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Abstract

In recent years, CubeSats have considerably extended their range of possible applications, from a low cost means to train students and young researchers in space related activities up to possible complementary solutions to larger missions. Increasingly popular, whereas CubeSats are still not a solution for all types of missions, they offer the possibility of performing ambitious scientific experiments. Especially worth considering is the possibility of performing Distributed Space Missions, in which CubeSat systems can be used to increase observation sampling rates and resolutions, as well as to perform tasks that a single satellite is unable to handle. The cost of access to space for traditional Earth Observation (EO) missions is still quite high. Efficient architecture design would allow reducing mission costs by employing CubeSat systems, while maintaining a level of performance that, for some applications, could be close to that provided by larger platforms, and decreasing the time needed to design and deploy a fully functional constellation. For these reasons many countries, including developing nations, agencies and organizations are looking to CubeSat platforms to access space cheaply with, potentially, tens of remote sensing satellites. During disaster management, real-time, fast and continuous information broadcast is a fundamental requirement. In this sense, a constellation of small satellites can considerably decrease the revisit time (defined as the time elapsed between two consecutive observations of the same point on Earth by a satellite) over remote areas, by increasing the number of spacecraft properly distributed in orbit. This allows collecting as much data as possible for the use by Disaster Management Centers. This paper describes the characteristics of a constellation of CubeSats built to enable access over the most remote regions of Brazil, supporting an integrated system for mitigating environmental disasters in an attempt to prevent the catastrophic effects of natural events such as heavy rains that cause flooding. In particular, the paper defines the number of CubeSats and the orbital planes required to minimize the revisit time, depending on the application that is the mission objective. Each CubeSat is equipped with the suitable payloads and possesses the autonomy and pointing capabilities needed to meet the mission requirements. Thanks to the orbital features of the constellation, this service could be exploited by other tropical countries. Coverage of other areas of the Earth might be provided by adjusting the number and in-orbit distribution of the spacecraft.

Keywords	Earth Observation, CubeSat, Disaster Management, Satellite Constellation
Manuscript category	Space Systems Operations & Utilisation

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Submission Files Included in this PDF

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CoverLetter.pdf [Cover Letter]

Rebuttal_ACTA_2017_282_R1117.pdf [Response to Reviewers]

ACTA_2017_282_Highlights.pdf [Highlights]

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Fig1.eps [Figure]

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Dr. Eva Yi-Wei Chang
Managing Editor
Acta Astronautica
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February 28, 2017

Dear Dr. Chang:

I am writing on behalf of Prof. Giancarlo Santilli, with regard to your invitation email (sent on December 07, 2016)to submit a paper considering that our paper presented in the 67th IAC held in Guadalajara, Mexico on 26 to 30 September 2016 has been pre-selected for peer review process of the Acta Astronautica.

I am pleased to submit our research article entitled "CubeSat Constellations for Disaster Management in Remote Areas" for consideration for publication in your journal. We have slightly changed the title, the original, presented in IAC was:" Disaster Management of Remote Areas by Constellation of Cubesats".

We believe that this manuscript is appropriate for publication by Acta Astronautica.

This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose.

Thank you for your consideration!

Sincerely,

Cristian Vendittozzi, PhD
Professor, Curso de Engenharia Aeroespacial
Universidade de Brasília - Faculdade Gama

Rebuttal File: ACTA_2017_282_R1117
Paper title: CubeSat Constellations for Disaster Management in Remote Areas

To Reviewer 1: We acknowledge your criticism and advice; we can fully integrate your feedback.

L. 139/140: ION/Swisscube: Please check if ION and Swisscube really carried instruments with a NIR band (which is not the case to the reviewer's knowledge). It would be very beneficial to state the actual wavelengths these two satellites intended to measure. E.g., to the reviewer's knowledge, Swisscube had a 767nm channel, and ION at ~763nm, which, although close, most people would not identify as NIR (the authors themselves state a definition of NIR as 770-900nm on L 291). It would therefore be beneficial to provide the satellite's wavelength to allow the reader to come to an assessment of how applicable these missions are to a true NIR channel.
Also, I suggest adding "(lost in launch failure)" to ION, to avoid that readers get the impression that the spectrometer was tested in space.

We agree. Rephrased as: "other CubeSats developments such as Ion [13], and SwissCube [14] have proved that it is technologically possible to design and build a CubeSat incorporating a NIR band (763 nm for Ion and 767 nm for Swisscube), even though Ion was lost in a launch failure."
Such wavelengths can be actually considered NIR, albeit at the low-wavelength end of the NIR region, according to authoritative references such as
1) James B. Campbell and Randolph H. Wynne, "Introduction to Remote Sensing," 5° edition
2) Thomas M. Lillesand, Ralph W. Kiefer and Jonathan W. Chipman, "Remote Sensing and Image Interpretation," 5° edition
This, in particular, defines the NIR region as starting from 720 nm (see table below).

TABLE 2.3. Principal Divisions of the Electromagnetic Spectrum

Division	Limits
Gamma rays	< 0.03 nm
X-rays	0.03–300 nm
Ultraviolet radiation	0.30–0.38 μm
Visible light	0.38–0.72 μm
Infrared radiation	
Near infrared	0.72–1.30 μm
Mid infrared	1.30–3.00 μm
Far infrared	7.0–1,000 μm (1 mm)
Microwave radiation	1 mm–30 cm
Radio	≥ 30 cm

We have accordingly changed our definition of the NIR band as "720-1300 *nm*") on L 291.

Minor:

L. 45: To my knowledge, Planet Labs changed its name to Planet. And Terra-Bella (I assume this refers to Skybox) was acquired by Planet

Done, updated to current name.

Table 5: It is probably better to state revisit time and average gap in minutes or hours to enhance clarity.

We agree. Done, as suggested.

L. 255: Please specify "data collection system" What kind of data was collected would be interesting, especially considering the small data rates discussed.

We agree. Now reading "providing a data collection system (e.g., meteorological data, water levels, etc.)".

