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Low Earth Orbit Earth Observation CubeSat Classification in its second decade

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Abstract *CubeSats have become a relevant technology and philosophy for the private space sector, using them for operational missions like Planet's constellation for Earth Observation with 3m resolution.*

To understand the evolution of optical capabilities different small satellite databases were reviewed, focusing on LEO, optical payloads, and missions deployed over the last decade. The classification was performed to break down and organized nearly one thousand spacecraft.

Capabilities of this spacecraft were compared to "traditional" missions such as Chile's 140 kg SSOT and theoretical limits for their telescopes.

It was found that almost ¾ of them are deployed in the most active orbits in LEO, SSO, and ISS. The capabilities of the latest generation Planet Dove are getting near the order of magnitude for SSOT. The main difference is the challenge in the number of spacecraft and ground segment required to be able to download and process the data.

Keywords: CubeSat; LEO; Small satellites; Nano satellites;

1. Introduction

Since the appearance of the CubeSat and its "container," the Pico Satellite Orbital Deployer or POD proposed by Bob Twiggs and Jordi Puig-Suari in 1999 [1] over one thousand have been deployed into orbit and hundred more are announced or planned for the next years [2]. The later can be observed in different databases that keep track[1] and estimate future trends, as can be seen in Fig. 1, the second decade of the CubeSat has seen a significant increase in their numbers, driven by the role of commercial players, such as Planet, Spire

[1] Note due to the shorter development cycles, and the many new and/or amateur organizations involved in the integration of this type of spacecraft, it has become harder to have "official" numbers and characteristics. Especially when compare to traditional projects where, likely due to effort, price, there is a series of publications in press and technical sources.

Global, and others who have successfully deployed constellations in LEO for operational service provision in the last decade.

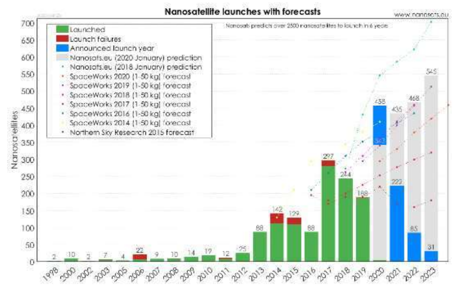

Fig. 1 Nano-satellites[2] in the past two decades and forecasts [Source: [2]**]**

The goal of this research is to identify and classify the last decade earth observation (VIS and NIR) in CubeSats deployed in LEO (200 to 1000 km altitude), through a state-of-the-art review regarding CubeSat Passive Earth Observation (EO) payloads and identifying the mission parameters available in reliable databases, to quantify the evolution in performance over time of payloads concerning “physical” limitations.

2. Methodology

The data for missions over the last decade was obtained from different databases as Nanosats.eu [2], Swartwout CubeSat Database [3], Gunter’s Space Page[4]. Then the data was narrowed to fit for CubeSats, as a form factor rather than weight, and orbit and mission definition was used to select the data in the scope of this study (LEO between 200 and 1000 km altitudes, and Earth Observation in the Visible (VIS) and Near Infrared (NIR)).

With this subset, characteristics of orbit data were analyzed and the payload is assessed taking the declared performance, and comparing to handbook design relations for passive VIR and NIR payloads were used [5], [6].

The particular results for the biggest nano-satellite constellation, Planet’s Dove 3 Unit CubeSat, was compared to the “traditional” EO spacecraft platform used for Chile’s SSOT (FASat-Charlie) mission.

3. Results and Discussion

General spacecraft breakdown by orbit, owner and application

Concerning satellite ownership and following registry as stated in the Space Treaties applicable the UN Registry Data as of October 2019 [7] shows a significant percentage of spacecraft not being registered, as can be seen in Fig. 2 almost one-third of the spacecraft have not been registered in the UN registry (which is a mandatory role of states subscribed to the Registration Convention and Outer Space Treaty).

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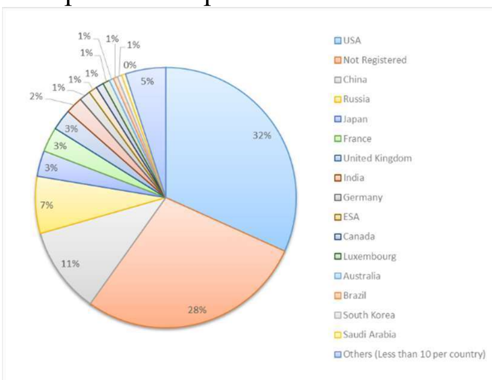
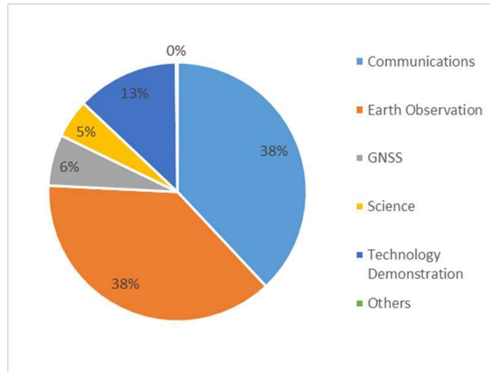
[2] Note that Kulu’s database uses the term nanosatellite implying: all CubeSats from 0.25 to 27 U; Nanosatellites from 1 to 10 kg, Picosatellite from 100 g to 1 kg; PocketQubes, TubeSats, SunCubes and ThinSats as defined in their website.

