METHODOLOGY FOR CONCEPTUAL DESIGN PHASE ASSESSMENT OF TRADITIONAL VS SMALL SATELLITE MISSION SPACE SEGMENT CONCEPTS PART 1: INPUT AND OUTPUTS

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The NanoSatDev Project, at INPE, looks into ways to analyze "traditional" spacecraft concepts into "small" satellite designs where a bigger number of spacecraft, coupled with the use of different hardware (non-space heritage necessarily) and processing strategies can make new space segment feasible. For the later a strategy to assess the performance of the systems at an early design stage (either phase-0 or A) is required.

As the first step for this development, key high-level mission inputs and Key Performance Indicators (KPI) outputs are identified. Being power, mass, orbital altitude (and type), Rough Order of Magnitude (ROM) budget/cost of mission per spacecraft critical aspects for comparison amongst missions.

The study is constrained on CubeSats, as they represent 92% of the spacecraft in the nano-satellite range (1 to 10 kg) launched since 1998. Furthermore, there has been a steep increase in the launches over the last decade, becoming the standard configuration for the nano-satellite class, allowing for the development of several suppliers of hardware, software, and services (such as launch brokerage, amongst others).

Only specific Low Earth Orbit (LEO) earth observation and communications type of missions are considered, as this is a practical constraint to the search space and true or existing nano-satellites due to physical constraints and accessibility to orbit (as no maneuvering capability is available and they are deployed according to the launch vehicle capabilities and prime payload's requirements). Furthermore, only space segment aspects are considered, without any institutions legacy aspects taken into consideration, and assuming vendor specifications are accurate

Use of basic well understood physical concepts to assess performance form LEO specific orbits and power, mass and volume constraints prove useful to take into account for nano-satellite capabilities. Literature review of the state-of-the-art capabilities for this spacecraft sets an upper limit to feasible capabilities of stand-alone systems

Regarding costs of recurrence, costings schemes have been reviewed and are interesting when constellations of CubeSats come as an alternative.

A relevant issue for the further advancement relates to the effort required for mapping previously flown missions, some decades old, versus designing a new solution from "scratch".

1. Introduction

Small satellites are being used for science as well as service provision and have become an invaluable tool in the current private sector developments in the space business. Start-Up Companies like Planet Labs, Spire Global and others have to change the paradigms, which lead the industry over the past decades. Their non-traditional approach to space and “mass production”, coupled with the fast developments of commercial electronics, yields the “traditional ways” in need for revision.

The NanoSatDev Project [1], being developed at the Brazilian National Institute for Space Research (INPE), looks into ways to analyze and trade-off “traditional” spacecraft concepts into “small” satellite designs, where the potential for a much bigger number of deployed spacecraft, coupled with the adoption and use of not only space developed hardware and software, as well as different design and risk approaches can make new concepts feasible. The role of the private sector, coupled with the previously described approach is normally referred to as “New Space”.

The present article deals with the early stages of strategy development for assessing the performance of early design concepts by a fly-alone, formation flying, constellation or other distributed space segment built using traditional spacecraft or small satellites. This is further constrained to the nano-satellite (1-10 kg) class and its major representative the CubeSat, since the latter represents over 92% of the spacecraft in the class [2] and considers only specific Low Earth Orbits (LEO) for Remote Sensing (RS) or Communication payloads due to practical accessibility to SSO and International Space Station (ISS) as secondary-payloads onboard different launch vehicles (See Fig. 1, where it is clear that the majority of CubeSats are deployed at variations of the main Earth Observation Sun-Synchronous Orbit (SSO) or deploy from ISS at 51.6° inclination)