L. 330: I do not think the manuscript provides enough data to come to a conclusion ("the only way") such as "CubeSat constellations could be the only way to overcome the revisit time limits"… there might be other alternatives not based on the Cubesat standard that provide similar solutions.
We agree. Attenuated as "CubeSat constellations could be an interesting way to overcome"
L.334: Please change the company name to their current name.
Done, as suggested.
L.335: this may be a minor point, but Surrey is mostly known for their Smallsats, which are not Cubesats.
We agree. Changed to "small satellites", meaning any spacecraft below 500 kg.
L. 341ff: "In order to be effective in increasing the remote observation opportunities of a given area after a disastrous event, as well as to the revisit time, specific attention should be devoted to the spatial resolution of the instrument, because a revisit time of minutes or hours requires the satellites to be located on different orbital planes"… this sentence is confusing: it bases the value of observation, together with revisit time, implying that this is somehow coupled to instrument spatial resolution, which is then connected to orbital planes. While I agree that these are inter-dependent, it would be better to rephrase to a clear train of thought, so that the reader can follow.
We agree. Rephrased as:" In order to be effective in increasing the remote observation opportunities of a given area after a disastrous event, as well as the revisit time, specific attention should be devoted to the spatial resolution of the instrument, because a revisit time of minutes or hours would otherwise require the satellites to be located on different orbital planes."
L 353: "making a major contribution to science" no science missions are proposed in this paper.
We agree. Rephrased as "making a major contribution to disaster management and society"

ACTA_2017_282_Highlights

1. A dedicated Cubesats constellations integrating a Disaster Management System.
2. UH CubeSats constellations to increase observation sampling rates and resolutions.
3. Examples of Cubesats payload sizing used for disasters monitoring.
4. Distributed Space Missions to solve tasks that a single satellite is unable to solve.
5. Methodology to establish the EO missions most suitable for disasters monitoring.

CubeSat Constellations for Disaster Management in Remote Areas

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Abstract

In recent years, CubeSats have considerably extended their range of possible applications, from a low cost means to train students and young researchers in space related activities up to possible complementary solutions to larger missions. Increasingly popular, whereas CubeSats are still not a solution for all types of missions, they offer the possibility of performing ambitious scientific experiments. Especially worth considering is the possibility of performing Distributed Space Missions, in which CubeSat systems can be used to increase observation sampling rates and resolutions, as well as to perform tasks that a single satellite is unable to handle. The cost of access to space for traditional Earth Observation (EO) missions is still quite high. Efficient architecture design would allow reducing mission costs by employing CubeSat systems, while maintaining a level of performance that, for some applications, could be close to that provided by larger platforms, and decreasing the time needed to design and deploy a fully functional constellation. For these reasons many countries, including developing nations, agencies and organizations are looking to CubeSat platforms to access space cheaply with, potentially, tens of remote sensing satellites. During disaster management, real-time, fast and continuous information broadcast is a fundamental requirement. In this sense, a constellation of small satellites can considerably decrease the revisit time (defined as the time

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elapsed between two consecutive observations of the same point on Earth by a satellite) over remote areas, by increasing the number of spacecraft properly distributed in orbit. This allows collecting as much data as possible for the use by Disaster Management Centers. This paper describes the characteristics of a constellation of CubeSats built to enable access over the most remote regions of Brazil, supporting an integrated system for mitigating environmental disasters in an attempt to prevent the catastrophic effects of natural events such as heavy rains that cause flooding. In particular, the paper defines the number of CubeSats and the orbital planes required to minimize the revisit time, depending on the application that is the mission objective. Each CubeSat is equipped with the suitable payloads and possesses the autonomy and pointing capabilities needed to meet the mission requirements. Thanks to the orbital features of the constellation, this service could be exploited by other tropical countries. Coverage of other areas of the Earth might be provided by adjusting the number and in-orbit distribution of the spacecraft.

Keywords: Earth Observation, CubeSats, Disaster Management, Satellite Constellation

1. Introduction

Disaster management is organized in a well-defined structure that refers to four different phases: prevention, preparedness, relief, and reconstruction (Disaster Management Cycle, DMC). Earth Observation Satellites (EOSs) are the ideal tool for disaster management, covering many tasks over all the phases of the DMC. An important aspect to emphasize is the opportunity to collect information over large areas, in short time intervals, at a safe distance and with a resolution that can increase depending on the level of required detail. EOSs allow rapid and targeted intervention, enabling the mitigation of the effect of disasters of natural or anthropic origin. The Brazilian territory is vulnerable to disasters due to heavy rainfall, sea level rise, drought, fires and floods. The latter, focus of the present work, have plagued the country in recent years. Ac-

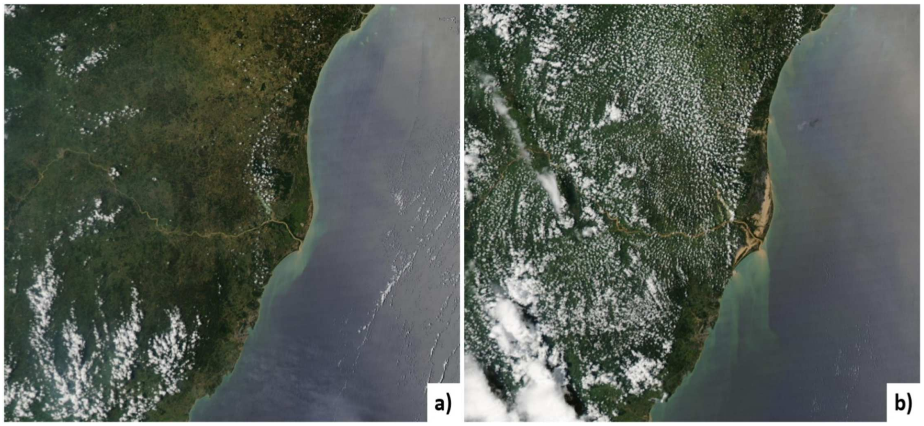

Figure 1: **Image from MODIS on NASA's Aqua satellite acquired: a) on December 27, 2012, normal conditions for the season; b) on December 30, 2013, floods along the Doce River in the Espirito Santo state. Courtesy of NASA. https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=82755**