Furthermore, the role of SpaceX's Starlink constellation in the LEO region has become very relevant. As of June 13th, 2020[3] the number of operational satellites is up to 538 and growing, which when compared to the total number of operational satellites, in different orbits, as of October 2019 as summarized in Table 1 and Table 2, represents almost one-quarter of the total operational spacecraft.





a) UN Registry of spacecraft b) **Main mission**

Fig. 2 Spacecraft breakdown as of October 1st, 2019 [Source: Adapted from [7]**]**

Table 1 Spacecraft breakdown by major registry country, orbital region and owner organization (data up to October 1st, 2019) [Source: Adapted from [7]**]**

Total number of operating satellites			2.218
US: 704	Russia: 157	China: 238	Not Registered: 623
LEO: 1.468	MEO: 132	Elliptical: 56	GEO: 562
Civil: 155	Commercial: 1.037	Government: 565	Military: 461

CubeSat in the interest region of LEO

The focus of the study is in CubeSats which in number[4] represent around one-third of the spacecraft currently in orbit, as can be seen in Table 2.

Table 2 Orbit breakdown as of July 8th, 2020 [Source: [3]**]**

	All Launched	Decayed	Still in orbit	
All CubeSats	1184	407	777	65.6%
Constellations	535	181	354	66.2%
Non-Constellation	649	226	423	65.2%
All US-built	870	332	548	63.0%
Rest of the world	314	85	229	72.9%
Starlink spacecraft	600	3	597	

[4] Note that in terms of mass this is significantly different, as one GEO telecommunications satellite will be in the order of tons, hence counting for thousand CubeSat units.

Regarding the altitude at which CubeSats are deployed (in the LEO region between 200 and 1.000 km altitude), it can be seen in Fig. 3, where grey represents the satellites that have decayed due to atmospheric drag, and blue the ones that remain in orbit.

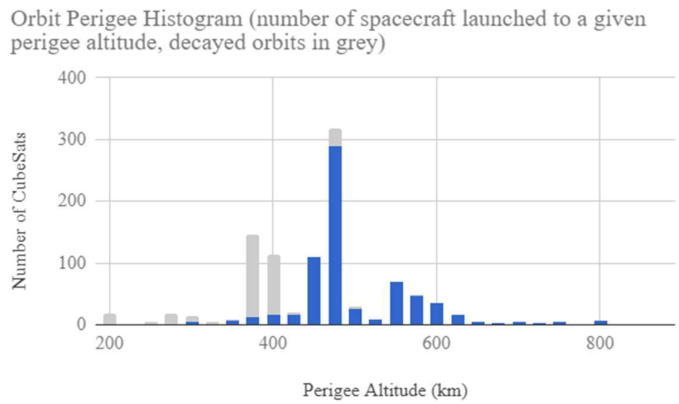


Fig. 3 Perigee altitude of launched CubeSats [Source: self-made from [3]**]**

Taking into account the data available for approximate orbits of 1227 nanosatellites, and plotting their inclination an altitude Fig. 4. One can appreciate that there is a significant correlation of missions in SSO orbits and a second group in the range of International Space Station (ISS). ISS orbital characteristics as stated by ESA [8], has a nearly circular orbit with an inclination of 51.6°, and an altitude range between 330 and 460 km (typically maintained in a narrower 340 to 385 km altitude range). CubeSats deployed from ISS are released from Japanese Kibbo Module, by astronauts, and might also consider ones deployed from rockets used for resupply missions.