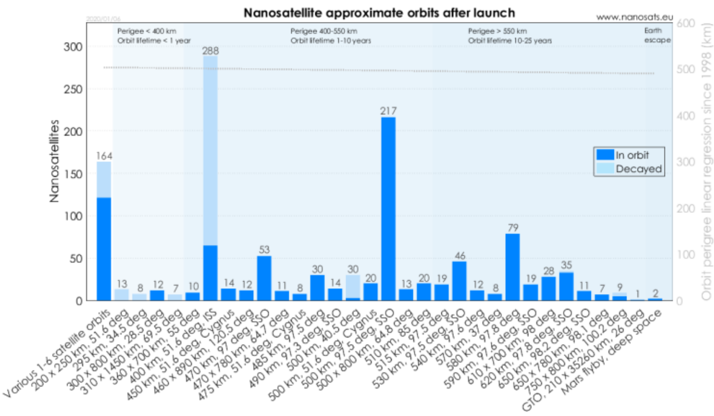

Fig. 1 Nanosatellite orbits (Source: [2]**)**

To asses, the concepts, high-level mission inputs and Key Performance Indicators (KPI) outputs are identified, together with the use of well understood physical concepts to constrain the search space. Cost estimates, for recurring space segments, have been reviewed, being of special interest for constellations. Yet a challenge remains regarding the effort of mapping previously flown mission, some decades-old in conception and analogously documented, versus developing the “traditional” concept from scratch.

2. Small satellite definition and scope of this research

The concept of small satellites has several definitions in terms of weight. Depending on the source it can go up to 500 kg (Traditional definition), and down to 180 kg [3] or 150 kg [4]. For the purposes of the present discussion and considering several “traditional” spacecraft for Earth Observation such as Fasat-Charlie launch in 2011 with a mass of 142 kg [5], SSTL DMC first-generation satellites launched in early 2000s and with a mass around 100 kg [6], and several other “traditionally developed” earth observation missions are under the 150 kg threshold, there is a need to define a boundary (other than mass alone) to separate traditional to small satellite concepts. Furthermore, the mission capabilities, both in indigenous capacity and distributed/constellation capacity of distributed systems has become a reality on the last decade (examples as Planet Labs Dove, Spire’s Lemur, with many others under development (or announced) as can be seen in Fig. 3)

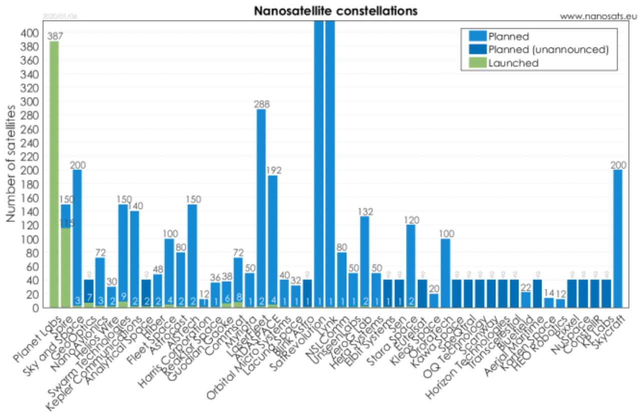

Fig. 2 Nano-satellite constellations (announced and launched as of January 2020) (Sorce: [2]**)**

Note the number of nano-satellites, especially over the last decade (see Fig. 3 and Fig. 3), represent a significant fraction of the operational LEO spacecraft (as of December 2019, 2.218 satellites orbit the Earth [7]). Hence the definition for this project is that CubeSats are to be treated as the small satellite enabler for the future analysis, having the different configuration in a multiplier of the basic unit of 10x10x10 cm^3 as proposed by Twiggs and Puij-Suari [8] and its evolution (with some charge in the height constraints).

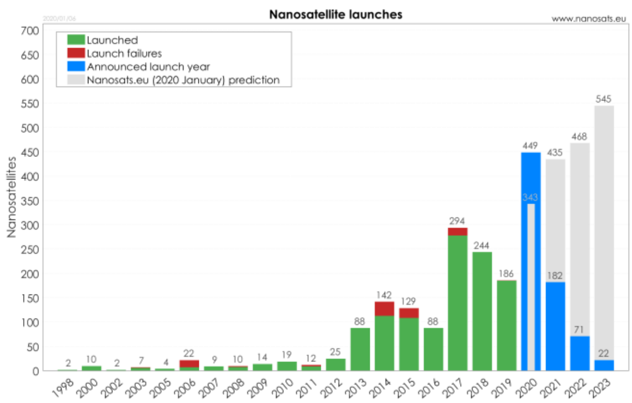

Fig. 3 Nanosatellites launched over the past two decades (and projections) (Source: [2]**)**

