical for many applications, and class diversification continues to grow, enabling greater mission flexibility. The advancements in

integrated circuit (IC) and micro-electromechanical systems (MEMS) manufacturing methods enabled mass-produced devices. Advancements in MEMS technology and the use of COTS components have facilitated the miniaturization of systems such as sensors and actuators, enabling smaller and more affordable designs. These advancements have reduced development time and benefited from the proven reliability of mass-produced electronics in specific applications [2]. However, this miniaturization often introduces challenges, including increased failure rates, reduced redundancy, and vulnerability to radiation effects, particularly in small satellite platforms such as CubeSats [3]. Despite these limitations, tailored strategies like ‘Careful COTS’ selection and modular design approaches have demonstrated that miniaturized systems can meet mission requirements effectively in cost-sensitive applications. This has led to an increase in small satellite mission success rates, in turn, which enables more small satellite missions to be proposed by various institutions, universities, companies, and space agencies. The best example of this is the CubeSats standard in nano- and microsatellite formats. Some satellites weigh as little as 1 kg, resulting

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**Fig. 1.** Number of Satellite Launched Per Year [1,5,6]. The colors represent different satellite classes for launched satellites: light blue indicates all satellites, orange indicates nanosatellites, and dark blue indicates satellites below 100g. Additionally, in green, canceled or conceptual atto/femto satellites are displayed to illustrate the general interest in these classes. Note that the Y-axis is presented on a logarithmic scale to clearly visualize all satellite classes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Satellite classification up to 100 kg Mass [7] and the world first in the corresponding class.

Classification	Weight [kg]	World first(s)
Micro satellite	10–100	Sputnik
Nano satellite	1–10	Vanguard 1
Pico satellite	0.1–1	PICO21 & PICO23
Femto satellite	0.01–0.1	Pocket-PUCP
Atto satellite	≤0.01	Sprites

in an almost 80% reduction in average satellite mass from 2012 to 2016 and a subsequent threefold increase in the number of small satellites launched into orbit [4]. This trend is shown in Fig. 1, the majority with masses of 1–10 kg or more than 100 kg.

Parallel to the CubeSat developments, various different concepts started to emerge with the goal of creating spacecraft smaller than nano- and picosatellites. The latest of these are the femto- and attosatellites. Although there are currently a limited number of missions launched in this class of satellites, the growing number of concepts underscores their benefits—low cost, fast production, and multi-point measurements. Therefore, they may see an increase in usage in the future, as shown in Fig. 1. The development of these satellites often appears to be from a ‘bottom-up’ approach, where the design starts with achieving the smallest possible size with the mission itself as an afterthought. Designs are predominantly influenced by the individual’s knowledge of specific electronic components and the necessary satellite functions. Early examples of such satellite design concepts that can be classified as atto/femtosatellite are ChipSat [8–11], and PCBSat [12]. Although the initial conceptual designs, such as ChipSat and PCBSat, were not launched, they served as the foundation for subsequent missions like WikiSat, RyeFEM, and ThumbSat [13–15]. Some of these later missions, including Suchai-3 Femto satellite and Sprite, successfully reached orbit, expanding on the early concepts. Previously, there are three surveys on femtosatellites [16–18] and one survey on attosatellites [19]. Tahri et al. focus on ultra small satellite (USS), explaining the process of how the satellites become even smaller and compare two femtosatellites (PCBSat, WikiSat) on multiple aspects such as subsystems, and cost [17]. Perez et al. combine the information

on the available femtosatellites and give a brief insight on how to control the attitude and orbit of femtosatellites [16]. Niccolai et al. focus on dynamics and mission applications with a brief explanation of the state-of-the-art femtosatellites as a step to develop a “Smart Dust” femtosatellite [18]. Hein et al. explain the evolution of spacecraft size, later focusing on attosatellite characteristics and capabilities, and provide an overview of various mission possibilities [19].

The classification of small satellites, particularly those under 100 g (femtosatellites and attosatellites), traditionally relies on mass alone. However, as satellites decrease in size, design characteristics—such as dimensional ratios and flat, plane-like configurations—become increasingly important in distinguishing their functionality and potential applications. In this paper, we propose the term PlanarSat to classify a subset of femto- and attosatellites characterized by flat, single-plane designs with significant disparities between their smallest and largest dimensions. This term aims to emphasize the modularity, compactness, and suitability of these satellites for distributed applications and multi-point measurements, distinguishing them from other small satellites with bulkier configurations. However, the convergence in design approaches and the common requirements for environmental testing, frequency coordination, documentation, insurance, and launch agreements further diminish the mass-based classifications and practical differences at this scale.

Although a comprehensive survey aimed at establishing a framework for PlanarSat development has not yet been conducted, this paper attempts to fill that gap by analyzing femto- and attosatellite missions characterized by flat, single-plane designs. It includes an analysis of femto/attosatellites at various stages—launched, failed, canceled, or conceptual. By introducing a systems engineering approach and conducting a comparative study of PlanarSat versus CubeSats and PocketQubes, this work aims to provide insights into the performance and costs associated with these satellite platforms, with a particular focus on understanding PlanarSat. The existing information collected may vary between sources due to limitations in data availability during the preparation of this study. A total of 30 femto/attosatellite, including launched, failed, canceled, and conceptual studies, have been analyzed in this paper and found from various sources, including journal papers, conference proceedings, theses, news articles, project websites, and social media pages.

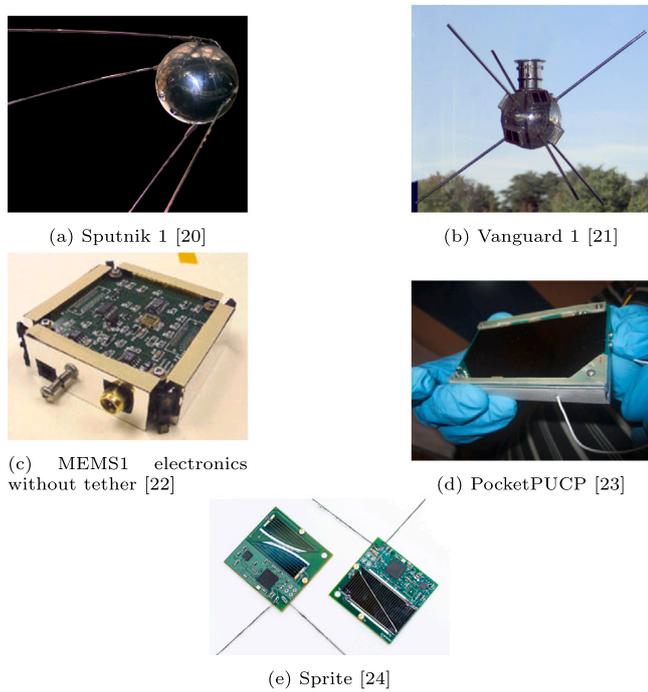


Fig. 2. The first satellites launched in their respective classes. Micro(a), nano(b), pico(c), femto(d), atto(e) satellite.

This study proposes that PlanarSat should encompass both atto and femtosatellite classes, along with other mass categories that share a focus on a flat-shape design of a single plane, where one or both faces are utilized. This broader classification reflects the diversity within the CubeSats group, which spans multiple satellite classes based on their design specifications and functionalities. While this flat design bears similarities to space sails, PlanarSats serve distinct operational purposes. Space sails leverage solar radiation pressure for propulsion [20], whereas PlanarSats function mostly as miniaturized satellites focused on sensing, communication, and distributed missions. Still due to their overlap, sails can also be seen as specialized PlanarSats.

Section 2 gives a brief explanation of each world-first satellite in their respective mass class and provides an overview on femto- and attosatellite missions. Section 3 explores the miniaturization challenges faced by femto- and attosatellites, focusing on their subsystem design, power limitations, and deployment strategies, with emphasis on innovative solutions like integrated circuits and modular designs. Section 4 introduces the concept of PlanarSat, a classification for flat, single-plane designs within femto- and attosatellite categories. It discusses how these satellites' modularity and compactness enable distributed applications, and argues for design-based classifications over mass-based ones, emphasizing shared features and operational requirements. Section 5 provides the information for how femto-attosatellites reached their orbit, rather if the satellites were deployed or attached to a larger satellite. Section 6 discussed the PlanarSat subsystems and their dependencies. Additionally talking about the functionalities of the launched femto- and attosatellites. Section 7 summarizes the possible operational modes for PlanarSat as a result of their limited size. Section 8 compares the performance of PlanarSat against CubeSats and PocketQubes in order to provide a boundary condition with respect to the required number of PlanarSat to achieve a certain data rate. Additionally, providing a cost comparison of their hardware and launch.

## 2. Path to Femto/Atto satellites and missions

Sputnik (Fig. 2(a)), launched on October 4, 1957, the world's first artificial satellite started its journey as a 83.6 kg beach ball sized object

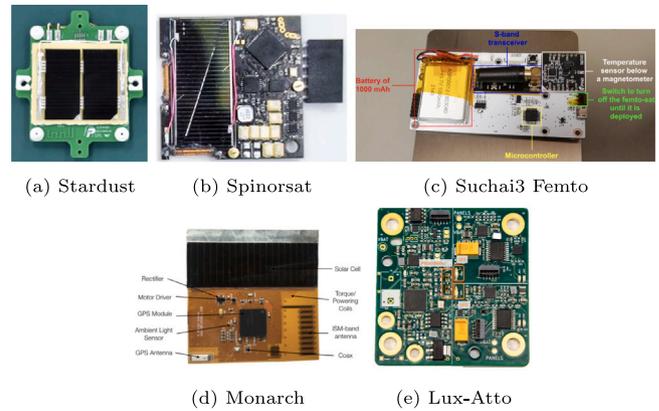


Fig. 3. Launched and planned femto/attosatellites [31–35].

of 58 cm in diameter [21]. Developed by OKB-1, now known as Energia Corporation, Sputnik, can be classified as the very first microsatellite according to today's standards (see Table 1). It was designed to transmit a signal to be received by common receivers around the planet and to be visible with small telescopes [5].

Approximately six months after the launch of Sputnik, Naval Research Laboratory in US developed Vanguard 1 (Fig. 2(b)), the first nanosatellite which was launched on March 17, 1958. Vanguard 1 was a 1.47 kg sphere with 16.5 cm diameter. It was designed to test the effects of the space environment on satellite systems in orbit, as well as the launch capabilities of a three-stage rocket [22].