cording to the 2015 World Disasters Report, floods and landslides accounted for 49% of all natural disasters in 2014, causing 63% of the total number of disaster related deaths and 34% of the total number of people affected by disasters, more than any other natural hazard, including storms, which accounted for 41% of all disasters [1]. Major landslides occurred in 2015 in Brazil, with many people left dead or injured. Several rivers overflowed causing flooding in many densely populated areas of the São Paulo and Rio de Janeiro states, damaging houses and causing severe disruption to local transport. Many roads and railway lines were temporarily interrupted, causing major issues to commuters working in the metropolitan regions. This type of event has repeatedly occurred in recent years due to intense rains concentrated in the same season. December 2013 was an extremely wet month in southeastern Brazil, and rainfall in the Espirito Santo state reached 714 millimeters, an all-time record monthly rainfall (Fig. 1). As of December 30, at least 45 people had died and an estimated 70,000 people had been evacuated. Others were left isolated after the collapse of hundreds of kilometers of roads [2].

Satellite constellations are used by governmental agencies in order to support the disaster management infrastructure. Satellite size has been shrinking and small satellites have become a reality in the last twenty years, starting to be employed also in this field [3], [4].

This paper proposes a constellation of CubeSats for monitoring the territory in the presence of natural disasters, with particular focus on the case of Brazilian remote areas. The effectiveness of the system consists in its ability to monitor areas that are usually not accessible, such as the Amazon region, or areas where it is not possible to use other monitoring systems (as for example during conflicts). In terms of constellations and data, CubeSats represent a solution capable of providing a large amount of information in order to monitor future extreme weather events and to aid the efforts in anticipating natural disasters and mitigating their effects. By using nanosatellites and modern technologies, total costs can be reduced and, at the same time, performance and system flexibility with respect to other mission concepts can be improved. CubeSat constellations have started to be proposed and implemented in recent years, as evidenced by the Terra-Bella and Planet constellations. Another interesting case is the Humsat project, which is an international educational initiative for building a constellation of nanosatellites providing worldwide communication capabilities to areas without infrastructure [5].

With a CubeSat constellation it is possible to offer a multi-purpose data collection system, providing information that is not limited to environmental data, such as weather information, emergency reports from ground networks, monitoring of electrical or water networks delivering wide-ranging risk maps to help civil protection.

This paper is organized as follows. Section 2 describes characteristics of the constellation that are desirable in order to fulfil the application with a focus on the main features of disaster monitoring missions. Section 3 reports the results of some case studies. Section 4 describes the satellite bus being considered. Conclusions and final comments are given in Section 5.

2. Data and methods

2.1. Rating Satellite Systems Against Emergency Related Applications

According to the indications of the European Commission (EC) [6], security concerns both civil and military matters: response to terrorism, natural and anthropogenic disasters (especially those that occur rapidly, such as earthquakes and tsunamis), industrial accidents and shared threats. Once the context has been defined, the existing systems can be considered and the gaps between perceived requirements and current capability can be identified. With respect to the requirements for each specific disaster [7], a value to each present and future space-based remote sensing system can be assigned. This is possible because, as explained in the following paragraphs, there is a methodology that defines an appropriate index associated with each space-based remote sensing system, which allows for comparison between different EO systems to individuate the most suitable system for monitoring a particular event [8]. Once the main features of the space mission, such as spatial resolution, spectral resolution, revisit time, swath and so on, are defined, it is possible to calculate the performance of the system. It remains understood that the main limit of EO space systems consists in their reduced capability to respond to phenomena requiring simultaneously high spatial and temporal resolutions. Some of the possible emergency/security fields for which remotely sensed information can be used are: Terrorism, Proliferation of Weapons of Mass Destruction (WMD), Regional Conflict, Natural Disaster, Local Instability, State Failure, Organized Crime, Active Engagement, etc. [9] [10].

A way to gather information using satellite based data consists in defining a series of key elements characterizing the objects being searched. Such key elements can be used to identify, in satellite imageries, several characteristic items in an extended area; once the validity of the key elements has been established, object-based image analysis methods can be used to broadly classify a large-area image; thus, an analyst could narrow down areas of interest. Considering for instance the problem of monitoring inter-border conflict, the objective is *to* *apply space-based techniques for giving early warnings of potential conflicts*:

- determine deployment mode of military hardware;
- using change detection methods, estimate if there are any troop movements;
- determine concentrations of military hardware along international borders.

These new applications of space-based remote sensing systems create new issues. Generally speaking, in the space segment three distinct parts can be distinguished: Platform (Position and Attitude), Sensor (Spectral Band Resolution, Resolution, etc.) and Configuration (Repetition Rate, etc.). The combination of these three parts allows creating a dedicated system, suitable to provide the required information, satisfying even the needs of unskilled users. In order to properly compare sensor performance and assess the suitability of a sensor for a specific task, it is important to remember that different applications show different requirements (see Tab. 1, [7]).

For instance:

- Threat monitoring ⇒ temporal resolution is not critical but high spatial resolution is required;
- Border monitoring ⇒ high temporal resolution and medium/high spatial resolution are required.

Therefore, to judge a satellite system the following parameters must be considered [8]:

A = pixel / km^2,
B = observations / day,
C = frame size / event extent,
D = spectral bands,
E = interval of the electromagnetic spectrum being sampled.

Table 1: **Spatial (m) and temporal (hours, h and days, d) image resolution necessary for different levels of analysis on targets/events of interest [7].**

Emergency	Phase	Spatial Resolution	Time Resolution
Floods	Monitoring	30-100 m	12 h
	Management	10-100 m	3-12 h
Landslides	Monitoring	30-250 m	1 d
	Management	10-100 m	3-12 h
Earthquakes	Management	1-100 m	3-12 h
Volcanoes	Monitoring	30 m	1 d
	Management	10-30 m	6 h - 1 d
Fires	Monitoring	100 m	1-3 h
	Management	30 m	0.25 h
Sea pollution	Monitoring	1 km	1 d
	Management	100 m	6-12 h
Border monitoring	Monitoring	1-10 m	3 h
Humanitarian Emergencies	Management	1-10 m	1-3 h

These terms will be considered all together and opportunely weighted, for each specific application, in order to define an index characterizing the remote sensing system performance, thus allowing the selection of the most suitable one with respect to that application.