Therefore, the definition of small satellites will be up to a mass of 180 kg (Based on FAA's definition [3]) and launched after 1999 (hence the appearance of the CubeSat standard[9]). Furthermore, the scope of this study is the CubeSats, which are the main representative of the nano (1 to 10 kg) and picosatellite (0.1 to 1 kg) classes (having representatives in multiples above the 10 kg boundary, as can been seen in the commercially available structures in Fig. 4)

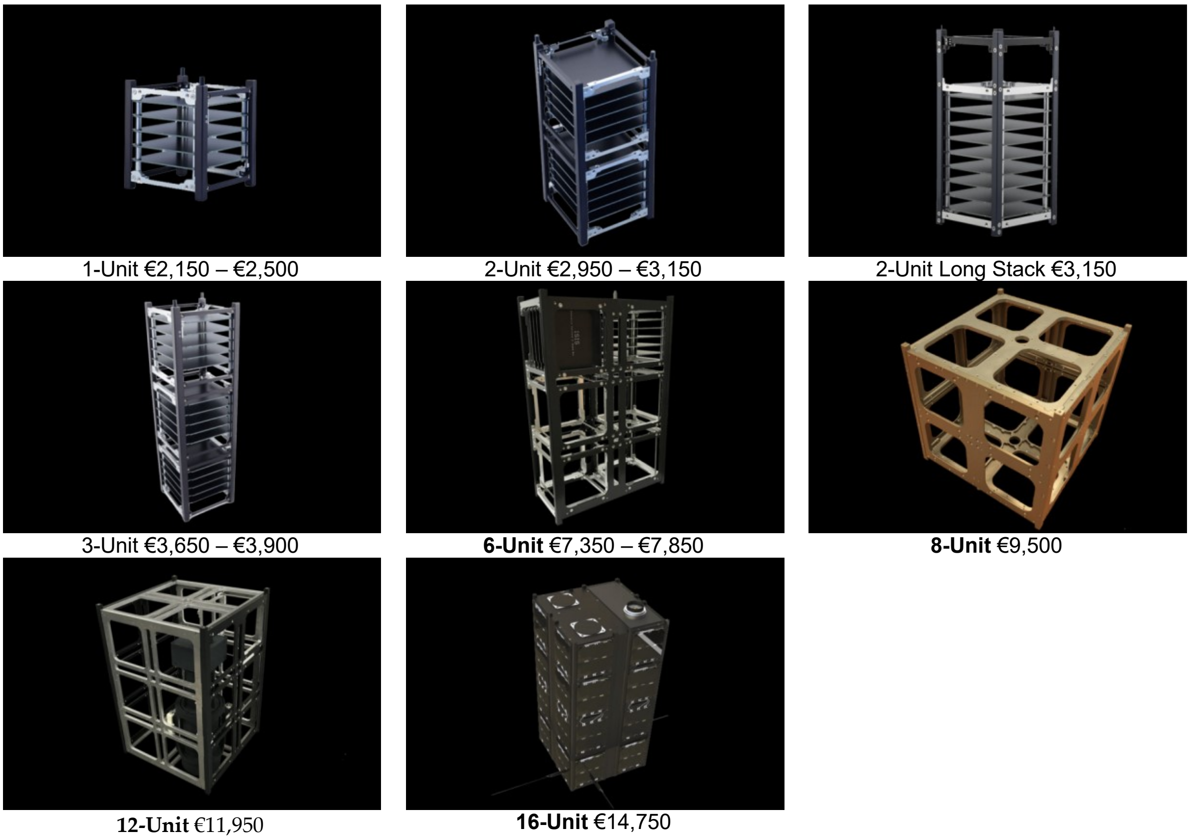

Fig. 4 Some examples of Commercial Off the Shelf CubeSat standard-based structures and their prices as of January 25th, 2020 (Source: Adapted from [10]**)**