The transition from nanosatellites to picosatellites and smaller classes, such as femtosatellites and attosatellites, introduces a noticeable gap in the timeline of satellite miniaturization. While nanosatellites quickly gained popularity in the early 2000s, driven by advancements in miniaturized electronics and the CubeSat standard, the progression to sub-100 g satellites has been slower. This disparity largely reflects the technological and operational challenges inherent to extreme miniaturization, including limitations in power generation, communication systems, and deployability [16]. Additionally, regulatory concerns surrounding the trackability [23,24] and deorbiting of such small spacecraft have posed barriers to widespread adoption [25,26]. Although sub-100 g satellites may not achieve the same level of ubiquity as CubeSats, they are gaining traction in specialized applications such as distributed sensor networks [12], space weather monitoring [8], and swarm missions [27]. As enabling technologies continue to mature, these satellites are likely to carve out distinct niches within the broader space ecosystem, complementing rather than replacing larger platforms.

This renewed interest in smaller satellite classes started with missions like the Orbiting Picosatellite Automatic Launcher (OPAL) project, which marked the deployment of the first picosatellites in 2000. OPAL's successful launch and deployment of Tethered Picosats provided a critical demonstration of the feasibility of sub-1 kg satellites in orbit.

On January 27, 2000, OPAL was launched [28]. It deployed the first-ever picosatellites, developed by the Aerospace Corporation, on February 6, 2000, known as Tethered Picosats (Fig. 2(c)), also referred to as MEMS1 A & MEMS1B or also Pico21 & Pico23 [29]. Each picosatellite weighs 250 gram and measures 25 × 75 × 100 mm in dimensions. This pair of picosats was deployed together, after which they released a 34 m tether to simulate constellation flight, their mission was to survive launch, listen/respond for a ground station, test MEMS radio frequency (RF) switches and transmit experimental and house keeping data [30].

More than a decade later the Pontifical Catholic University of Peru (PUCP) developed PUCP-SAT -1 and Pocket -PUCP (Fig. 2(d)). On December 6, 2013, Pocket -PUCP was deployed from PUCP-SAT-1.

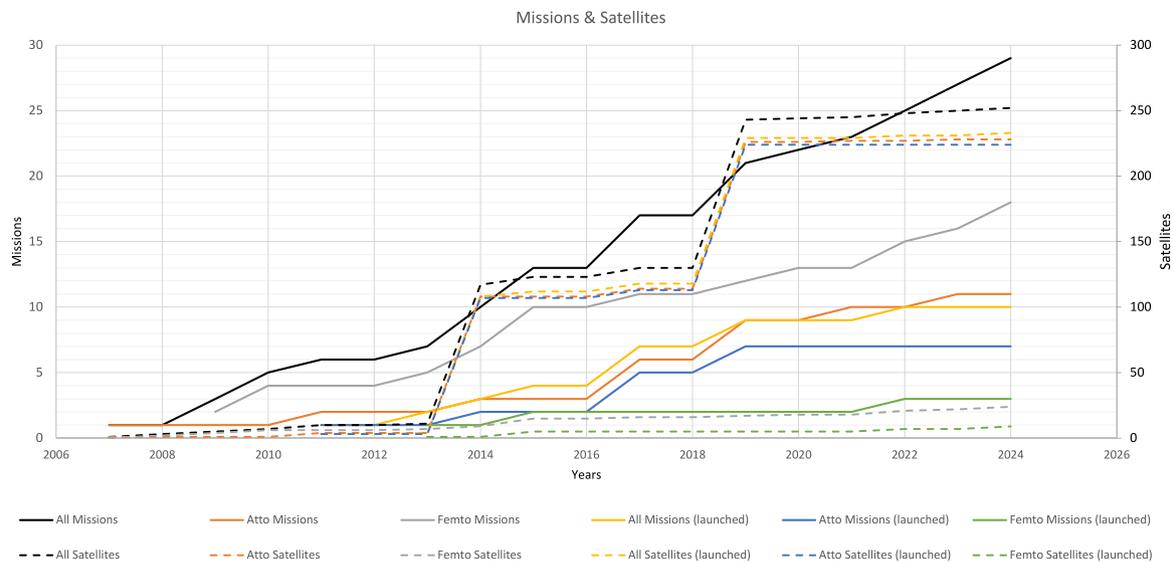


Fig. 4. Cumulative output of miniaturized satellite missions.

This satellite had itself been deployed from UNISAT-5 on November 21, 2013, which was also the launch date for UNISAT-5 [36]. It was designed to promote education and research in Peru [16]. In addition to calculating its distance and time around Earth's orbit, Pocket-PUCP also collected temperature data and transmitted this via a low-power transmitter to PUCP-SAT-1 [37].

The pursuit of miniaturization in satellite technology continues to progress, involving developments beyond femtosatellites. Sprite satellites were experimental PlanarSat (called a ChipSat by its developers) to demonstrate a different paradigm in space technology to enable cost-effective missions; if all missions were successful, there would have been 214 satellites in orbit. On March 19, 2019, the first attosatellites, known as Sprite (Fig. 2(e)) developed by Cornell University, were successfully launched aboard Kicksat-2 [38]. It is worth noting that three prototypes of the first version of Sprite satellites were tested on the International Space Station (ISS) previously in 2011. Although there was an attempted deployment of 104 Sprites from KickSat -1 in 2014, the deployment failed due to a systems malfunction [39]. Subsequent attempts in 2017 to deploy four Sprites from the Max Valier satellite also failed [40]. Additionally, in 2017, one Sprite was attached to the Max Valier satellite and another to the Venta-1 satellite [41,42]. Since the first successful deployment of a free-floating, operational satellite occurred in 2019, that mission is recognized as the inaugural launch for the attosatellite class.

In addition to Pocket-PUCP and Sprite satellites, there are three more missions which were launched into space. These are Xingchen also known as Stardust, Spinorsat, Suchai-3 Femtosatellites. Moreover, there are two more planned missions, Alpha Sail and University of Luxembourg Attosatellites (Lux-Atto, given name by the author of this paper), initially scheduled for launch in 2024 but at the time of writing it is planned for 2025.

Xingchen(Stardust), which is shown in Fig. 3(a), was launched in 2015 and developed by the National University of Defense Technology, China. Four Stardust satellites were carried on the Tiantou-3 mission. All of the satellites were mechanically attached to larger satellites. Two were connected to the Tiantou-3 satellite and the other two to the phone-sat CubeSat. The femtosatellites, Xingchen (Stardust), were designed to conduct in-orbit experiments to test the effects of space environment on such satellites and to observe the performance of a distributed space system for in-orbit measurements [31]. The combination of all these 6 satellites creates a cluster to communicate with each other and share magnetic field measurements.

Spinorsat, deployed from Kicksat -2 in 2019, together with Sprites [43]. Spinorsat, shown in Fig. 3(b) is based on Sprite satellites and

was designed by Berkeley students. The goal of the satellite was to extend the capabilities of such satellites by mass-producing them for large satellite constellations [32]. Information on the status of Spinor's mission is currently not available.

Space and Planetary Exploration Laboratory at the University of Chile developed and launched Suchai-2 and Suchai-3 CubeSats, which carried two femtosatellites (Fig. 3(c)). One of the goals of the femtosatellites was to increase measurement points in the ionosphere and magnetosphere through the mission [44]. The gathered data would be sent to the CubeSats and femtosatellites would receive the global navigation satellite system (GNSS) data sent by the CubeSats. The aim was to study the feasibility of femtosatellites estimating their position by using the radio-links [33]. The received GNSS data would be used as a reference in combination with the time difference of arrival (TDOA) and the angle of arrival (AOA) [45].

Monarch, one of several satellites inspired by Sprite technology, was developed by Hunter Adams as part of his PhD work [34,46]. Monarch, with a mass of 5 grams and dimensions of  $5 \times 5 \text{ cm}^2$ , is a printed circuit board on a kapton substrate. They are designed to be deployed in large batches from a mothership and create a swarm to collect data from multiple locations simultaneously [34]. Monarch's first launch opportunity is planned as a part of a solar sail, Alpha Sail developed by Cornell University. Four Monarchs would be placed, two on each face of the sail. This mission was designed, to test the effectiveness of a highly reflective material intended for light-sail propulsion [47].

At the time of writing, in 2024, the University of Luxembourg was planning to launch a PocketQube called POQUITO, which was scheduled for launch that same year. Three attosats are placed on a single printed circuit board (PCB). This network is approximately 18 g. In this paper, an independent satellite is defined based on system-wise independence: each satellite must operate with its own dedicated power, communication, and control subsystems, irrespective of physical connections. Therefore, the POQUITO attosatellite network, which shares components, is considered as one femtosatellite system, whereas attosatellites attached to larger satellites but operating independently remain individually classified. As a result, the whole system can also be described as a femtosatellite. The goal of this network is to demonstrate an LED-based communication in between attosatellites to transmit their data. The network's primary element can transmit data via its RF transmitter [35].

In addition to the explained launched/planned missions, various conceptual studies have been conducted by different agencies. Each investigates a different approach or application. The status and the overview of these satellite missions will be explained briefly in the following section.

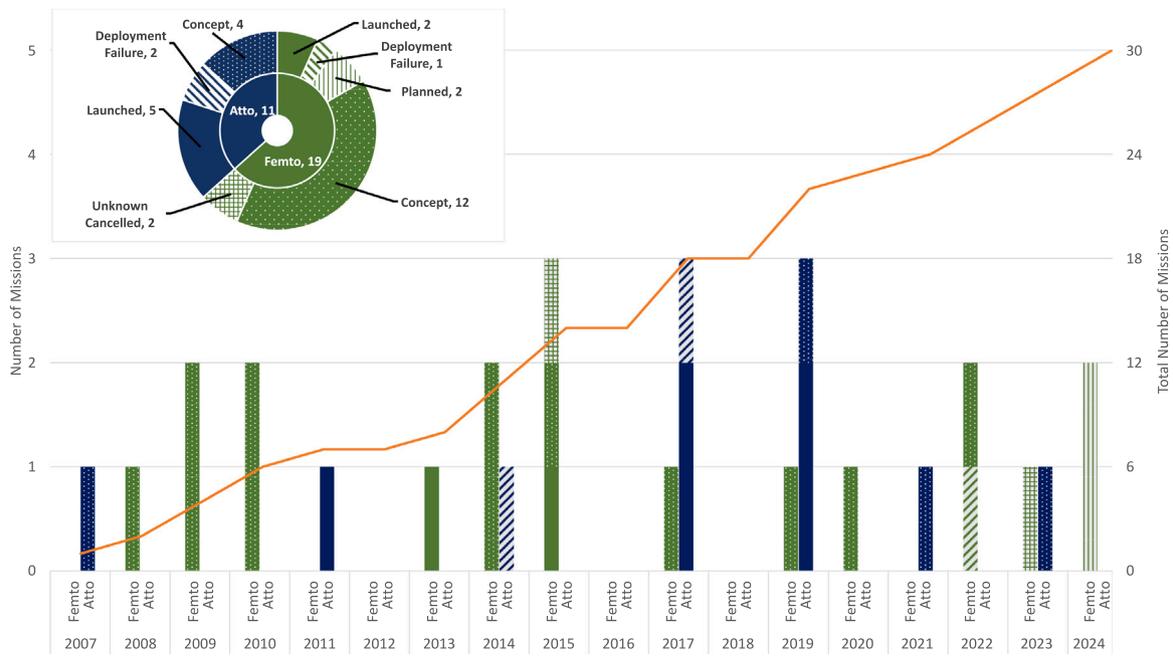


Fig. 5. Types of miniaturized satellites, their missions, and status over the years. At the time of this research, one of the planned missions by the University of Luxembourg had rescheduled its launch date to January 2025.