2.2. Disaster Monitoring

Disaster monitoring is an extremely broad term encompassing natural catastrophes such as floods, fires, earthquakes, tsunamis, and volcanic eruptions, as well as other disasters that benefit from a large field of view from space, e.g., nuclear disasters. Most of these applications present common characteristics:

- they are related to phenomena occurring on very fast time scales, in the order of the hour or tens of minutes;

- they occur on a local scale, with relatively small spatial scale, in the order of tens of meters or less, even though there may be a need to acquire regional events globally;
- they require some situational awareness, which translates into a reasonable swath;
- they typically have relatively low spectral content and resolution requirements, with a few channels in the visible and one in the infrared usually being sufficient, with the possible exception of fire monitoring, which benefits greatly from a channel in the Mid-Infrared (MIR).

CubeSats represent the promise of affordable, global, sub-hour disaster monitoring. However, given the state-of-the-art of CubeSat technology [11], the combination of high spatial resolution and large swath, together with the stringent data rate requirements, seems very difficult to obtain (Tabs. 1, 2).

Several CubeSats have been specifically designed for disaster monitoring and provide useful references, despite their mission history not having been always successful. For example, the M-Cubed is designed to provide 200 m spatial resolution imagery in the visible [12]. Although M-Cubed lacks a channel in the Near-Infrared (NIR) for atmospheric correction that would improve several disaster monitoring data products, other CubeSats developments such as Ion [13], and SwissCube [14] have proved that it is technologically possible to design and build a CubeSat incorporating a NIR band (763 nm for Ion and 767 nm for Swisscube), even though Ion was lost in a launch failure. Among the missions that are currently being developed, it is worth mentioning C^3EO (Competitive CubeSat Constellation for Earth Observation), capable of providing both high spatial and temporal resolutions through an innovative design, which will possibly include a deployable telescope [15].

2.3. Enhancing the revisit frequency

CubeSats represent a useful tool to respond to the need for a high temporal observation frequency (in the order of hours) posed by applications concerning

Table 2: **Assessment of the utility of CubeSat-based missions for Disaster Monitoring [11].**

Parameter	Disaster monitoring
Selected measurement	High resolution cameras
Utility compared to traditional systems	Comparable
CubeSat technology readiness	In development
Scientific readiness	Mature

the use of satellite images for disaster management, as shown in Tab. 1. It is well known that a constellation of satellites located on the same orbital plane cannot reduce the revisit time to less than a nodal day (at equatorial latitude), assuming a sensor that only exploits the reflective part of the electromagnetic spectrum in our case. There exists a rich literature on orbital constellations and their design criteria for the distribution of satellites on various orbital planes to improve the revisit time or resolution of the ground tracks [16], [17], [18], [19].

In order to further reduce the revisit time to fractions of nodal days (down to 8-12 hours) a multiple orbital plane constellation must be designed. By adding one or more orbital planes to the constellation, it becomes possible to improve the revisit time and the spatial coverage. In the case of a Uniform Homogenous Constellation (UHC), the relationship between satellites and orbital planes of the constellation to maximize the number of revisits in the repetition period of a single satellite can be written [17], [18], [19]. Considering N satellites equally displaced on P orbital planes, N_p satellites each plane, $\Delta\Omega$ and ΔM are the relative right ascension and mean anomaly, respectively, between two satellites on the orbital planes. After d days, the longitude at the orbit node of the $l-th$ satellite on the $p-th$ plane, in the range $\pm\, S_t/2$, with respect to the longitude of the satellite 1 of the plane 1 at the day 0, is given by:

$$\lambda_{p,l,d} = \lambda_{1,1,0} + S_t \mod \left[d\frac{k}{m} + \frac{l-1}{N} + \left(\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t} \right) \right] \tag{1}$$

where:

- $p = 1, \dots P$;
- $l = 1, \dots, N_p$;
- d = number of days from the starting time of the revisit period m;
- S_t = distance between two consecutive equatorial crossings.

If the ground tracks are suitably combined, the minimum distance between two adjacent tracks can be reduced to $S_m = S_t/(P \cdot lcm)$, with lcm the least common multiple of m and n, whereas the revisit frequency will be maintained unchanged with respect to a constellation on a single plane.

The uniform distribution of the ground tracks capable of reducing the minimum track distance is obtained if the satellites and orbital planes are phased according to:

$$\frac{1}{P} = frac\left[lcm\left(\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t}\right)\right] \tag{2}$$

If the target is increasing the revisit frequency (with observations performed at different local times), the satellites and orbital planes must be phased by equating to zero the right-hand side of Eq. 2:

$$0 = frac\left[lcm\left(\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t}\right)\right] \tag{3}$$

In this case the number of observations obtainable in the repetition period of a single satellite m is equal to $P \cdot m \cdot N/lcm$, corresponding to a revisit frequency of, in nodal days, $r = lcm/P \cdot N$. Table 3 provides, synthetically, the entire set of possible enhancements obtainable from a UHC on single or multiple planes [16], [19], [20].

These results provide the theoretical basis that will be used for the design and simulation of UHC constellations in the Satellite Tool Kit (STK) environment, in order to achieve the revisit time needed for the two case studies proposed.

Table 3: **Synthesis of all possible enhancements obtainable from a UHC on single or multiple planes**

	r [nodal days]	S_m **[km]**	**m/r**
P (highest revisit frequency)	lcm/P·N	S_t/lcm	P·m·N/lcm
P (minimum ground track spacing)	lcm/N	S_t/P·lcm	m·N/lcm

3. Results

Two examples are presented in this section, describing the selection of the most suitable constellation orbits and architectures in order to improve performance and results for an EO mission designed for monitoring the effects of an environmental disaster.