In Fig. 4, each dot represents a combination of altitude and inclination, and not the number of spacecraft deployed there. In blue the line that corresponds to the relationship between inclination and altitude for a Sun Synchronous Orbit (SSO). When taking the number of CubeSats in each orbit, the pie chart in Fig. 5 yields a clearer picture of their distribution by the numbers. Note that ISS and SSO account for almost three-quarters of all deployed nanosatellites

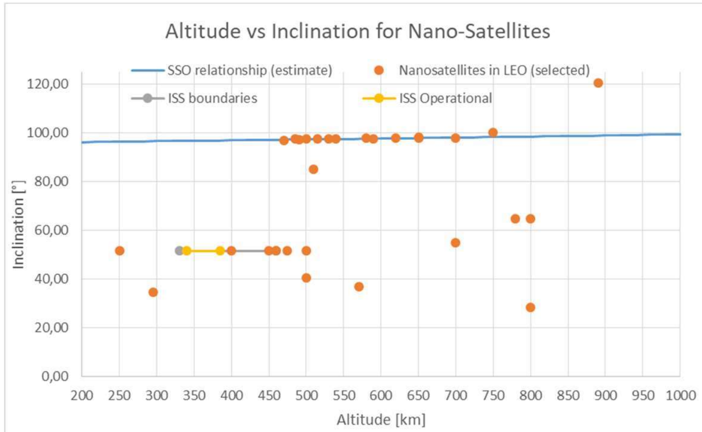


Fig. 4 Plot for LEO Nano-satellites altitude and inclination. [Source: Elaborated using for approximated orbit after launch as of April 20th, 2020 [2]**]**

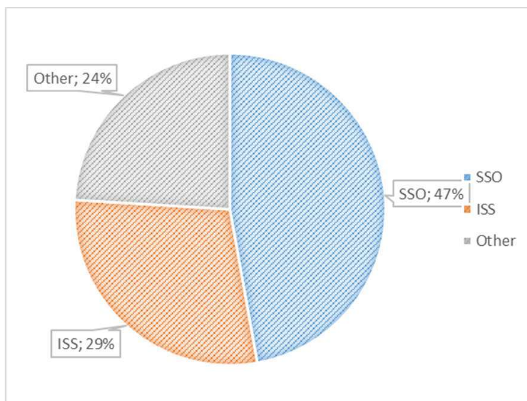


Fig. 5 Orbit "type" classification, by the number of nanosatellites in each "class". as of April 20th, 2020 [Source: self-made from data on orbit estimates [2]**]**

Passive Earth Observation Payloads in VIS and NIR metrics

The following is based on the work by Valenzuela & Reyes [5] regarding spatial resolution metrics. The following are assuming nadir imaging and provides the basics for the performance comparison of different spacecraft

The Ground Sample Distance (GSD) depends only on detector level pitch "*p*", satellite altitude "*H*" and instrument focal length "*f*". All are input in meters

$$GSD_{GSD} = \left(\frac{p}{f}\right) H$$

For the Rayleigh Diffraction Limit (RDL), in the case of an unobstructed circular aperture of diameter "D"[5] and an average wavelength "λ" (that we use as $550[\mu m]$ in the middle of the green band[6])

$$GSD_{RDL} = 1.22\left(\frac{\lambda}{D}\right)H$$

The Ground Spot Size (GSS) of the optics is defined as

$$GRD_{GSS} = GSS = \left(\frac{\lambda}{D}\right)H = \frac{GSD_{RDL}}{1.22}$$

The optical factor "Q", which is a fundamental design parameter of an optical sensor is

$$Q = \frac{GSS}{GSD_{GSD}} = \frac{\lambda}{D}\frac{f}{p}$$

Taking these relationships, and design values provided by BST, the SSOT, Dove, PeruSat-1 and a fictitious 1 unit CubeSat deployed from ISS at 400 km altitude are used as cases and their results provided in Table 4

Further detailed estimates for specific bands in other EO spacecraft are provided in **¡Error! No se encuentra el origen de la referencia.**.

Table 3 In Orbit performance measurements [Source: Adapted from Table II [5]]

Satellite	Sensor	GSD [m]	GSS [m]	Q	FWHM [pixels]
CBERS-1	Blue	19,50	2,90	0,15	2,2
Spot 5	B2 Red	10,00	1,58	0,16	2,0
CBERS-1	Green	19,50	3,32	0,17	2,3
Sentinel 2	B5 Red edge	20,00	3,69	0,18	1,7
CBERS-1	Red	19,50	3,95	0,20	2,4
CBERS-1	NIR	19,50	4,97	0,25	3,3
Sentinel 2	B4 Red	10,00	3,48	0,35	2,2
Cartosat 1	PAN aft	2,22	0,87	0,39	1,8
OrbView 3	PAN	1,00	0,71	0,71	1,6
Kompsat 2	PAN	1,00	0,80	0,80	2,8
Kompsat 3	PAN	0,70	0,58	0,83	1,7
Ikonos	PAN	0,82	0,71	0,86	1,6
Quickbird	PAN	0,61	0,55	0,90	1,5
GeoEye	PAN	0,41	0,39	0,94	1,5
WorldView 2	PAN	0,46	0,44	0,95	1,5
Pleiades	PAN	0,70	0,70	0,99	1,5
WorldView 1	PAN	0,50	0,54	1,08	1,5

[5] For the case of CubeSats, the unit limits the maximum physical aperture to 10 cm, however this is not feasible as some structure is still require. Therefore, the maximum aperture is 9 cm.