### 3. Overview of Femto&Attosatellite missions and characteristics

Investigated miniaturized missions mentioned in this paper are studies from the 2000s onwards. There are 30 missions in different statuses, such as launched, failed deployment, planned, concept, and unknown/canceled. In these missions, shown in Fig. 5, 11 are attosatellite and 19 are femtosatellite missions. All missions this paper investigates are presented in Table 2. The missions were categorized according to the publication date or the launch date. These missions range from technology demonstration, in-orbit measurements (temperature, gyroscope, accelerometer), location estimation, formation keeping, proof of concept, and distributed spacecraft capability to education. One-third of the missions made it to space. Fig. 4 shows seven atto-class missions, five of which use Sprite Satellites, and three femto-class missions. One of the femto-class missions is a satellite formed by combining three attosatellites on a single board. The number of satellites per mission varies from 1 to 104 satellites. Specifically in two missions, Sprite satellites planned to be deployed from Kicksat –1 (2014, deployment failure) and from Kicksat –2 (2019, successful deployment), seen in Fig. 4 have the largest impact in the total number of miniaturized spacecraft. It should be noted that these miniaturized satellites were deployed in low-Earth orbit to ensure a short orbital lifetime, thus preventing them from becoming space debris. Unlike substrate-specific categories such as ChipSats or WaferSats, the PlanarSat category explicitly encompasses a broader range of small satellites defined primarily by their planar geometry rather than substrate type. Additionally, we explicitly note that the term ‘FlatSat’ is already commonly used in spacecraft engineering to denote tabletop integration and test platforms. To prevent ambiguity, we explicitly introduce ‘PlanarSat’ here as referring specifically to operational planar spacecraft, clearly distinguishing them from these ground-based test systems.

Efforts to deploy multiple satellites in a single mission emphasize the desire to demonstrate multi-point measurements, or in other words, swarm applications. The number of satellites deployed or planned in a single mission is shown in Table 2 and Fig. 4. Although studies highlight the potential for swarm applications of femto/attosatellites, they do not specify the required number of satellites, as these missions are not yet planned and the studies primarily focus on the satellite technology itself. Studies on such satellites are conducted in eight countries: Chile,

Luxembourg, Peru, and Spain each contribute to one mission, while the US contributes to fourteen, the UK six, China three, and Canada two missions.

Most of the femto/atto satellites studies shown in Table 2 are designed for LEO just like a CubeSat or a PocketQube, their orbital lifetime is shorter for the same orbit. Various orbital perturbations and their effects are given in Ref. [67] for various altitudes. Atmospheric drag and solar radiation pressure (SRP) are the most prominent perturbations for femto/attosatellites, more than their heavier class counterparts, CubeSats and PocketQubes. Two physical characteristics affect the orbital lifetime of a spacecraft according to the expressions describing atmospheric drag and solar radiation pressure perturbations [68]. Firstly, the mass, especially the low mass of femto/ attosatellites. Secondly, since most femto/atto satellites are flat, almost 2D structures, their surface area is flat. Their largest surfaces have been used for mass –to –area calculations. To be consistent, the largest surfaces of CubeSats and PocketQubes have been used. 1 unit PocketQube is called 1P, with 5 × 5 × 5 cm<sup>3</sup> dimensions and mass 250 grams [69]. 1 unit CubeSat is 10 × 10 × 10 cm<sup>3</sup>, and in the latest CubeSat design specification, it is given that 1U CubeSat can have a mass of 2 kg [70]. Their largest surface and mass-to-area ratio characteristics are shown in Fig. 8. Femto/Atto satellites are all below 70 kg/m<sup>2</sup> as shown in Figs. 7 and 8, exhibiting a clear difference from CubeSats and PocketQubes. Similar clusters of satellites have been formed in both sub-figures. Their large area-to-mass ratios suggest that femto/atto class satellites would decay faster.

This analysis utilizes a simplified orbital decay time equation derived from orbital energy and atmospheric drag acceleration. The drag acceleration ( $\kappa_{\text{drag}}$ ) acting on a satellite is given by [71, p. 84], [72, p. 552]:

$$\kappa_{\text{drag}} = -\frac{C_D \rho A V^2}{2m} \tag{1}$$

Combining this equation with the orbital energy relationship and integrating over a small altitude interval yields the simplified orbital decay time ( $\Delta t$ ) between two altitudes:

$$\Delta t = \frac{2m(\sqrt{a_{\text{initial}}} - \sqrt{a_{\text{final}}})}{C_D \rho A \sqrt{\mu}} \tag{2}$$

**Table 2**

Studied Mission/Satellites and References. In ‘Missions Status’ column, acronyms represent: ‘C’ is Concept, ‘L’ Launched, ‘DF’ is Deployment Failure, ‘U’ is Unknown, ‘P’ is Planned. In ‘Mass’ column, information in **RED** is for attosatellites, **BLACK** is for femtosatellites, ‘e’ stands for estimated.

Mission ID	Satellite name	Mission status	Number of satellites	Semi-major Axis [km]			Mass [gr]	Dimensions [cm]	Year	References
				Eccentricity	Inclination [deg]					
1	Spaceship	C	1	6871	0.000	Low	<b>10</b>	2 × 2 × 0.3	2007	[8–11]
2	RyeF <sup>3</sup> ex	C	2	N/A	N/A	N/A	100	N/A	2008	[48,49]
3	PCBSat	C	1	6871	0.000	Low	70	9 × 9.5	2009	[12]
4	Wikisat	C	1	6871	0.000	N/A	<20	16 × 3.3	2009	[13,50–53]
5	RyeFem	C	1	6917	0.029	N/A	25	9 × 9 × 1	2010	[14,49]
6	ATOM	C	1	N/A	N/A	N/A	<100	8 × 8 × 0.15	2010	[49]
7	Sprite	L	3	6788	0.001	51.6	<b>5</b>	3.5 × 3.5 × 0.25	2011	[54,55]
8	Pocket-PUCP	L	1	6995	0.003	97.8	97	8.35 × 4.95 × 1.55	2013	[36]
9	Sprite	DF	104	6691	0.001	51.5	<b>5</b>	3.5 × 3.5 × 0.25	2014	[43]
10	Swift-A	C	1	N/A	N/A	N/A	93.5	4 × 4 × 4.25	2014	[56]
11	Swift-B	C	1	N/A	N/A	N/A	104.7	4 × 4 × 4.25	2014	[56]
12	Xingchen (Stardust)	L	4	6901	0.002	97.5	28	6.5 × 5.5 × 0.4	2015	[31]
13	Thumbsat	C	1	N/A	N/A	N/A	25	4.9 × 4.9 × 3	2015	[15,57]
14	Aoxiang	C	1	6951	0.000	40	<100	19.6 × 19 × 31.5	2015	[58]
15	SunCube	C	1	N/A	N/A	N/A	35	3 × 3 × 3	2017	[59]
16	Sprite	DF	4	6882	0.001	97.5	<b>5</b>	3.5 × 3.5 × 0.25	2017	[40,41]
17	Sprite	L	1	6882	0.001	97.5	<b>5</b>	3.5 × 3.5 × 0.25	2017	[40,41]
18	Sprite	L	1	6882	0.001	97.5	<b>5</b>	3.5 × 3.5 × 0.25	2017	[40,42]
19	Sprite	L	104	6645	0.000	51	<b>5</b>	3.5 × 3.5 × 0.25	2019	[43,46]
20	Spinorsat	L	7	6645	0.000	51	<b>10</b>	3.5 × 3.5 × 0.4	2019	[32]
21	Wafersat	C	1	N/A	N/A	N/A	<100	8 (diameter)	2019	[60]
22	UoG-Fem	C	1	N/A	N/A	N/A	<b>10</b>	3.5 × 3.5 × 1	2019	[61]
23	Wafer-Like	C	1	N/A	N/A	N/A	<100	10 (diameter)	2020	[62]
24	Pinpoint	C	1	6921	0.029	45	<b>&lt;10</b>	2.5 × 2.5 × 0.4	2021	[63]
25	SUCHAI 3 Femtosatellite	L	2	6883	0.001	97.4	51	5.4 × 10.305 × 1.2	2022	[33,45]
26	PCBSat Fold	C	1(3)	N/A	N/A	N/A	68(18,25,25)	9 × 9.6 × 3	2022	[64]
27	Monarch	C	1	N/A	N/A	N/A	<b>2.5</b>	5 × 5 × 0.15	2023	[34]
28	Ambasat-1	U	1	6651	0.000	85	25e	3.5 × 3.5 × 0.5	2023	[65]
29	Lux-Atto	P	1(3)	6896	0.004	97	18.3	5 × 5 × 0.4	2024	[35]
30	Alpha (sail)	P	1(4)	6791	0.000	51	93.5	57.5 × 57.5	2024	[34,47,66]

Eq. (2) does not directly appear in Refs. [71,72], but is explicitly derived under simplified assumptions (constant atmospheric density, drag coefficient, and circular orbits), as detailed step-by-step in Appendix. Here,  $\Delta t$  represents decay time,  $m$  is satellite mass,  $V$  is orbital speed,  $A$  is satellite cross-sectional area perpendicular to its motion,  $a_{\text{initial}}$  and  $a_{\text{final}}$  are initial and final semi-major axes (equal to orbital radius for circular orbits),  $C_D$  is the drag coefficient,  $\rho$  is atmospheric density, and  $\mu$  is Earth’s gravitational parameter.