3.1. Case Study 1: Flood Monitoring by Collecting Environmental Data in the Amazon Forest

A CubeSat constellation suitably distributed in space can ensure an extremely high collection rate/low revisit time of environmental data, thus providing important information to decision makers. Using two orbital planes, each with two uniformly distributed CubeSats, inclined at 10° from the equator and at an altitude of 500 Km, it is possible to ensure the desired revisit time (some tens of minutes). The constellation was simulated in the STK environment (Fig. 2). With five ground stations disseminated in order to provide coverage across the entire Amazon region, the system gets an average revisit time of about 10 minutes, allowing environmental ground terminal data to be downloaded as soon as possible.

The satellites receive these data from a network of about 1200 ground terminals uniformly spread over the Amazon territory. The data, consisting of text messages carrying information about the environment (e.g., water level in a water basin, temperature, humidity, etc.), are stored by the spacecraft and downloaded to the ground stations during the passages. This mission architecture

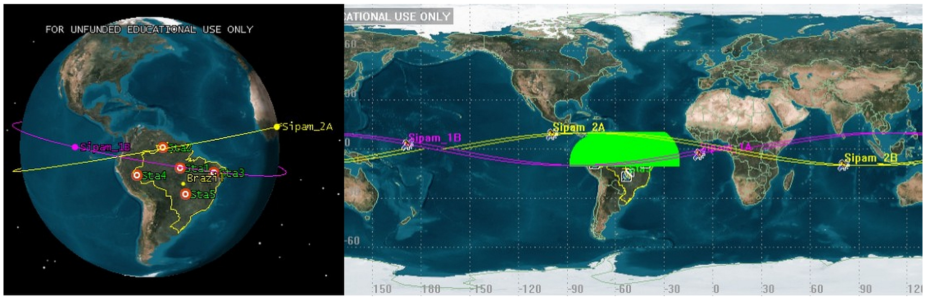

Figure 2: **Configuration of CubeSat constellation used to reduce the revisit time in flood monitoring. The system has 4 uniformly distributed satellites on two orbital planes with 10° of inclination, mainly dedicated to collecting environmental data from stations distributed in the territory (Simulations thanks to STK-AGI).**

has been tested in the Humsat project, which includes the Serpens nanosatellite, launched in 2015 by a consortium of Brazilian universities, led and developed by the University of Brasilia (UnB) [21]. The CubeSat constellation revisits the ground sensors with a variable time, which is a function of the latitude and longitude sensor coordinates within the Amazon territory. Table 4 shows the main parameters provided by the simulation in terms of revisit time, number of accesses per day, coverage time, etc., depending on latitude and longitude of the environmental ground sensor.

The calculation is related to four ground sensors located at the boundaries of the area of interest and the revisit time goes from 57 minutes (target 2) to 90 minutes in the worst case (target 4). The system can be used continuously or in stand-by until activated in an emergency case. This feature makes the system very versatile and capable of adjusting the revisit time as needed, allowing the monitoring and management of floods, as shown in Tab. 1.

3.2. Case Study 2: Disaster Monitoring by Collecting Images in the Amazon Forest

Another important case, in the monitoring of disasters in remote areas, is represented by the possibility of acquiring satellite images with high spatial resolution (3-10 m) and temporal resolution (some hours). With an altitude

Table 4: **Synthesis of the main parameters provided by STK simulations on target points placed at the boundaries of the Amazon forest (case 1)**

Parameter	**Target1 (lat: 3.2°, long:-62.22°)**	**Target2 (lat: -7.2°, long:-40.62°)**	**Target 3 (lat:-7.8°, long:-72.15°)**	**Target4 (lat: -15.68°, long:-52.47°)**
Access Duration (average [min])	1.96	2.18	2.25	3.05
Coverage Time (per day [min])	38.33	53.18	52.01	47.30
Aver. Accesses per day	19.52	24.39	23.13	15.52
Revisit Time (average [min])	71.64	56.76	59.89	89.47
Time Average Gap [min]	196.37	71.71	85.67	221.30

of 500 km, a 97°, 30/5/1 Walker constellation [20], [22] has been simulated in STK, with the results shown in Tab. 5).

This choice allows us to decrease the revisit time down to the desired value, but because of the five orbital planes uniformly-shifted in RAAN (Right Ascension of the Ascending Node, UHC), the local time of a generic location will be different for each orbital plane. Consequently, the same illumination conditions will not be achieved for images captured by satellites belonging to different orbital planes. This implies the need for a pre-processing phase in order to correct the different illumination conditions in the images. This constellation is shown in Fig. 3.

The simulations were conducted under the hypothesis of payload with a fixed nadir pointing. However, to further decrease the revisit time, in the most demanding cases, this parameter can be improved by using steerable payloads, a technology compatible with 3U CubeSats nowadays. Global coverage reaches 93% with this system.

Table 5: **Synthesis of the main parameters provided by STK simulations on target points placed at the boundaries of the Amazon forest (case 2)**

Parameter	**Target1 (lat: 3.2°, long:-62.22°)**	**Target 2 (lat:-7.8°, long:-72.15°)**	**Target3 (lat: -15.68°, long:-52.47°)**
Access Duration (average [min])	0.08	0.07	0.07
Coverage Time (per day [min])	0.14	0.14	0.14
Aver. Accesses per day	1.85	2	1.885
Revisit Time (average [min])	759.18	1642.45	1026.86
Time Average Gap (min)	1560.42	1642.45	1026.86

4. Satellite bus

4.1. Case Study 1: Data collection constellation

The concept of this mission is similar to the one tested with the Serpens nanosatellite [21]. Serpens main goal was the in-orbit testing of new technologies developed by Brazilian universities. Furthermore, it was also part of the Humsat project, being the second nanosatellite of the constellation dedicated to providing a data collection system (e.g., meteorological data, water levels, etc.) over the Brazilian territory and, in particular, support to areas with no access to communications. The main payload was a digital transceiver for data collection developed by the *Universidad de Vigo*, Spain. The data provided by the spacecraft until its reentry in the atmosphere demonstrated that its bus was adequate for the case considered. The Serpens spacecraft is shown in Fig. 4.