3. Methodology

At first, the search space was constrained by having the CubeSat standard-based concepts represent the small satellite alternatives. This was further constrained to certain orbits, such as SSO or ISS like, due to feasibility of reaching this as piggy-back with respect to other orbital planes and altitudes. Furthermore, practical applications for this class, due to physical constraints and environmental (like radiation) have been addressed by selecting only LEO region and remote sensing and communications missions (Note that we are not aiming to replace a GEO Communications Satellite, nor the Hubble Space Telescope, as this will be impossible, but rather provided solutions where the higher number and hence the lower temporal resolution allows for serving needs in a ways that might not be feasible, for example, due to cost, by following traditional approaches for spacecraft design and manufacture).

Maneuver capabilities are not yet there, though serious research and development in this area are being done. According to NASA's State of the Art- Small Spacecraft Technology [11], a wide range of options for propulsion exists for small satellites, however, the miniaturization required for them has been particularly challenging. It also states that:

In the near future, the focus is placed on non-toxic propellants that avoid safety and operational complications and provide sufficient density and specific impulse despite high cost per kg. The application of this technology in CubeSats is still in development, as some of the components need to be scaled down to comply with volume, power, and mass constraints.

After having constraint the search space and capabilities, a review of key concepts in order to identify Key Performance Indicators (KPI) to trade in both tradition and small missions space segments. Furthermore, the use of well understood physical concepts is used to obtain the Rough Order of Magnitude (ROM) KPIs.

Preliminary model concepts

With the previous section work, a preliminary conceptual flow for a model was elaborated. One of the key aspects, following Pareto's Principle, was to trade a lower performance at a much lower cost (both in terms of money and development time). If not so, the performance of a mission stated for a custom-built satellite segment will be nearly impossible to reach using smaller spacecraft (simply due to focal length, data rate, power, and other limitations inherent to their size and weight). The flow, Fig. 5, starts by determining the key performance parameters, from the phase 0 or A level design, and obtaining a number of CubeSats capable of producing the required data, under the temporal resolution, without exceeding the maximum feasible power for a 1U class, this is then costed (preliminary at 100.000 USD per kg and 70.000 for launch (RoM cost estimates for a stand-alone mission), after this the OUTPUT KPI are compared to the ones of a "reference" traditional mission. If not satisfied, the size of the CubeSat is increased and/or the number of Spacecraft, this is then put in the same look until and 80% performance or 20% cost is achieved (when the problem should either solve or a new approach is required). At an increased number of satellite, replicability factors as those proposed by Nag et al [12] are used.