The drag coefficient  $C_D$  is taken as 2.2, a typical value for satellites in the upper atmosphere using a flat plate model [72, p. 551]. Eq. (2) highlights that the satellite-specific parameters influencing orbital lifetime are mass  $m$  and cross-sectional area  $A$ , while other parameters depend primarily on altitude. This analysis is only aimed at demonstrating the effect of mass to area ratio in the orbital decay time due to atmospheric drag. This analysis may admittedly be limited as at these altitudes atmospheric drag is more akin to rarefied flow instead of compressible flow that was considered here. Detailed orbital decay analysis is beyond the scope of this paper, but may be found in the literature, for example [73–78].

As mentioned, the second prominent perturbation on femto/attosatellites is SRP, again, due to their low mass-to-area ratio. Acceleration due SRP is given in Eq. (3), in which  $P$  is the solar radiation flux which is  $1367 \text{ W/m}^2$  at the average Earth–Sun distance, i.e. 1 Astronomical Unit,  $A$  is the effective cross-sectional area of the satellite exposed to the sunlight,  $C_R$  is the reflectivity coefficient of the satellite depending on the external material,  $c$  is the speed of light,  $m$  is the mass of the satellite [68]. While comparing femto/attosatellites with CubeSats and PocketQubes, the assumptions are that all will be in the same orbit,  $C_R$  will be the same considering that their surfaces are covered with solar cells and facing the Sun directly,  $P$  is the same since all are considered in a low-Earth orbit, and  $c$  is the same regardless of the orbit these satellites are in.

$$\kappa_{SRP} = \frac{A P C_R}{m c} \quad (3)$$

As a result, satellite-specific variables are  $m$ , the mass of the satellites, and  $A$  (largest) surface area facing the Sun. Given that the investigated femto/attosatellites have a low mass-to-area ratio (high area-to-mass ratio), the effect of the solar radiation will vary depending on the satellite’s orientation and orbital configuration. In cases where solar radiation pressure acts against the direction of motion, it can contribute to orbital decay. However, when the force acts in the direction of motion, it may increase the satellite’s altitude or alter the eccentricity of the orbit [79,80]. For most of the orbit, excluding eclipse periods, if the satellite’s largest surface continuously faces the Sun, the cumulative effect can enhance drag or modify the orbital shape, potentially accelerating decay [81,82]. In contrast, if these satellites were to be used for deep space applications, this same characteristic would be beneficial for using SRP as a form of propulsion. The current femto/attosatellites have a high area-to-mass ratio, with the highest being the Alphasail  $3.53 \text{ m}^2/\text{kg}$ , designed for deployment and operation in Earth orbit as a precursor to eventual interplanetary missions.

These missions typically exhibit two main characteristics. First, most missions utilize a single plane, PCB, or a similar substrate, using both surfaces in a single plane configuration. A direct implication of this approach is the limited surface area available to house solar cells for power generation, affecting the rest of the system and mission design (see Section 6). The second common characteristic is the method of deployment. Miniaturized femto/attosatellites do not have a standardized deployer; as a result, they rely on another satellite for deployment into orbit or attached to the body of the main satellite(see Section 5).

#### 4. Highly-miniaturized satellite classification: PlanarSat

As satellites decrease in size, the differences between consecutive satellite classes becomes less distinct, particularly for femto- and attosatellites. This ambiguity arises due to the shared design methodologies and challenges these satellites face in communication, power

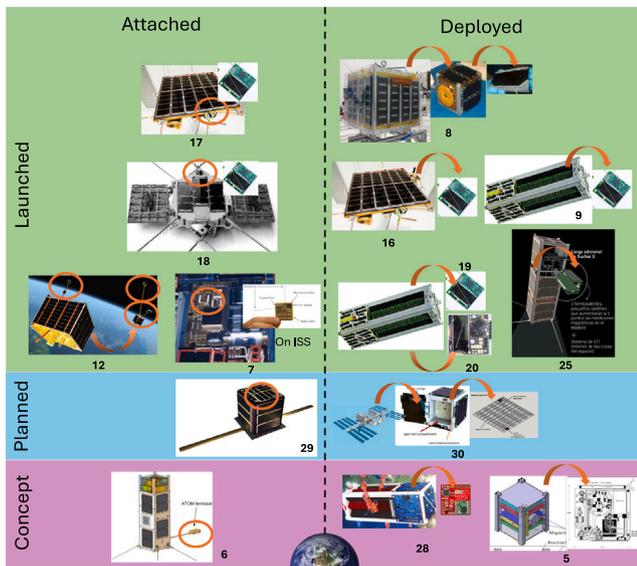


Fig. 6. Access to space of PlanarSat. Numbers indicate the Mission ID, see Table 2.

generation, payload integration, and space access. While mass has traditionally served as the primary classification criterion, increasing miniaturization has highlighted the importance of design features like dimensional ratios and functional adaptability. To address this, we propose the term PlanarSat, representing a subset of femto- and attosatellites characterized by flat, single-plane designs with significant disparities between their smallest and largest dimensions. This term emphasizes the modularity and suitability of these satellites for distributed applications, offering unique advantages for spatial and temporal resolution in multi-point measurements. Furthermore, the convergence in design approaches and shared procedural requirements—such as environmental testing, frequency coordination, and launch arrangements—blur distinctions between mass-based classifications at this scale.

Given the design similarities and capabilities between femto and atto satellites and the limited number of femto/atto satellite missions, merging these classes could solidify the foundation for future miniaturized spacecraft. Mass classifications are made irrespective of a satellite's shape. ChipSat commonly refers to atto satellites with flat shapes designed on a single PCB [19,47]. Hein et al. emphasize an approach similar to the distinction between PicoSats and CubeSats—the former categorized by mass, the latter by cubic shape. In Fig. 7, which illustrates mass in relation to the mass-to-area ratio (MAR), the distinctions among satellite classes by mass are evident. However, while the figure shows that femto- and attosatellites overlap and form a single cluster, this overlap primarily reflects shared design characteristics rather than operational performance. In practice, the MAR plays a more significant role in determining orbital perturbations, drag, and solar radiation pressure effects. As a result, although this design overlap highlights potential commonalities, it does not fully justify merging femto- and attosatellites into a single operational class. The term 'PlanarSat' may better describe flat, printed satellites that align closely with the original conceptual design, while other flat femto- and attosatellites might warrant classification under a broader category. This result may also suggest the joint satellite class PlanarSat. Due to the nature of a flat-shaped satellite, the density of such satellites stays relatively the same unless the base material changes. PocketQubes and CubeSats can belong to either the picosatellite or nanosatellite and, in some cases, to the microsatellite class. Thus, this study proposes that PlanarSat encompass both atto/femto satellite classes and other mass classes that focus on a flat-shape consisting of a single plane where one or both faces are utilized, similar to how CubeSats span multiple classes.

## 5. Access to space for PlanarSat

One of the common characteristics is the way PlanarSat access to space. Half of the missions in Table 2 use another spacecraft, mothership, to reach orbit. These motherships are; five 3U CubeSats, four 1U CubeSats (one 1U deployed from a microsatellite and another one from ISS), and four microsatellites. Three of these missions are conceptual, and two were planned for launch in 2024, one of which was the Luxembourg mission (POQUITO) planned during the writing of this paper in 2024. Ten missions managed to reach orbit, though some failed to be deployed. In Fig. 6, mission IDs, their status, orbit configuration (deployed or attached) are given. Collectively, missions where access to space strategy was explicitly stated would have deployed (including deployed, deployment failures, and planned) 233 PlanarSats, including non-planar sub-100 g satellites, to orbit (238 if combined satellites, such as Alphasail with 4 Monarchs) and Lux-Atto combination of 3 attosatellites, are counted separately). This number would increase to 252 satellites if all studied missions were counted, Table 2 and Fig. 4.

This approach is understandable due to the lack of dedicated launchers/deployers for PlanarSat, but it is also contradicting concerning mission cost, especially when the launch is included. The cost-effectiveness of miniaturized satellites is mentioned by unit cost (mostly hardware), which can be reduced further if “mass-produced” and to utilize economics of scale, and these satellites have to be “mass launched” due to the unavailability of dedicated PlanarSat launchers. The unit cost might be lower, but the overall mission cost will still be comparable to that of larger satellites such as PocketQubes and CubeSats. PlanarSats are launched from, deployed by, or attached to larger satellites (i.e., motherships), as illustrated in Fig. 6. Sprites were launched from Kicksat -1, Kicksat -2, Max Valier, and were attached on ISS, Max Valier and Venta-1 satellites. Suchai-3 femto satellites were deployed, as they are called, from Suchai-3, a 3U CubeSat. Pocket-PUCP was deployed from PUCP-SAT1. A pair of Xingchen(Stardust) satellites were attached to Tiantuo-3 and another to PhoneSat. Lux-Atto will be attached on POQUITO, a 1P PocketQube, and AlphaSail will be deployed from AlphaSat, a 1U CubeSat. In these examples, if the launch is considered a “given”, mission costs will simply be the final PlanarSat.

The cost of launching a CubeSat and PocketQube varies between service providers. It depends on bilateral contracts with specific requirements, such as the final orbit, as LEO is still a wide description. The lowest and highest launch costs per standardized CubeSats and PocketQubes are given in Fig. 9, with the addition of cost per gram and per cubic centimeter. Figures are given cost per gram and cubic centimeter due to the nature of femto/atto satellites being small and mentioned with their low mass in grams and low volume either in  $\text{mm}^3$  or  $\text{cm}^3$ . The first trend visible is that the launch cost per gram and per cubic centimeter are increasing as the satellites get smaller. It should be noted that there are launches which are cheaper per kg, for example, Falcon Heavy 1.5k, Falcon 9 2.6k, Angara 4.5k, Long March 5 7.9k, LVM3 8, Ariane 5 10.2k, Shian Quxian 17.3k and Electron 23.1k USD [83–85]. However, the whole mission/launch needs to be procured to achieve the stated cost per kg values. The total cost of such missions would be in the same order: 95, 60, 110, 182, 63, 263, 5, and 5 million USD, respectively [83].