The communications subsystem operates with a UHF transceiver. The typical data rate for CubeSat radios in low Earth orbit (9600 *bps*) is sufficient for transmitting telemetry and the collected data, consisting of text messages sent by ground terminals to the spacecraft. Considering a passage of 10 minutes over

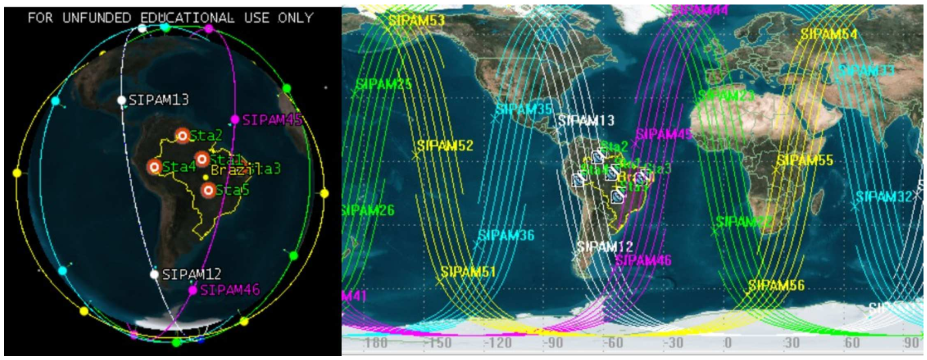

Figure 3: **Configuration of the Walker CubeSats Constellation of 97°: 30/5/1 used to reduce the revisit time and increase accesses to a particular remote area by the constellation (simulations by STK-AGI).**

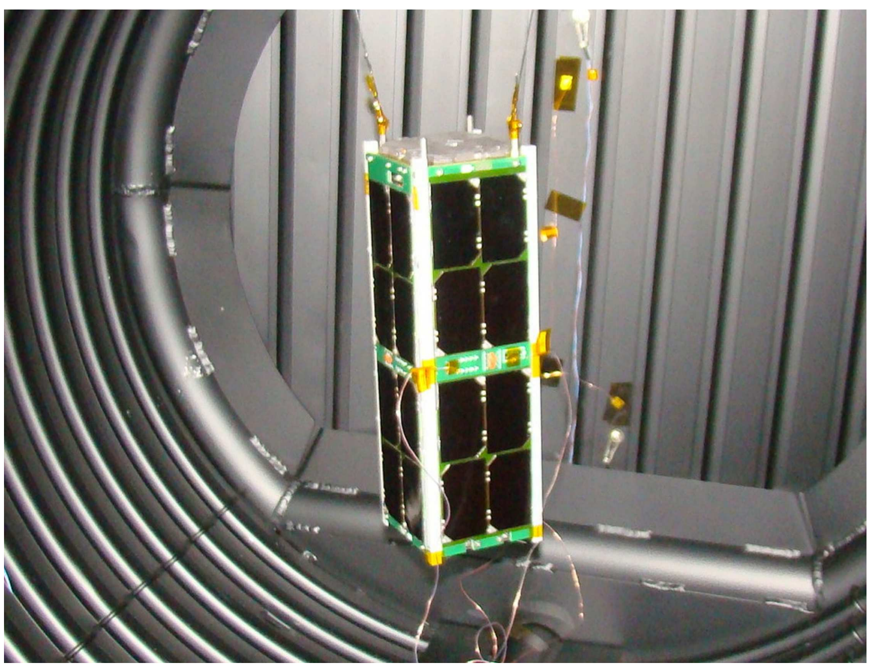

Figure 4: **The Serpens nanosatellite.**

Table 6: **3U CubeSat design specifications to implement the bus needed for case 1 and case 2**

	Case 1	**Case 2**
Dimensions	3U CubeSat	3U CubeSat
TT&C	UHF transceiver (9600 bps) for telemetry and data download	X band transceiver (4 Mbps) for data download S band transceiver (100 kbps) for telemetry
Power produced	> 6 W	> 15 W (foldable solar panels)
ADCS	None	Magnetorquers + reaction wheels $< 1°$ pointing accuracy

a ground station, at the considered data rate one has a total amount of 720 KB of data to transfer. With an average size of 75 B for each message sent by the sensors, and even allowing for a very high number of messages received from the sensors (say 1000) between one passage over a ground station and another, it is possible to download all these information while still having enough data link for the spacecraft telemetry. The amount of power produced by solar panels on board a 3U CubeSat can exceed 6 W, as demonstrated during the Serpens mission. This, along with two commercial batteries with a capacity of 1.276 Ah each, is enough for onboard consumption. The nominal consumption when the payload is activated is less than 2 W, while the maximum consumption during the data download to the ground station is of 4.5 W. Since the passage and the data download last only for 10 minutes on average, the required power can be easily provided by the panels and the batteries. The bus does not include an Attitude Determination and Control System (ADCS), because the payload does not have pointing requirements. The 3U CubeSat design specifications to implement the bus needed for the two cases are shown in Tab. 6.

Table 7: **FOV, covered area and GSD relative to the optical payloads of Planet missions**

	HFOV (km)	VFOV (km)	Area (km^2)	GSD (m)
Case study 1				
Altitude: 500 km	13	8.7	113	3.2
Case study 2				
Altitude: 600 km	15.6	10.4	162	3.9

4.2. Case Study 2: Image collection constellation

In this case, the idea is to board an optical payload on a 3U CubeSat bus to satisfy the mission requirements described in Section 3.2. Optical payloads for Earth observation missions performed by constellations of nanosatellites based on the 3U-CubeSat standard have been developed and flown. A first approximation estimate of the optical payload needed for the mission can therefore be based on actual, space-tested equipment, such as that on board Planet spacecraft, which is briefly described below [23]. Planet Scope 0 (PS0), Planet Scope 1 (PS1) and Planet Scope 2 (PS2) all operate in the visible spectrum, more precisely in the red (630-714 nm), green (515-610 nm) and blue (424-478 nm) bands. A NIR (720-1300 nm) sensor is currently being tested, in order to extend PS2 capability into the NIR region of the spectrum. PS0 and PS1 both feature a 2-element Maksutov-Cassegrain optical system paired with an 11MP CCD detector, the only difference being in the system mounting. PS2 features a more advanced 5-element optical system, paired with a 29MP CCD detector, thus providing a wider Field Of View (FOV) and superior image quality, together with a uniformly high pixel quality and usability over the entire sensor. Since the former system presents a more traditional architecture, and therefore a lower cost, and has been flown at altitudes of 620 km and 420 km, we are using it as a base for the preliminary design of our optical payload. The main design parameters, like across-track FOV (HFOV), along-track FOV (VFOV), covered area and Ground Sampled Distance (GSD), are summarized in Tab. 7.