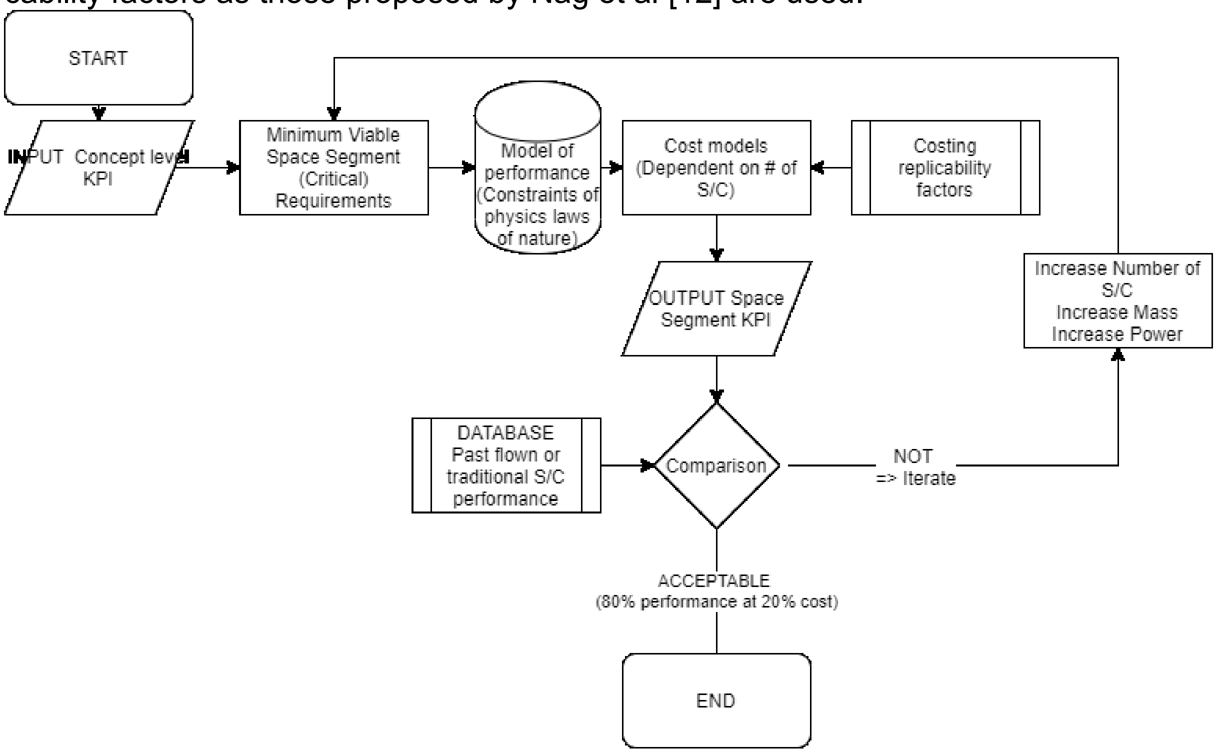

Fig. 5 Preliminary flow for an assessment of alternative mission concepts

4. Physical rules/laws of nature

The satellite bus, due to state of the art communications subsystems (mostly Software Defined Radios (SDR) on-board CubeSats) allows for dynamic download data rates, however, this is still limited by the available power, and link budget. Hence the Payload data generation, coupled with the ground's segment capability for downloading limits the maximum data than can be practically obtained, processed and stored onboard (before requiring to download). Furthermore, for the case of communication missions, the power budget in and operational scenario will limit the power and time available for the mission.
Regarding the design requirements, this will end up in a cost due to hardware and software development, and multiple spacecraft assembly and integration, as well as launching into orbit. The relation with the reliability of the space segment is yet to be developed, however, in principle, a distributed system is more reliable than a stand-alone due to the fact not all capabilities are placed in a single entity.
This is schematically described in Fig. 6, where the KPI is shown.

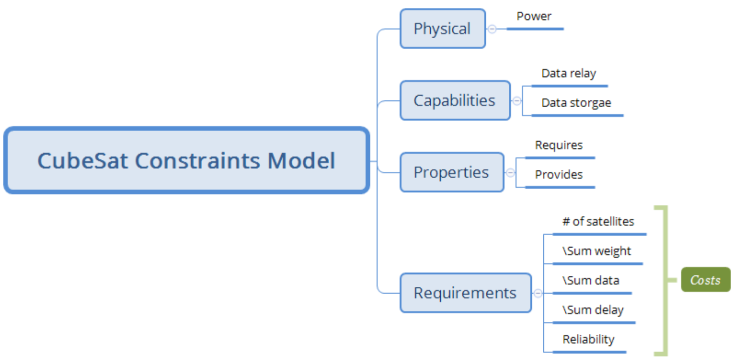

Fig. 6 Key performance parameters for assessment

5. Conclusions

The division between a traditional and small satellite mission was defined by using the CubeSat standard and further dividing the weight class down to 180 kg, as stated by FAA, and considering missions flown over the last decade.

Power, data generation, downlink, and storage, have been identified as key performance parameters for the components to be integrated for elaborating the preliminary solutions (i.e. the minor size and number CubeSat). Note at this level, the datasheet information should be considered true, as the effort for assessing the performance is well out of the scope.

Physics principles, and well understood and characterize design relations allow to constrain the components by the sum of their mass, power demand, volume, data, etc.

Work remains to be done in identifying, cataloging, and structuring up-to-date databases of components to allow for realistic capabilities and requirements (in terms, for example of power, download data rate, storage, of the components in the market).

The preliminary model is yet to be ran using a test case, where the design requirements and produced outputs are well documented.

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