Assuming a 100% infill for simplification, the number of launched femto/atto satellites that can fit within certain PocketQube and CubeSat envelopes are presented in Table 3. Table 4 provides the number of PlanarSats that can fit in standardized nano/pico satellite envelopes, considering their actual shapes. The relative volumes are shown in Fig. 10. It is evident that these simplified numbers are indicative. In practice, 200 Sprites can be launched from Kicksat -1/2, which also uses 1U of its volume for the 3U satellite bus. Therefore, in missions where PlanarSats are deployed from larger satellites, the dimensions of both the motherships and the PlanarSats will affect the number of PlanarSats that can be launched. Additionally, there will be the electronics of the mothership, deployment mechanism, and other necessary

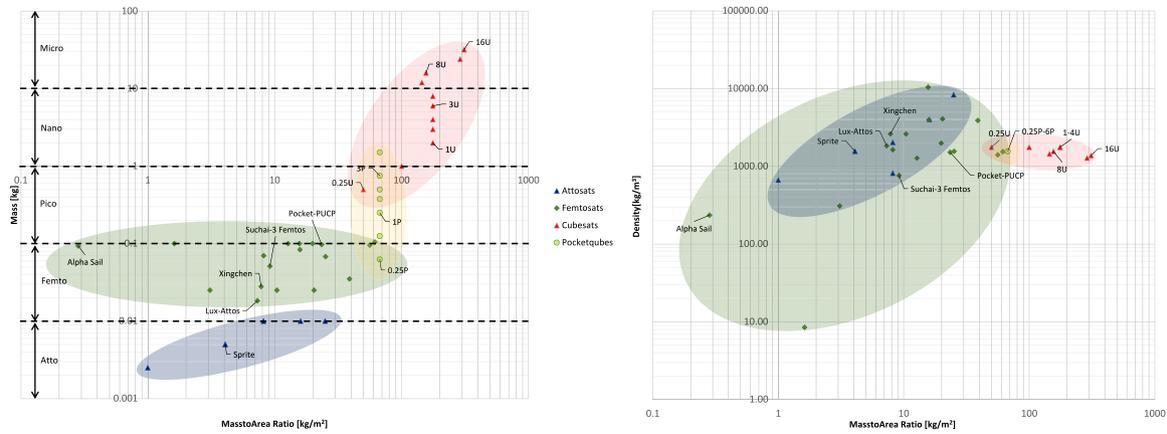


Fig. 7. Satellite Comparisons with respect to Mass vs. Mass-to-Area Ratio (left) and Density vs. Mass-to-Area Ratio (right). Launched satellites and most common standard satellites are labeled.

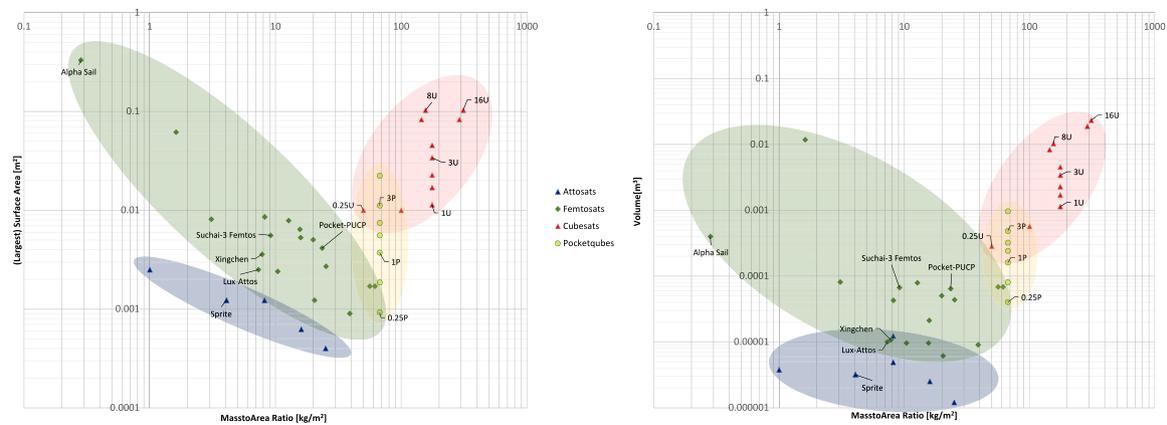


Fig. 8. Satellite Comparisons with respect to Surface Area vs. Mass-to-Area Ratio (left) and Volume vs. Mass-to-Area Ratio (right). Launched satellites and most common standard satellites are labeled.

systems to consider. This results in an increased “unit cost” of such PlanarSat missions, in this example potentially four times higher than the launch cost compared to simple calculations where 1034 Sprites could be deployed.

When launched with the mentioned rockets or in the deployers of the mentioned CubeSat and PocketQube envelopes, the unit cost might get lower, but the overall mission cost will still be high. Details of the cost per unit of a PlanarSat compared to various standard satellite forms are explained in Section 8. Currently, the cheapest option for PlanarSats to reach orbit is to hitch-hike on another satellite as a “guest” payload, whether attached to the main satellite or deployed from it.

6. PlanarSat subsystems and subsystem dependencies

In this section, a general approach to PlanarSat architecture is explained, along with the findings from the survey. Just like a normal satellite, PlanarSat can be divided into subsystems, mainly electrical power system (EPS), attitude determination and control system (ADCS), structure, communications, on-board computer (OBC), and payload. Unlike the bigger satellites, on PlanarSats, due to the way they are defined, available space, in other words, the surface area is limited. With this limited surface area, power generation and placement of all the components have to be optimized. The first optimization step happens by combining the subsystems into the satellite itself, hence turning the subsystems into functions.

Table 3

Number of PlanarSats that can fit in standardized nano/pico satellite envelopes. Assuming a 100% infill rate, with respect to volume.

Launched PlanarSats	1P	2P	3P	1U	2U	3U
Alpha Sail	0	0	0	2	4	6
Suchai-3 femto	1	4	6	15	31	49
Pocket-PUCP	1	4	6	16	33	51
Xingchen	8	17	26	71	142	214
Lux Atto	13	29	45	100	210	330
Spinor	25	50	75	200	400	600
Sprite	41	93	145	327	686	1078

Table 4

Number of PlanarSats that can fit in standardized nano/pico satellite envelopes, with respect to actual shapes.

Launched PlanarSats	1P	2P	3P	1U	2U	3U
Alpha Sail	0	0	0	2	4	6
Suchai-3 Femto	0	0	0	8	16	24
Pocket-PUCP	0	3	6	14	28	48
Xingchen	0	0	0	48	96	144
Lux Atto	16	32	47	112	224	340
Spinor	16	36	60	144	288	432
Sprite	25	60	100	240	480	720

In Fig. 11, functions in “black” are required for a simple satellite, and those in “orange” are not essential but good to have functions.

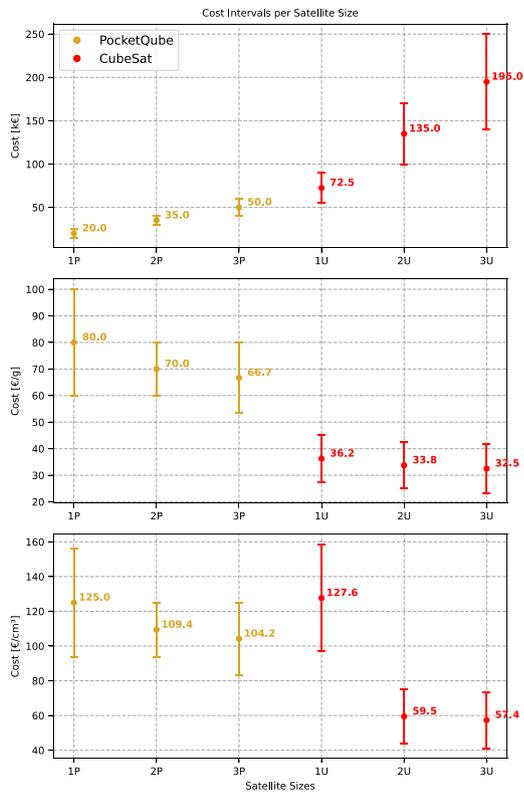


Fig. 9. Lowest and Highest launch costs of PocketQubes and CubeSats to LEO. Shown points are the middle values to provide a better indication [86–89].

Black functions are the bare minimum requirements for a functioning satellite, power generation, power conditioning, power distribution, microcontroller unit (MCU), payload sensors, transmitter, and antenna. This function approach distributes the tasks in the satellite to IC level. This allows the entire satellite to be controlled and operated from a single MCU, saving valuable space and reducing power consumption. The disadvantage is that the single MCU will be operational for a long duration and possibly with a high computational load. ADCS currently is a preferred system to have on PlanarSats, but its need depends on the payload requirements or the mission itself. Surveyed PlanarSats have some of the sensors for attitude determination, and some even house a magnetorquer, although there are no orbit results from such ADCS. A propulsion system is the most challenging to have on a PlanarSat. Currently, there are some proposed propulsion systems, and recommended approaches to “propel” a satellite by using SRP or Lorentz force [19,90]. In the following subsections findings of the survey per subsystem/function is provided.

### 6.1. Electrical power

Electrical power is the most essential element of a PlanarSats. Due to the limited surface area, power generation is directly affected. The available surface to place a solar cell is directly proportional to the possible maximum power generation. Considering that a space-qualified solar cell is used on the satellite, with an approximate efficiency of 30%, generated power can approximately be 0.04 W/cm<sup>2</sup>. Since PlanarSats are almost 2D satellites, the effect of the available surface has the highest impact on the overall satellite design. The less surface area available, the less operational time for other functions.