The 3U bus is composed of commercial off-the-shelf (COTS) boards and

Table 8: **Size of images that can be captured by the CubeSat constellation, depending on the satellite altitude, pixel spatial resolution and the average access duration to the region of interest.**

	Image Size Captured in 1 sec	**Image Size Captured in 4.5 sec**
Pixel Area at 500 Km = 10.3 m^2	62.5 MB (85,8 km^2)	280.8 MB (386 km^2)
Pixel Area at 600 Km= 15.2 m^2	50.8 MB (103 km^2)	228.6 MB (463.5 km^2)

occupies 1.5 U. The remaining 1.5U is sufficient to host the optical cameras [24]. The size of each image varies between 51 MB (worst spatial resolution and duration) and 281 MB (best spatial resolution and duration), as can be seen in Tab. 8. This table summarizes the various types of images that can be acquired by the system as functions of the satellite altitude, pixel spatial resolution and average access duration to the remote area.

Assuming that at least one image is downloaded at each passage over a ground station, an X band transceiver with a data rate of 4 Mbs is considered for data download. The X band transceiver with such features can guarantee downloading of images in 10 minutes (in the worst case) using a good network of ground stations covering the territory as it exists in Brazil (Cuiabá, Belém, Manaus, Porto Velho, Brasília, São José dos Campos, etc.). A supplementary down-link channel for telecommunications, tracking and command is provided by another system operating in the S band [23]. The use of an optical payload for Earth imaging requires strict pointing accuracy capabilities. Precise ADCS for CubeSats are being studied and developed at the University of Brasília [25]. They include reaction wheels and magnetorquers that guarantee pointing accuracies of less than 1°, while occupying 1/3 of a CubeSat unit. The total electric power requested by all the subsystems (optical cameras, radios, attitude control and onboard data handling) is provided by six foldable solar panels, supplemented by a battery package of eight Li-Ion cells [23].

5. Conclusions

CubeSat systems are becoming a very popular way of reducing the costs of access to space and training students and young researchers in space sciences and systems engineering. Today these systems can be built and run with a significantly lower cost than traditional systems. CubeSat constellations could be an interesting way to overcome the revisit time limits of the Very High Spatial Resolution (VHSR) satellite systems, which reduce their operational use for the management of disasters.

In fact, satellite remote sensing for disaster management could take advantage of the potential availability of tens of small satellites like those of Planet, Surrey and other similar systems, thanks to the features highlighted above. The equations needed to distribute the satellites on a homogeneous uniform constellation were presented, and the characteristics of the payload for special telecom and Earth imaging applications have been described, together with the STK simulations of the orbital scenarios to get an appropriate revisit time. The bus for the spacecraft considered in this constellation has been described. In order to be effective in increasing the remote observation opportunities of a given area after a disastrous event, as well as reducing revisit time, specific attention should be devoted to the spatial resolution of the instrument, because a revisit time of minutes or hours would otherwise require the satellites to be located on different orbital planes. This naturally involves the need for a pre-processing phase to compensate the different illumination conditions associated with data coming from different orbital planets.

Finally, the available instruments and design of the type of mission presented in this paper can be enabling tools for a richer and more sustainable Earth science program. In particular, it is our hope that universities around the world that are planning to conceive, design, implement, launch, and operate CubeSats in the next few years will be inspired by the mission ideas proposed in this paper, making a major contribution to disaster management and society while educating their students.