[6] Note the specific bands for SSOT are blue 455 to 520 [nm], Green 528-588 [nm], Red 625-695 [nm], NIR 758-881 [nm], PAN 455-744 [nm]. And the declared spatial resolution is 5.8 [m] for the multispectral bands and 1.45 [m] for the panchromatic (PAN) [10]

Table 4 Observation payload performance characteristic estimations.

Satellite	**Pixel pitch**	**satellite altitude**	**instrument focal length**	**Ground Sample Distance**	**Average wavelength**	**Diameter**	**Rayleigh Diffraction Limit**	**GSD w.rt.t RDL**	**Ground Spot Size**	**Optical factor**
	p [m]	**H [m]**	**f [m]**	GSD_GSD [m]	λ **[m]**	**D [m]**	**GSG_RDL [m]**	$GSD_{GSD} > GSD_{RDL}$	GRD_{GSS} **[m]**	**Q [-]**
SSOT[7]	7,40E-06	6,20E+05	3,2	1,43	5,5,E-07	0,20	2,08	no	1,71	1,19
Dove_SSO[8]	5,50E-06	6,00E+05	0,9	3,67	5,5,E-07	0,09	4,47	no	3,67	1,00
Dove_ISS[9]	5,50E-06	4,00E+05	0,9	2,44	5,5,E-07	0,09	2,98	no	2,44	1,00
PeruSat-1[10]	1,20E-05	6,95E+05	12,2	0,68	5,5,E-07	0,09	5,18	no	4,25	6,21
1U CubeSat ISS[11]	5,50E-06	4,00E+05	0,3	7,33	5,5,E-07	0,09	2,98	yes	2,44	0,33

[7] FASat Charlie or SSOT, Chilean Earth Observation Satellite deployed on December 2011

[8] Scenario for Planet's Dove 3 unit CubeSat deployed on SSO like orbit

[9] Same Planet's Dove 3 Unit CubeSat, deployed from ISS, hence lower orbit.

[10] Peruvian Earth Observation Satellite, manufactured by Airbus and currently with the best EO resolution in Latin America.

[11] Analysis for the geometrical/physical constrain of a 1 U platform as deployed into an ISS like orbit.

Planet satellites and ground segment

The results estimated in Table 4, are in line with the declared performance for the systems Planet Dove 3 to 5 [m] GSD [9], and one should consider several Dove's CubeSats, see Fig. 6, are deployed from ISS at a lower altitude which increases the GSD.

Fig. 6 Planet Dove 3 U CubeSat in operational configuration (Solar panels deployed and communication antenna flap opened) [Source: [9]**]**

Due to the number of spacecraft in operation, in the order of hundreds, planet operates 45 ground stations throughout the world, and as stated in their website www.planet.com: *"Our Mission Control team uses patented automation software to manage our fleet of satellites, allowing just a handful of people to schedule imaging windows, push software in orbit, and download images to 45 ground stations throughout the world."*

As for 2016 these operations translated up to 777 GB, and in an example case as seen in Table 5 for UHF and X bands.

Table 5 March 2016 Planet Ground segment operations[12]

UHF:	**X-Band:**
333 passes scheduled, 239 good passes, 71% 97k commands received	207 passes scheduled, 157 good passes, 76% 559 GBytes downloaded = 161k pics = 39M sq km * CONUS is 8M sq km

When compared to the operation of SSOT, with 4 passes per day and one ground station fully equipped, see Fig. 7, one sees the need for a completely different approach towards operating a constellation.

Fig. 7 SSOT mockup and ground station dual-band (S and X) antenna [Source: www.ssot.cl]

[12] http://mstl.atl.calpoly.edu/~workshop/archive/2016/Spring/Day%202/Session%204/1_BryanKlofas.pdf

4. Conclusion

An orbital classification for CubeSats in LEO was performed, this showed two main regions exist, with SSO and ISS like orbits being the principal ones. The latter likely due to the availability of regular launches to those regions.

The increasing number of spacecraft deployed has challenged the UN's registration, and requires a different approach as operational constellations, like Starlink, continue to be deployed.

The altitude and several design performance parameters where estimated and review against specifications, yielding in agreement. Since SSO yields global coverage in a matter of time, the constellations can theoretically map the entire glove, however, the challenge relies on the size of their swath and the ability to download and process the data on time.

The progress obtained by Planet and other "new actors" is remarkable, as their 4-5 kg spacecraft can perform at GSD 3 to 5, versus SSOT 140 kg with 1.45 m GSD. This allows for future analysis and conceptual design trade-offs to be performed in the case of future missions in this performance range.

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