In the investigated missions, all 11 atto satellite missions have solar cells [8–11,32,34,43,54,55,61,63]. Among the Femto satellite missions, 15 have solar cells [12,14,15,31,33–36,45,47,49,56,57,59,60,64–66], 3 do not have any solar cells [13,48,49,49–53], and the status of a

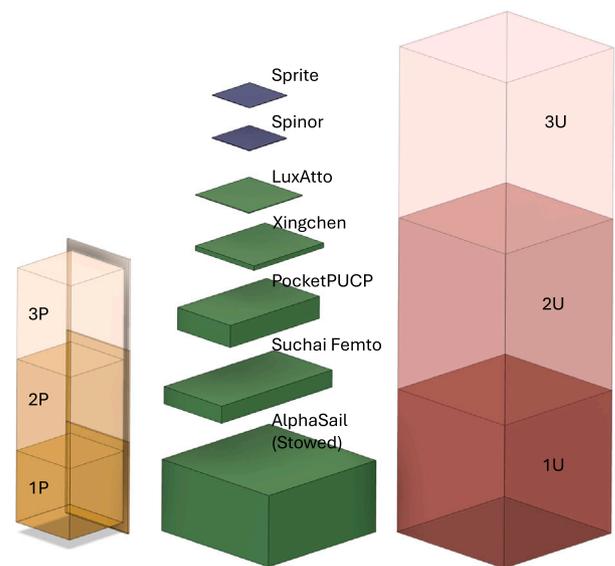


Fig. 10. Satellite Volume Comparisons, Standard PocketQubes, launched Femto/Atto Satellites and Standard CubeSats (scaled) [31,32,35,36,43,45,47,69,70].

mission is unknown [58]. The reasoning behind these design choices was not explained in the mission descriptions.

Only three atto satellite missions have a battery [32,61,63], while eight do not [8–11,34,43,54,55]. This is primarily due to limited space. Additionally, the batteries would be exposed due to the shape of these satellites, and their low thermal capacities would cause higher temperature changes, making battery protection difficult.

In the Femto satellite class missions, 14 have batteries [12–15,33,35,36,45,48–53,56,57,60,64], while three of them do not [31,34,47,59,65,66], and the status of two are unknown [49,58]. In this context, “unknown” is used because it is unclear whether the information about a battery or solar cell was specifically provided for these satellites.

The disadvantage of having such a smaller system is that it has less available power, but it also means dealing with smaller voltage and current levels. Most of the ICs used in the investigated missions can work at 3.3 V, with the maximum being 5 V. Considering that a single space-qualified solar cell generates approximately 2.4 V and 0.5 A, the use of step-up converters will be sufficient for a basic and rather efficient satellite. In the event of a multi-solar cell satellite design, connecting them in parallel will enable an easier design for PlanarSats, since low current power elements such as inductors and capacitors are smaller. The main disadvantage is that the available electronic elements for protection are normally not designed for low power levels. Custom or a combination of various ICs are needed.

Typically required functions are the ability to turn systems on/off or power cycle, which can be a MOSFET or an integrated switch IC with additional protection, V–I measurement, and DC–DC converter to provide the necessary supply voltage, preferably one single voltage for the whole PlanarSat. In order to maximize the generated power from the solar cells, a maximum power point tracking (MPPT) is necessary. The presence of a battery requires an additional protection circuit, which can be optimized, or sacrifices with respect to battery performance can be made with respect to the desired mission duration. As in the larger satellites, PlanarSats should consider remove before flight (RBF) and kill switches or inhibit switches activated/deactivated with RBF and kill switches to be compatible with launch provider requirements.

### 6.2. On-board computer

Throughout the investigated missions, there was not a dedicated OBC subsystem but the tasks were given to the central MCU which

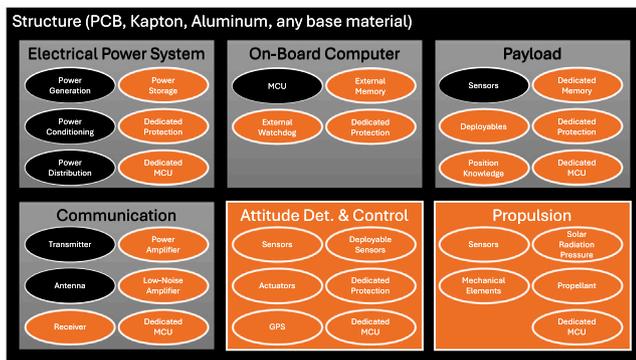


Fig. 11. PlanarSat Architecture highlighting essential (black) and optional (orange) functions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

everything else was controlled from one single IC. This is to use the space as efficiently as possible due to the relatively bigger size of MCUs and to reduce power consumption but combining various tasks to this single chip [12–14,31–35,43,45,47,49–55,61,62,64–66]. More than half of the missions, 16, used two-in-one MCUs to combine even the function of a transmitter IC [31,32,34,43,47,54,55,61,66]. Supply voltage of these systems range from 1.6 V–5.5 V and dimensions range from 16 mm<sup>2</sup>–196 mm<sup>2</sup>. The most used MCU is CC430F5137 because of the Sprite satellites and the other satellites which were inspired by it due to its heritage.

Depending on the needs, the MCU needs to get bigger, or a dedicated MCUs might be needed for ADCS and for payload. In order to choose an MCU, an important factor to take into account would be the number of functions that need to be controlled. Because of the small size of the PlanarSats, the number of functions that can be added would also be limited. A “pin” budget or a function budget needs to be created to be able to keep track of the desired capabilities.

### 6.3. Communication

Communication system is one of the essential functions a PlanarSat needs to have. Since most of the PlanarSats will not be able to reach the ground as a result of burning during the reentry, communication systems needs to be included to deliver the data. As explained in Section 6.2, 16 of the missions use a transceiver MCU and additionally 4 other missions specify their transmitter ICs [13,33,45,50–53,64,65]. Among the investigated missions, femto/atto satellite missions from the University of Luxembourg, in this paper referred to as LuxAtto, will have visible light communication in between the atto satellite modules on it [35].

In three missions, satellites communicated through their mother-ships: Pocket-PUCP with PUCP-SAT1, Xingchen (Stardust) communicated with Tiantuo-3 and Phonesat, and LuxAtto will be communicating with POQUITO to be able to send its data to ground [31,35,36] Depending on the amount of generated data, ground station capabilities and the transmitter on the PlanarSat transmission power can be optimized. Transmission powers range from 0.01 W (10 dBm) to 1 W (30 dBm), which can be optimized based on data volume, ground station capacity, and PlanarSat capabilities. Adding a power amplifier would improve the link budget, which in turn, would increase the amount of data that can be transmitted to the ground. Communication systems vary due to power limitations and frequency band regulations, with most using amateur frequency ranges in order to reduce costs. Specifically, 10 missions use 400 MHz band [15,35,36,43,54,55,57,58,63], five missions use 2400 MHz band [8–13,31,45,50,51], and four missions use 800–900 MHz [34,47,61,65,66].

### 6.4. Payload

Different payloads have been specified in the survey. Mostly being basic sensors such as temperature, gyros, magnetic, imager, and MEMS, with a focus on technology demonstration of the whole PlanarSat concept. Satellites were not necessarily designed around the payloads; payloads were used to utilize the system and use the available power and data budget.

The first Sprite satellite was in orbit attached to ISS with the goal of demonstrating a cost-effective, new type of space technology [54], which was further investigated with the other Sprite satellite missions. In 2013, Pocket-PUCP was deployed from PUCP-SAT 1 in order to create a secondary temperature measurement point to which the data would be sent via the CubeSat [36]. Xingchen femto-satellites, also known as Stardust, were deployed from Tiantuo-3 and Phonesat with the purpose of evaluating the performance of the distributed collaborative measurement system and to test the space environment effect on femto satellites [31]. Spinor satellites, inspired from Sprite, aimed to miniaturize the Sprite spacecraft even further for a mass produced large networks of satellites [32]. Suchai-3 femto satellites were deployed to remotely estimate the location of them using CubeSats, inter-satellite link between femto-satellites and CubeSats [33,45].

In 2024, there are two planned launches, including femto- and attosatellites. One is the set of attosatellites to demonstrate LED-based communication system for atto satellites. The satellites, referred to as “primary” and “secondary”, are designed to gather atmospheric data and transmit them via the “primary” to POQUITO PocketQube which transmits the data to the ground station [35]. Another mission is the Alpha Mission, which aims to deploy a solar sail from a CubeSat. This sail carries four Monarch PlanarSats as flight computers [34,47].

As seen in the launched missions and investigated missions, this could also be interpreted as the PlanarSats themselves being the payload. In the case of a successful mission or physicalization of a concept mission, being able to transmit its data would prove the concept of the PlanarSat with the aim of supporting the mission owner’s design.

### 6.5. Attitude determination and control system

ADCS is an optional function for PlanarSats shown in Fig. 11. Its sensors are relatively easier to place and use on the PlanarSats, but it is difficult to incorporate actuators. Magnetotorquers are the easiest to place in the PlanarSats thanks to the manufacturing technology. They can be placed in or on the PCB as a trace, making them confined and perfectly aligned. In general the limitation to place actuators is mainly because of limited space and limited power. Theoretically, thanks to their small size and low inertia, PlanarSats are rather “easy” to control with less power, given that there is enough available power. Depending on the mission profile and goals, the presence of an ADCS might force the system to include a battery. Another need for a battery system for ADCS might be the time it takes for algorithm filters to converge. If the satellite reboots during the calculations, it will cause ADCS to restart all the calculations.

In the investigated missions, only one mission has reaction wheels [12], eight missions have magnetorquers [12,14,32,34,47,51,61,64] and some missions have only sensors which can be used for attitude determination. Additionally, three missions provide specification of their magnetorquers; one of them has a dipole moment of 0.000024 Am<sup>2</sup> [14], one mentions the power consumption of 33 mW [12] and one can generate a dipole moment of 0.0025 Am<sup>2</sup>, with 70 windings at 30 mA current [61]. There is no data about the in-orbit demonstration of the mentioned systems.