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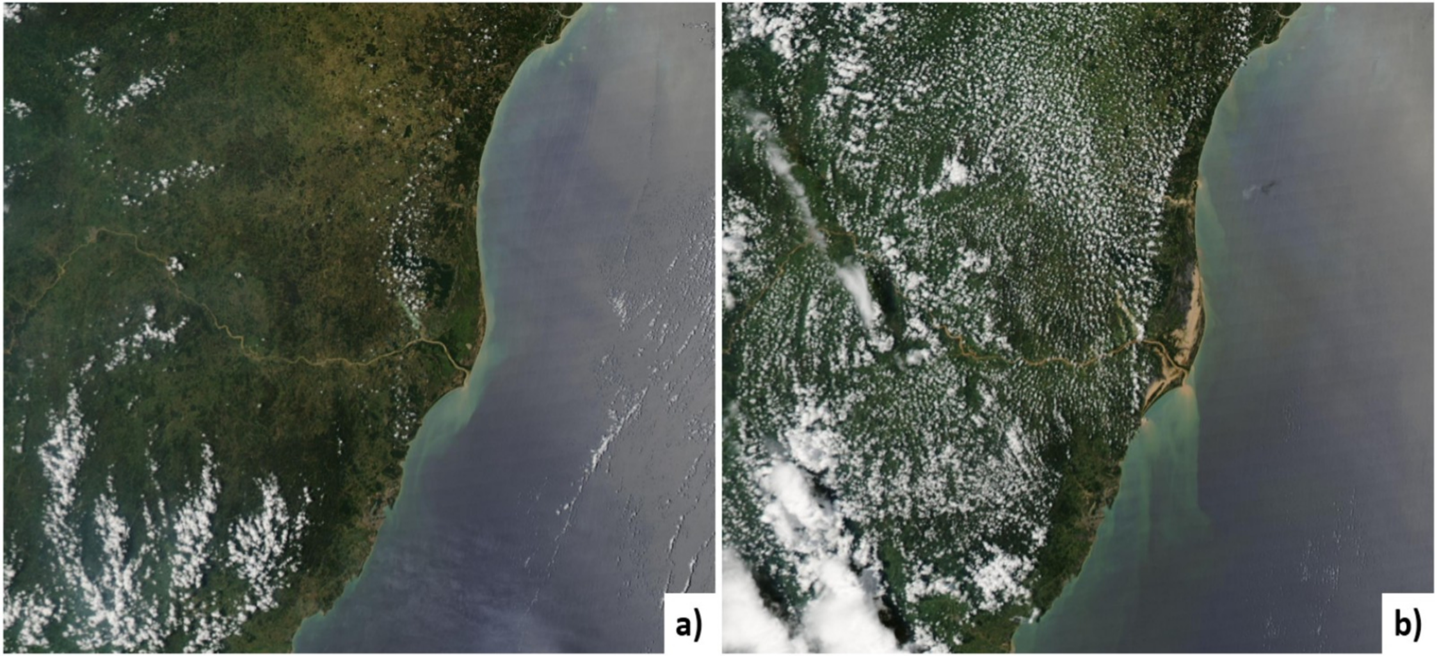
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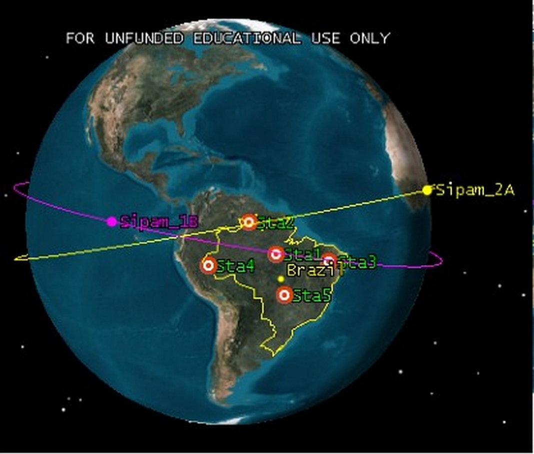
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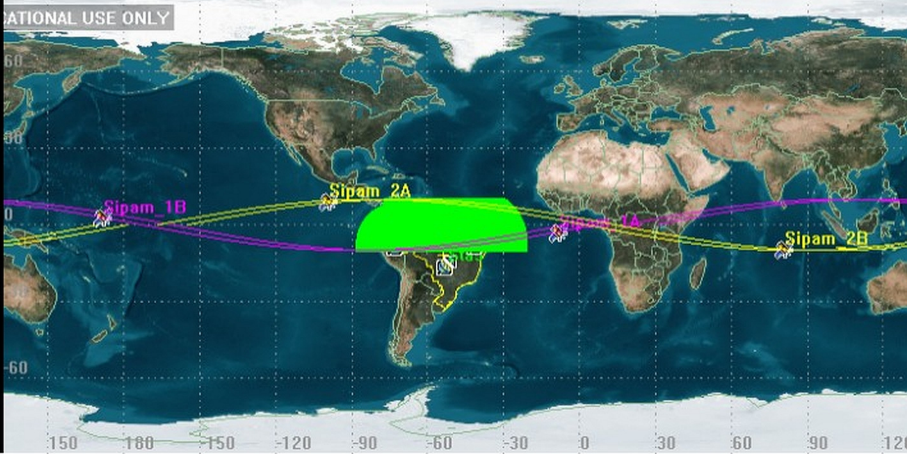
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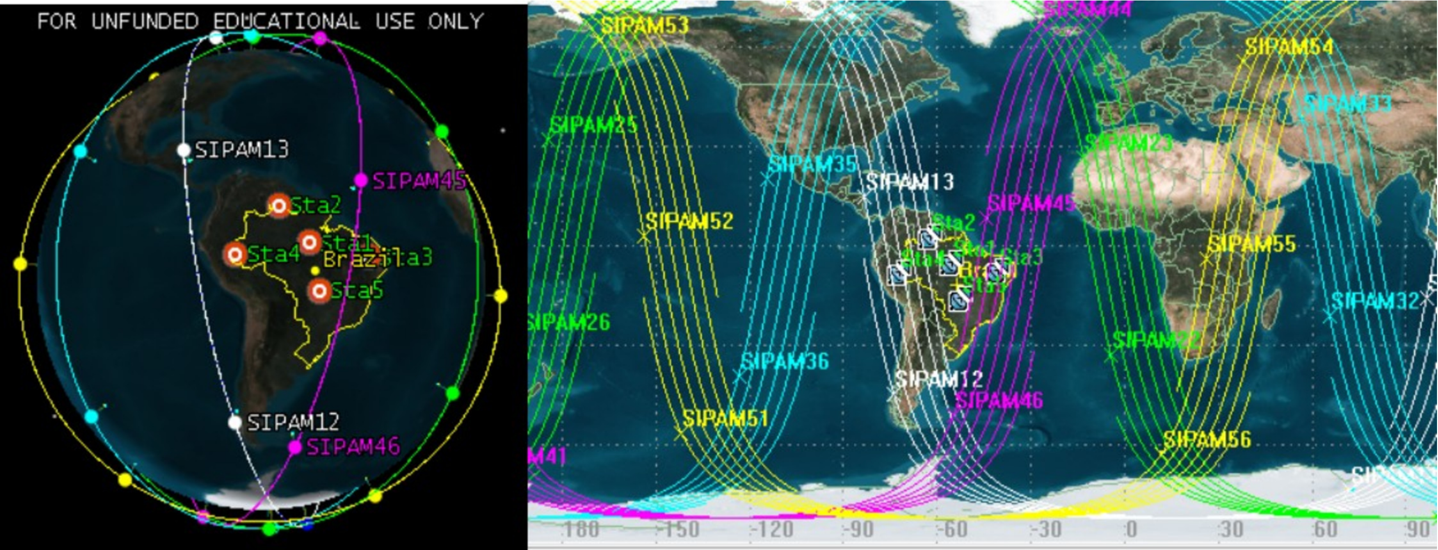
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