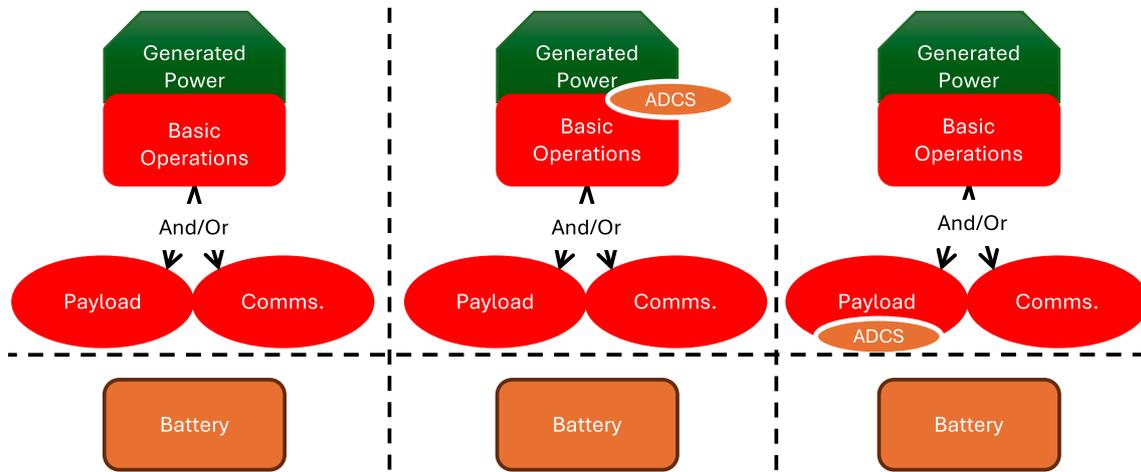


Fig. 12. Operational scenarios for PlanarSats based on power distribution and subsystem priority. Green represents power generation, red indicates continuous power consumption by essential operations, and orange denotes optional functionalities (e.g., ADCS and battery use). In all scenarios, the battery is considered an optional component, while payload and communication systems either operate simultaneously or alternate, depending on available power. In scenario two, ADCS assists in maximizing power generation, and in scenario three, ADCS supports payload operations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 6.6. Propulsion

Propulsion for atto and femtosatellites remains a significant challenge due to strict mass and volume limitations. Most missions investigated in this paper, except Alpha Sail, rely on passive deployment or orbital decay. However, emerging propulsion technologies are expanding possibilities for deep space, orbital maneuvering, and formation flying. These technologies can be both active systems on the satellite or “passive” systems as in using the SRP. There are conceptual studies on such propulsion methods on atto/ femto satellites.

Photonic propulsion, such as laser and solar sails, offers propellantless solutions which might be ideal for PlanarSats [20]. Project Glowworm investigates a laser sail propulsion, using a CubeSat to deploy a ChipSat (PlanarSat) with a reflective sail, achieving small but measurable orbital changes [91]. Atchison and Peck explored passive solar sails that leverage radiation pressure for maneuvering, highlighting their scalability and simplicity [90,92].

Another method is Lorentz-force propulsion. It utilizes interactions between charged spacecraft and planetary magnetic fields, providing continuous low-thrust propulsion suitable for deep space missions. This technique has been investigated for applications like Jovian orbit insertion [93,94].

Lubin’s research into directed energy propulsion explores wafer-scale spacecraft accelerated to relativistic speeds by phased laser arrays, presenting opportunities for interstellar probes and LEO missions alike [95]. Cold gas thrusters are another viable option, offering simple maneuvering solutions for small  $\Delta V$  adjustments [96].

While most PlanarSat missions target LEO, these propulsion methods open pathways to cislunar, interplanetary, and deep space environments. Scalable, low-mass and low-power propulsion would enable PlanarSats’ to expand their operational scope and driving future exploration.

### 6.7. Structure

The structure of a satellite houses all its subsystems and ensures it reaches orbit intact. CubeSats and PocketQubes have structures that follow the rules according to their respective standards [69,70,97]. This research identifies four commonly used structural types: silicon wafer substrate used in three missions [8–11,60,62], PCB substrate used in 20 missions [12,14,15,31–33,35,45,49,54,55,57,58,61,63–65], flex PCB substrate used in three missions [13,34,47,50–53,66], and framed structured, mostly metal based, used in five missions [36,48,49,56,59].

It should be noted that some missions concepts had multiple phases where they transitioned from one structure to another.

Thermal management is a common concern across all structure types, and ongoing research addresses this issue [31,98,99]. Each structure presents unique challenges. Planar substrate structures (silicon wafer, PCB, and flexible PCB) often offer limited surface area for components and are susceptible to radiation. Due to their low mass and thin profile, PlanarSats have limited thermal mass, leading to larger temperature swings and increased thermal stress. Frame structures provide more volume and subsystem protection, they can pose interconnection challenges.

## 7. PlanarSat operations

As a result of the surveyed satellites, their subsystems, and mentioned functionalities, essential tasks were shown in Fig. 11. Given the limitation on multiple aspects, various operational approaches need to be developed. Possible operational scenarios can be made with respect to the power consumption, and specific mission needs as much as the power budget allows. In Fig. 12, in each scenario, power generation, mostly via a solar cell, is shown in green, the consumption of the basic operations, which can be the voltage regulators, MCUs and power supply of other ICs in standby mode, are shown in red as in non-negotiable devices. Payload and communication functionalities can either be operational at the same time or one at a time to balance the instantaneous power consumption.

ADCS can be used if it is required for the payload, and ease of operational modes, this should be included in the payload but specified separately. Another usage of ADCS for PlanarSats can be to increase the power generation by pointing the satellite towards the Sun; this use case needs to be further investigated, and its benefits should be simulated, middle options in Fig. 12. Given that a PlanarSat could generate 15 mA/cm<sup>2</sup> with a space-qualified solar cell and that the example ADCSs in Section 6.5 with a consumption of 10–30 mA, the benefits of ADCS might outweigh its drawbacks of volume usage and power consumption.

The battery system is placed as an option to have on the PlanarSat; this mostly depends on the mission requirements, and the quantity of energy that can be stored depends on the available space. Limitations of batteries on PlanarSats are explained in Section 6.1. Batteries would allow ADCS to collect necessary information even while in eclipse to enable the satellite to be ready to point towards the Sun as soon as it is out of eclipse. Batteries, just as in the bigger satellites, can be used to collect and transmit data during eclipse.

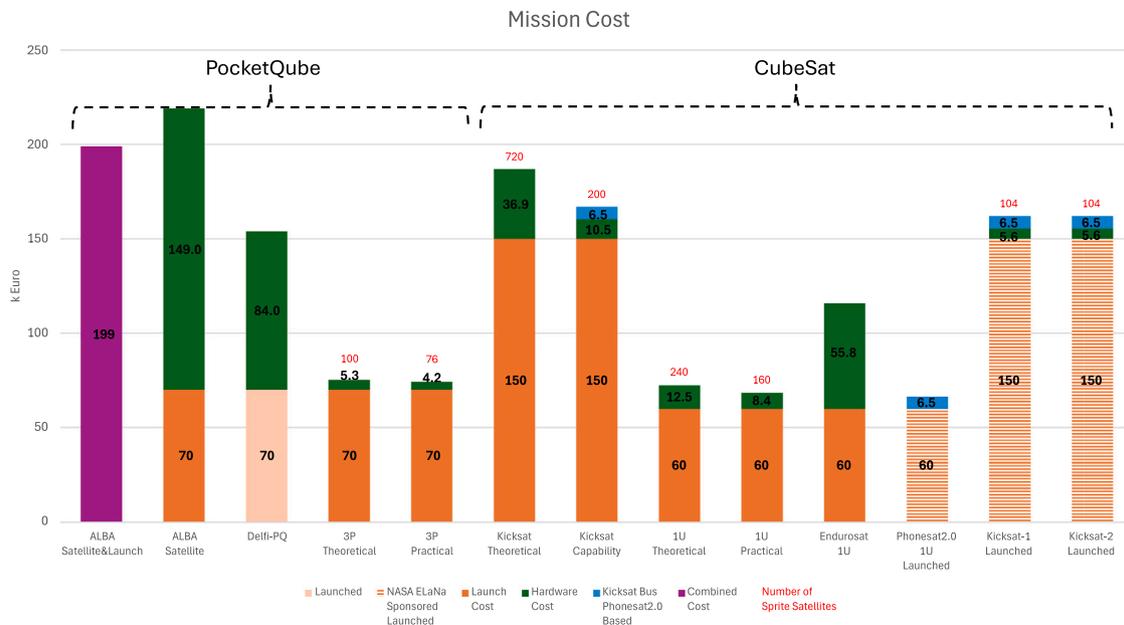


Fig. 13. Cost Comparison of Various Missions [89,100–106]. The combined cost for ‘ALBA Satellite&Launch’ includes both the satellite and launch service as a single package, while ‘Alba Satellite’ refers to purchasing only the satellite with a separate launch service.

### 8. Preliminary performance analysis & comparison

This section presents a preliminary performance analysis comparing various satellite classes, including PlanarSats, CubeSats, and PocketQubes, with an emphasis on understanding the practical implications, such as hardware cost, launch, and access to space, of their differing sizes and design specifications.

There are a limited number of PlanarSats and even fewer with detailed information. A basic comparison was made using instantaneous data rates, though a more in-depth comparison would require detailed orbital simulations, average power, and link budgets. This comparison represents an ideal case, meaning that actual missions will require more satellites than suggested.

The initial step is to find the number of satellites needed for data transmission. Table 5 compares data rates, transmission power, and maximum power generation for the largest surface of five basic satellites. These include; Sprite, the first flown PlanarSat; Phonesat2.0, a 1U CubeSat which was later used in Kicksat 1 & 2 as the satellite bus; Delfi-PQ, a 3P PocketQube launched by TU Delft; Endurosat 1U, a complete satellite solution provided by Endurosat; and Alba Unicorn-2, a 3P PocketQube, with imaging capabilities, provided by Alba Orbital. The number of required satellites with respect to the accumulated data rates is given in Table 5, and the cost of these satellites is also available.

The total cost of five PocketQube and eight CubeSat missions/concepts are given in Fig. 13. Four of these missions have flown, three are concept missions with the satellites purchased from providers, and six are concepts in which Sprites could be launched by placing them in the respective satellite sizes. Hardware costs are based on actual figures, including the updated component cost of Sprite satellite bill of materials (BOM) [89,102,105–107], while launch costs for PocketQube are publicly available on the ALBA orbital website [89], and for the CubeSats, the numbers are based on Fig. 9. Phonesat 2.0, Kicksat 1 and 2 launch costs are shown; however, the launches were sponsored by NASA’s CubeSat Launch Initiative [103–105]. The red text on top of the bars, Fig. 13, is the number of Sprite satellites that can fit in the respective missions. In the case of 3P and 1U; theoretical numbers consider that the PlanarSats are placed inside perfectly, whereas the practical numbers fit inside as a stack, which is a more realistic approach that might be deployed. In the case of Kicksat, theoretical is filling the entire 3U satellite with Sprites, and Kicksat capability is the actual number of

Sprites that can be deployed. During the later missions Kicksat –1 and Kicksat –2, 104 Sprite satellites were launched [43].

It has been assumed that these satellites are in the same orbit, generating maximum power and transmitting with an acceptable link budget. A Sprite satellite alone can transmit 125 bps with the possibility of generating a maximum of 0.13 mW. From the data point of view, 77 Sprites can match the instantaneous data rate of a satellite, PocketQube or CubeSat, with 9.6 kbps. In addition, combining the data from Tables 4 and 5, and Fig. 13 in the best-case scenario data performance of a 3P PocketQube, Delfi-PQ [108,109], can be achieved by 77 Sprites with the cost of 72.7k euros, Phonesat 2.0 can be achieved only 8 sprites and with the cost of one PhoneSat mission 160 sprites can be launched. However, the launch and deployment of 104 Sprites were achieved via 3U satellite, which also requires its own satellite bus and launch. Both Kicksat missions used a bus based on PhoneSat, and a custom deployment mechanism was developed, which can hold up to 200 sprites. Considering the capability and full utilization of a Kicksat, 200 sprites can be launched for 163k euros that can, in theory, and under ideal conditions, transmit 25 kbps combined.

The analysis reveals that while PlanarSats offer a compact and cost-effective solution for certain data transmission requirements under ideal conditions, their limited power and small size pose challenges for broader real world applications.

By contrast, CubeSats and PocketQubes, with their higher payload capacities, offer a better balance between cost and functionality for conventional missions focused on single-point measurements where high resolution is not critical. However, PlanarSats stand out in distributed applications, providing unique cost-effective opportunities to enhance spatial and temporal resolution, making them ideal for complex, multi-point measurement tasks that larger satellites cannot perform as efficiently.

To summarize, the data underlines the trade-offs involved in selecting satellite types for different mission profiles. While PlanarSats can be more economical in large numbers, the complexity and costs associated with their deployment must be carefully considered against the more robust capabilities of CubeSats and PocketQubes. It should be noted that personnel costs, testing costs, and required infrastructure costs are not included in this paper.

The insights gained from this preliminary analysis will guide more detailed simulations and studies, aiming to refine the deployment

**Table 5**  
Required number of satellites to match certain data rates.

Satellite	Maximum solar power [W]	Tx power [W]	Data rate [kb/s]	Number of satellites				
Sprite (UHF)	0.132	0.01	0.125	160 000	8000	800	77	10
Phonesat2.0 (S)	0.68	1	1.2	16 667	833	83	8	1
Delfi-PQ (UHF)	2.4	0.38	9.6	2083	104	10	1	–
Endurosat 1U (UHF)	2.4	1	19.2	1042	52	5	1	–
Alba Unicorn-2 (S)	19.2	–	200	100	5	1	–	–
<b>Data rates [kb/s]</b>				20 000	1000	100	9.6	1.2

strategies and enhance the design efficiency of PlanarSats and their larger counterparts. As these deployment strategies evolve, addressing operational risks and enhancing the resilience of smaller platforms like PlanarSats becomes increasingly important.

A critical challenge for PlanarSat missions, beyond the broader issue of space debris, is ensuring effective space situational awareness (SSA). The ability to track centimeter-sized and smaller objects in low Earth orbit (LEO) remains limited due to their low radar cross-section and minimal reflectivity [110]. This poses significant risks not only for collision avoidance but also for mission longevity and compliance with deorbiting regulations [111]. Unlike CubeSats and PocketQubes, which benefit from established tracking frameworks, PlanarSats often fall below the size threshold for many existing radar and optical tracking systems [110].

Efforts to address this issue include the development of deployable reflective surfaces [112] or active beacon systems [113] to improve detection, but these solutions introduce additional mass and power constraints. As the deployment of PlanarSats increases, enhancing SSA capabilities for sub-10 cm satellites will become essential to maintaining sustainable operations in space.

## 9. Conclusion

This research aims to provide a thorough evaluation of PlanarSat in relation to the well-established small satellites, CubeSats and PocketQubes, aiming to shed light on both the potential and the hurdles associated with these highly miniaturized satellites. In this paper, satellite independence was defined based on system-wise independence, emphasizing that each satellite must have its own dedicated power, communication, and control subsystems, regardless of physical connections. The first part of the paper reviews the current missions in terms of their size properties, access to space, and subsystems to provide an overview of state of the art to show the limitations and capabilities with comparisons to other small satellites. Then, a preliminary comparison of PlanarSat to CubeSats and PocketQubes is made under the ideal conditions of fixed instantaneous data rate, generating power with their largest surface area and neglecting the costs of insurance, labor, and tests; leading to a boundary condition for the required number of PlanarSat to satisfy the mentioned data rate in relation to their hardware and launch cost.

We have found that, currently, the main driving factor for the cost of a PlanarSat mission is the launch itself. The overall mission cost will still be relatively high (163k Euros) with respect to the unit cost of a Sprite PlanarSat, which is approximately 750 euros, considering that 200 Sprites can be deployed from Kicksat. A dedicated launcher or deployer may reduce the unit cost. Another cost-effective method is being attached to another satellite or just deployed from another mission, such as piggybacking another piggybacking satellite. Through our analysis, it has become evident that PlanarSat offer significant advantages in terms of cost and size reduction. However, they still require innovative solutions to address substantial challenges in communication, power management, and payload integration within their constrained dimensions.

We have determined that the viability of PlanarSat is contingent on the continuous evolution of MEMS and advanced integrated circuits, which are critical in minimizing component size while maximizing

functionality. The study underscores the necessity for a standardized approach to the design and operation of PlanarSat, suggesting that such standardization or a set of standards suitable for this form factor could lead to enhanced reliability and more predictable performance in space missions. Moreover, we recommend the development of a comprehensive systems engineering framework tailored to PlanarSat according to our review of the state of the art and analysis of their capabilities as compared to other small satellite classes. This framework should encompass rigorous environmental testing protocols, meticulous frequency coordination, and precise documentation and insurance procedures, all of which are crucial for the successful deployment and operation of these satellites. By establishing clear guidelines and standards, the space industry can better harness the capabilities of PlanarSat and integrate them into future space exploration and commercial endeavors.

While this study summarizes the sub-100 g missions, the next steps should be the definition of a PlanarSat standard or a set of standards including verification, certification etc., creating a systems engineering approach for such a class of satellites, and later designing a satellite employing that approach. There is a need for further studies that delve into the optimization of PlanarSat design to ensure that these satellites can perform robustly under the harsh conditions of space. Future research should also explore cost-effective launch strategies that could facilitate more frequent and accessible PlanarSat missions, which could unlock new possibilities for this technology while balancing the cost, size, and performance.

Looking ahead, PlanarSats present unique opportunities for mission concepts that extend beyond the current capabilities of CubeSats and PocketQubes. Their extreme miniaturization and low cost make them ideal for distributed sensor networks, planetary atmospheric entry swarms, or deployment in hazardous environments, such as asteroid or lunar surface exploration. Additionally, their scalability and potential for mass deployment could enable unprecedented Earth observation constellations or deep space exploration missions, where redundancy and coverage are critical. These novel applications highlight the transformative potential of PlanarSats, paving the way for innovative space science and commercial endeavors.

## CRediT authorship contribution statement

**Mehmet Şevket Uludağ:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alim Rustem Aslan:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly and OpenAI's ChatGPT in order to improve the language of the paper. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix. Derivation of orbital decay equation using energy and drag acceleration

In this appendix, we derive explicitly the orbital decay duration ( $\Delta t$ ) using a combination of orbital energy and atmospheric drag acceleration ( $\kappa_{\text{drag}}$ ). This explicitly illustrates how orbital decay duration is affected by the satellite's mass-to-area ratio ( $m/A$ ). It should be noted that this is the decay time approximation depending only to drag acceleration.

### Orbital energy and drag force

The specific orbital energy  $E$  for a satellite in a circular orbit with semi-major axis  $a$  is expressed as:

$$E = -\frac{\mu}{2a} \quad (4)$$

where  $\mu$  is Earth's gravitational parameter.

Atmospheric drag causes continuous energy loss at a rate given by the mechanical definition of power (force multiplied by speed):

$$\frac{dE}{dt} = -F_{\text{drag}} V \quad (5)$$

The drag force ( $F_{\text{drag}}$ ) acting on a satellite is classically defined as:

$$F_{\text{drag}} = \frac{1}{2} C_D \rho A V^2 \quad (6)$$

where:

- $C_D$  is the drag coefficient,
- $\rho$  is atmospheric density,
- $A$  is satellite cross-sectional area,
- $V$  is orbital speed.

Explicitly substituting Eq. (6) into Eq. (5), we obtain:

$$\frac{dE}{dt} = -\frac{C_D \rho A V^3}{2m} \quad (7)$$

Note that the division by satellite mass  $m$  converts total energy loss to specific energy loss, matching the units of Eq. (4).

### Derivation of orbital decay duration

Differentiating Eq. (4) explicitly with respect to semi-major axis  $a$ :

$$\frac{dE}{da} = \frac{\mu}{2a^2} \quad (8)$$

By the chain rule, we explicitly have:

$$\frac{dE}{dt} = \frac{dE}{da} \frac{da}{dt} \quad (9)$$

Combining Eq. (9) with Eq. (7) explicitly yields:

$$\frac{\mu}{2a^2} \frac{da}{dt} = -\frac{C_D \rho A}{2m} \left(\frac{\mu}{a}\right)^{3/2} \quad (10)$$

where  $V = \sqrt{\mu/a}$  for circular orbits. Rearranging Eq. (10):

$$\frac{da}{dt} = -\frac{C_D \rho A}{m} \sqrt{\mu a}$$

Separating variables explicitly and integrating from initial semi-major axis  $a_{\text{initial}}$  to final semi-major axis  $a_{\text{final}}$ :

$$\int_{a_{\text{initial}}}^{a_{\text{final}}} \frac{da}{\sqrt{a}} = -\frac{C_D \rho A \sqrt{\mu}}{m} \int_0^{\Delta t} dt$$

Performing explicit integration gives:

$$2(\sqrt{a_{\text{final}}} - \sqrt{a_{\text{initial}}}) = -\frac{C_D \rho A \sqrt{\mu}}{m} \Delta t$$

Solving explicitly for orbital decay duration ( $\Delta t$ ):

$$\Delta t = \frac{2m(\sqrt{a_{\text{initial}}} - \sqrt{a_{\text{final}}})}{C_D \rho A \sqrt{\mu}} \quad (11)$$

Eq. (11) explicitly shows the dependence of orbital decay duration on the mass-to-area ratio. This derivation explicitly assumes constant atmospheric density ( $\rho$ ), drag coefficient ( $C_D$ ), and circular orbits over small altitude intervals for clarity and illustrative purposes. In reality, both atmospheric density  $\rho$  and drag coefficient  $C_D$  are variable, but omitted here for brevity for the purposes of this paper.

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